

# Effects of Repetition on Associative Recognition in Young and Older Adults: Item and Associative Strengthening

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Young and older adults studied word pairs and later discriminated studied pairs from various types of foils including recombined word-pairs and foil pairs containing one or two previously unstudied words. We manipulated how many times a specific word pair was repeated (1 or 5) and how many different words were associated with a given word (1 or 5) to tease apart the effects of item familiarity from recollection of the association. Rather than making simple old/new judgments, subjects chose one of five responses: (a) *Old-Old (original)*, (b) *Old-Old (rearranged)*, (c) *Old-New*, (d) *New-Old*, (e) *New-New*. Veridical recollection was impaired in old age in all memory conditions. There was evidence for a higher rate of false recollection of rearranged pairs following exact repetition of study pairs in older but not younger adults. In contrast, older adults were not more susceptible to interference than young adults when one or both words of the pair had multiple competing associates. Older adults were just as able as young adults to use item familiarity to recognize which word of a foil was old. This pattern suggests that recollection problems in advanced age are because of a deficit in older adults' formation or retrieval of new associations in memory. A modeling simulation provided good fits to these data and offers a mechanistic explanation based on an age-related reduction of working memory.

*Keywords:* aging, associative recognition, recollection, familiarity, resource model

Dual-process theories of memory propose that two processes underlie recognition memory—recollection and familiarity (e.g., Diana, Reder, Arndt, & Park, 2006; Jacoby, 1991; Mandler, 1980; Reder, Nhouvanisvong, Schunn, Ayers, Angstadt, & Hiraki, 2000; Yonelinas, 1994, 1997, 2002). *Recollection* involves retrieving specific contextual associations, whereas *familiarity* is based on

item strength. An emerging consensus from the dual-process perspective is that the memory impairments characteristic of later adulthood are due primarily to deficits in recollection rather than familiarity (e.g., Buchler & Reder, 2007; Cohn, Emrich, & Moscovitch, 2008; Healy, Light, & Chung, 2005; Hoyer & Verhaeghen, 2006; Jacoby, 1999; Light, Prull, LaVoie, & Healy, 2000; Prull, Dawes, Martin, Rosenberg, & Light, 2006; Rhodes, Castel, & Jacoby, 2008; Yonelinas, 2002).

One line of evidence for this proposition is the pattern of age-related results in associative recognition studies. In associative recognition tasks, subjects are exposed to lists of paired stimuli (most often words) and are subsequently asked to discriminate studied (intact) pairs from various types of lure pairs. Lure pairs can consist of words that were studied but not together (rearranged pairs), one studied word and one new word (item pairs), or two new words (novel pairs) (see Castel & Craik, 2003; Humphreys, 1976, 1978). Recollection is required to discriminate intact pairs from rearranged pairs whose constituents were studied with different partners, because the individual words in these two types of pairs are equally familiar (Kelley & Wixted, 2001; Rotello & Heit, 1999, 2000; Rotello, Macmillan, & Van Tassel, 2000; Yonelinas, 1997). However, item familiarity can be used to discriminate among rearranged, item, and novel word pair foils (Buchler, Light, & Reder, 2008).

Older adults are less able than young adults to discriminate between intact and rearranged pairs in associative recognition (e.g., Castel & Craik, 2003; Healy et al., 2005; Light, Patterson,

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This work was supported in part by fellowship support to the first author in the form of an institutional training Grant 5T32-MH019983-07 to Carnegie-Mellon University from the National Institute of Mental Health, by Grant AGO 2452 from the National Institute on Aging to the third author, and also by Grant MH052808-08 from the National Institute of Mental Health to the fifth author. We thank J. C. Van Ocker and Darlene Olfman for their help with various phases of this project.

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## Report Documentation Page

*Form Approved*  
*OMB No. 0704-0188*

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1. REPORT DATE <b>MAR 2011</b>		2. REPORT TYPE		3. DATES COVERED <b>00-00-2011 to 00-00-2011</b>	
4. TITLE AND SUBTITLE <b>Effects Of Repetition On Associative Recognition In Young And Older Adults: Item And Associative Strengthening</b>				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>Army Research Laboratory, Aberdeen Proving Ground, MD, 21005</b>				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release; distribution unlimited</b>					
13. SUPPLEMENTARY NOTES <b>Psychology and Aging, Mar 2011</b>					
14. ABSTRACT <b>Young and older adults studied word pairs and later discriminated studied pairs from various types of foils including recombined word-pairs and foil pairs containing one or two previously unstudied words. We manipulated how many times a specific word pair was repeated (1 or 5) and how many different words were associated with a given word (1 or 5) to tease apart the effects of item familiarity from recollection of the association. Rather than making simple old/new judgments, subjects chose one of five responses: (a) Old-Old (original), (b) Old-Old (rearranged), (c) Old-New, (d) New-Old, (e) New-New. Veridical recollection was impaired in old age in all memory conditions. There was evidence for a higher rate of false recollection of rearranged pairs following exact repetition of study pairs in older but not younger adults. In contrast, older adults were not more susceptible to interference than young adults when one or both words of the pair had multiple competing associates. Older adults were just as able as young adults to use item familiarity to recognize which word of a foil was old. This pattern suggests that recollection problems in advanced age are because of a deficit in older adults? formation or retrieval of new associations in memory. A modeling simulation provided good fits to these data and offers a mechanistic explanation based on an age-related reduction of working memory.</b>					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>			

Chung, & Healy, 2004; Naveh-Benjamin, 2000; see Old & Naveh-Benjamin, 2008, for a review). In addition, Castel and Craik found that the false alarm rates for both young and older adults increased with the number of study words reinstated at test, from novel pairs (zero), to item pairs (one), to rearranged pairs (two), a result attributed to differences in accumulated word familiarity. Older adults had more false alarms for all types of word pair foils, consistent with the idea that their recognition judgments depend more on familiarity-based processes in the face of a deficit in recollection.

Manipulations involving pair repetition (word or face pairs) provide further evidence that associative recognition deficits in older adults derive from recollection deficits (e.g., Buchler et al., 2008; Gallo, Sullivan, Daffner, Schacter, & Budson, 2004; Kelley & Wixted, 2001; Light et al., 2004; Malmberg & Xu, 2007; Rhodes et al., 2008; Van Ocker, Light, Olfman, & Rivera, 2009). From a dual-process perspective, pair repetition should increase both familiarity and recollection because this repetition strengthens both associative and item information. Therefore, we would expect repetition to increase both the hit rate for intact pairs and the false alarm rate for rearranged pairs. Such a result—an increase in both false alarms and hits with repetition (a pattern dubbed by Jacoby (1999) as an ironic effect of repetition)—has been observed in associative recognition in older adults (Light et al., 2004; Rhodes et al., 2008; Van Ocker et al., 2009). However, in *young adults* repetition may dramatically increase the hit rate to intact pairs, while having little or no effect on the false alarm rate for rearranged pairs (Cleary, Curran, & Greene, 2001; Gallo et al., 2004; Kelley & Wixted, 2001; Light et al., 2004; Rhodes et al., 2008; Van Ocker et al., 2009, but see Malmberg & Xu, 2007, for exceptions).

One way to account for this set of results is to postulate a *recall-to-reject* mechanism (Jones & Jacoby, 2001; Kelley & Wixted, 2001; Rotello & Heit, 2000; Rotello, Macmillan, & Van Tassel, 2000; Yonelinas, 1997). The recall-to-reject account proposes that rearranged word pairs (e.g., OCEAN–PEAR) are rejected because the correct association is retrieved (e.g., OCEAN–TRIP) for one of the words in the rearranged word pair. Thus, increased familiarity because of repetition is offset by an increase in the success of a recall-to-reject strategy because of associative strengthening. If the encoding or retrieval of associative, but not item information, is impaired in older adults (Buchler & Reder, 2007; Chalfonte & Johnson, 1996; Naveh-Benjamin, 2000), then they should be less able to use the recall-to-reject process. In that case, older adults would be more vulnerable to familiarity-based (spurious) recognition for rearranged pairs that have been repeated. In fact, this pattern of more false alarms to repeated (rearranged) pairs is precisely the result observed by Light and her colleagues and by Rhodes et al. (2008).

### Dissociating Familiarity From Recollection Processes

The over-arching goal of this study was to further our understanding of the contributions of recollection and familiarity to memory performance differences between younger and older adults. We used three converging methods to achieve this goal. First, we varied both the number of times a given word pair was studied and also the number of other associations that were studied with each word of a given word pair. We postulate that the

repetition of the word-pair affects both item and associative strength. In contrast, the manipulation of the number of associations to a given item (fan) selectively strengthens items and actually interferes with retrieval of those associations by creating competitors at test. This point is elaborated later.

The second, relatively novel, method was to require a more complex response discrimination. Rather than simply making *old/new* judgments, subjects choose among five alternatives: (a) *Old-Old (original)*, (b) *Old-Old (rearranged)*, (c) *Old-New*, (d) *New-Old*, and (e) *New-New* (see Buchler et al., 2008); we call this task the 5-PAR paradigm. The advantage of providing a set of more fine-grained response categories is that, when combined with the manipulations of item strength, associative strength, and interference, it is easier to discern the role of recollection and familiarity-based recognition.

We included a third method, computational modeling, to help us disentangle the differential contributions of familiarity and recollection to pair recognition when comparing the young and the older adults' data. This seemed critical given that our study had two within subject encoding factors (repetition and fan), five types of targets or foils, and five possible responses, yielding 75 conditions per age group. Our goal was to build a computational model that can account for the pattern of data for young adults using representation and processing assumptions that we have used in the past (e.g., Reder et al., 2000) and also to fit the data for older subjects by using just one more free parameter that we postulate affects ease of forming new associations and subsequently retrieving them, that is, working memory (WM) capacity (Reder, Paynter, Diana, Ngiam, & Dickison, 2008).

### Overview of the Task

During the study phase, some word pairs were repeated five times and some words appeared five times, but never with the same partners. In the latter condition, the familiarity of individual words in a pair is strengthened by repetition but, instead of associative strengthening, there is interference in the ability to retrieve any one association. Figure 1 offers a representation of the items and associations in memory for the various intact, rearranged, item, and novel test probes to word pairs as a result of our experimental manipulations of repetition (one or five presentations) and interference (one or five associations). As shown, the five-fold repetition of word pairs (i.e., the Rep  $\times$  5 condition) increases both the item familiarity and the associative strength of the intact word pairs. The associative interference manipulation, in which words are presented with five different associates (Fan 5-5), allowed us to increase the item strength of the words without strengthening the association. Comparing the Fan 5-5 condition with the Rep  $\times$  5 condition allows us to assess the effects of strengthening the association independent of item familiarity.

In our previous study using the 5-PAR paradigm in young adults (Buchler et al., 2008), the data were consistent with the view that item and associative information are stored as distinct memory representations and make separate contributions at retrieval. These results supported both the representational and decision-making structure of local memory models such as the Source of Activation Confusion model (SAC; Reder et al., 2000). The SAC model proposes that item information and associative information are strengthened and retrieved as distinct units. It also offers an asso-

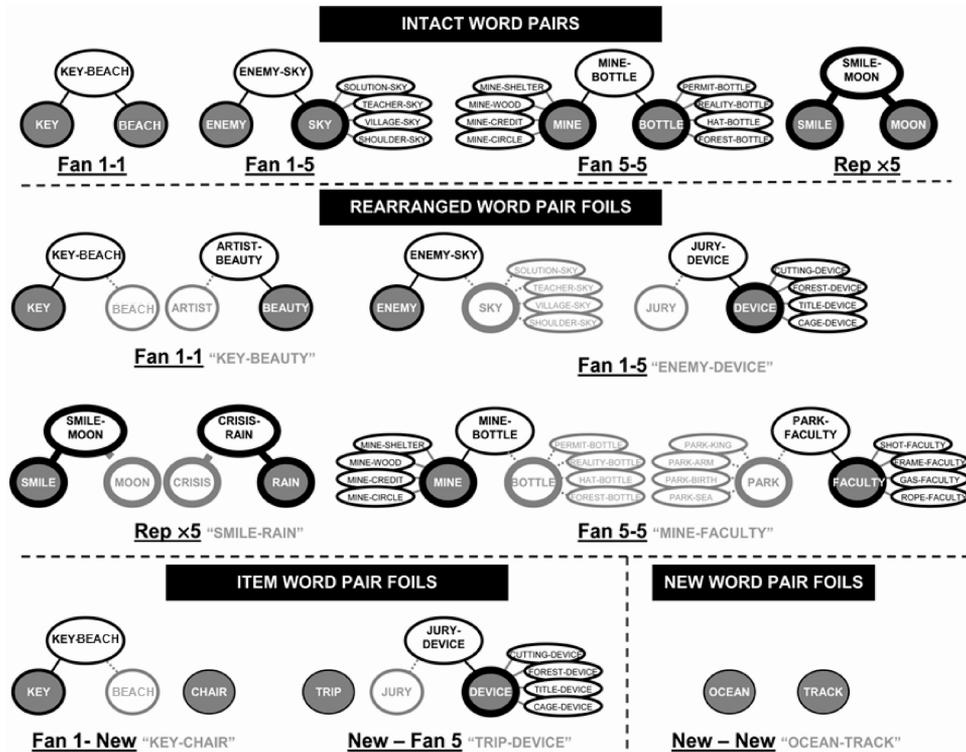


Figure 1. Conceptual illustration of how items (circles) and associations (ovals) are represented and linked in memory and their activation in response to the various *intact*, *rearranged*, *item*, and *novel* test probes to studied word pairs as a result of our experimental manipulations of repetition (1 or 5 presentations) and interference (1 or 5 associations). The filled items in gray depict the words that are activated during test probe presentation. Line thickness denotes item and associative strength resulting from the experimental manipulation of repetition and interference during encoding.

ciative interference mechanism based on diffusion of activation that accounts for fan effects (e.g., Buchler et al., 2008; Diana et al., 2006; Reder et al., 2000; Reder, Angstadt, Cary, Erickson, & Ayers, 2002). The experiment reported here provides incremental support for the new SAC assumption (Reder et al., 2008) that ease of encoding/binding stimuli is a function of available WM resources, and that these resources are diminished in older adults.

## Method

### Subjects

Thirty young adults (22 females) recruited from the Claremont Colleges and 30 older adults (17 females) from the Claremont community participated. The mean ages of the two groups were 19.70 years ( $SD = 1.49$ , range = 18–23) and 74.47 years ( $SD = 4.38$ , range = 67–82). Both groups rated themselves in good health on a 10-point scale, with means of 8.80 ( $SD = 0.92$ ) and 8.02 ( $SD = 1.89$ ), respectively, though the young adult ratings were somewhat higher,  $t(58) = 2.04$ ,  $p < .05$ . Older adults had had more years of education ( $M = 16.90$ ,  $SD = 2.72$ ) than young adults ( $M = 13.47$ ,  $SD = 1.46$ ),  $t(58) = 6.09$ ,  $p < .001$ . There was no effect of age on scores on the Mini-Mental State Examination (Folstein, Folstein, & McHugh, 1975) (young  $M = 29.03$ ,  $SD = 0.85$ ; old  $M = 28.83$ ,  $SD = 0.91$ ),  $t(58) = 0.88$ . Older adults

scored higher ( $M = 20.70$ ,  $SD = 2.32$ ) than young adults ( $M = 15.73$ ,  $SD = 3.42$ ) on 25 items from the Nelson-Denny vocabulary test (Brown, 1960),  $t(58) = 6.58$ ,  $p < .001$ , but they performed less well on a computation span task ( $M = 2.43$ ,  $SD = 1.10$ ) than young adults ( $M = 3.13$ ,  $SD = 1.14$ ),  $t(58) = 2.42$ ,  $p < .02$ . This pattern of higher vocabulary but lower WM scores for older adults is typical. Data from two additional older subjects were excluded, one for poor performance on a secondary task (Trail Making Test, Part B) and one for a score less than 26 on the MMSE. Young and older adults were tested during the same time period under identical conditions. Partial analyses of the young adults' data have been reported in Buchler et al. (2008, Experiment 2).

### Materials and Design

Table 1 illustrates the different experimental conditions used for both young and older adults. Subjects studied word pairs. Each word of the pair could be studied with four other words (Fan 5) or only used in a single pairing (Fan 1). In other words, subjects studied word pairs that consisted of words not studied with other words in the experiment (Fan 1-1), pairs in which either the right word (Fan 1-5) or left word (Fan 5-1) was used with four other pairings, or both words in the pair were each studied with four other word pairs (a total of 5 associations each—Fan 5-5). In addition, half of the Fan 1-1 pairs were repeated 5 times (Rep ×

Table 1

List Composition for the Study and Test Phases as a Function of Levels of Repetition and Fan at Study and Pair Type at Test

Study condition	Number of stimuli	Study word-pairs	Test condition	Level of fan	Number of stimuli	Tested word-pairs			
Fan 1-1	30	KEY-BEACH ARTIST-BEAUTY	Intact	1-1	10	KEY-BEACH			
			Rearranged	1-1	10	KEY-BEAUTY			
			Item	1-new	10	KEY-CHAIR			
			Item	New-1	10	FACULTY-BEACH			
Fan 1-5	20	ENEMY-SKY SOLUTION-SKY TEACHER-SKY VILLAGE-SKY SHOULDER-SKY JURY-DEVICE CUTTING-DEVICE FOREST-DEVICE TITLE-DEVICE CAGE-DEVICE	Intact	1-5	10	ENEMY-SKY			
			Rearranged	1-5	10	ENEMY-DEVICE			
			Item	5-new	10	VILLAGE-PARK			
			Item	New-5	10	TRIP-DEVICE			
			Intact	5-1	10	(see Fan 1-5)			
			Rearranged	5-1	10	(see Fan 1-5)			
			Fan 5-1	20	(see Fan 1-5)	Intact	5-1	10	(see Fan 1-5)
						Rearranged	5-1	10	(see Fan 1-5)
			Fan 5-5	30	PERMIT-BOTTLE REALITY-BOTTLE HAT-BOTTLE FOREST-BOTTLE MINE-BOTTLE MINE-SHELTER MINE-WOOD MINE-CREDIT MINE-CIRCLE PARK-FACULTY SHOT-FACULTY FRAME-FACULTY GAS-FACULTY ROPE-FACULTY	Intact	5-5	10	MINE-BOTTLE
						Rearranged	5-5	10	MINE-FACULTY
Intact	1-1	10				SMILE-MOON			
Rearranged	1-1	10				SMILE-RAIN			
Novel	New-new	30				OCEAN-TRACK			
Rep $\times$ 5	$10 \times 5 = 50$	SMILE-MOON SMILE-MOON SMILE-MOON SMILE-MOON SMILE-MOON CRISIS-RAIN ( $\times 5$ )				Rearranged	5-5	10	MINE-FACULTY
						Intact	1-1	10	SMILE-MOON
						Rearranged	1-1	10	SMILE-RAIN
						Novel	New-new	30	OCEAN-TRACK
						Novel	New-new	30	OCEAN-TRACK

Note. Total pairs studied = 200 Total pairs tested = 170.

5). All other word pairs were studied only once. There were a total of 200 word pair study events (see Table 1).

The recognition test included 170 word pairs that were either reinstated (intact) study pairs or were one of three different types of foil pairs: rearranged, item, or novel. Foil-type was crossed with the repetition and fan manipulation factors with the constraint that rearranged pairs involved reassignment within the same level of fan condition. To illustrate, a Fan 1-5 pair would be rearranged with another Fan 1-5 word pair. Word position within a pair was always preserved in rearranged and item foils. Of the 20 word pairs repeated 5 times during study (Rep  $\times$  5), 10 word pairs were assigned to a rearranged Rep  $\times$  5 condition at test, in which they were randomly swapped, preserving word order. New, previously unstudied, words were used in the item and novel foil pairs. All of the previously presented study words were used, either in word pairs or as part of a foil pair.

The study and test pairs consisted of two words, each 4 to 12 characters in length ( $M = 6.1$ ,  $SD = 2.0$ ). The assignment of words to conditions and order of presentation were randomly

determined for each subject. Stimuli were selected from a pool of 320 common nouns generated from the MRC psycholinguistic database (Wilson, 1988) with word-frequencies between 55 and 95 occurrence per million (Kucera & Francis, 1967).

## Procedure

Subjects were informed before study that some word pairs would be repeated and that some words would be presented several times, each time with a different associate. Word pairs were presented one at a time for 4 s, followed by a 1.5 s delay before the next pair. The words were presented in the center of the display in 18-point font separated by a dash. After study and just before test, subjects were informed about the different types of foil stimuli and about the five possible responses they could make. Their understanding was confirmed by having them describe the five response choices to the experimenter. Test pairs were presented one at a time and each test pair remained on the screen until the subject selected one of the five alternatives listed at the bottom of the

screen in left-to-right order (i.e., *Old-Old (original)*, *Old-Old (rearranged)*, *Old-New*, *New-Old*, *New-New*). The screen was cleared immediately after a response and remained blank for .5 s followed by a fixation stimulus of two dashed lines presented for 1 s before the next test trial began.

## Results

Table 2 (young adults) and Table 3 (old adults) display the proportions of responses to each of the five possible choices for the four different types of test probes (intact, rearranged, item, and novel word pairs) as a function of study condition. The young adult data in Table 2 are reproduced from our previous study (Buchler et al., 2008, Experiment 2). Each row in Tables 2 and 3 represents a response distribution across the five possible memory decisions for a given type of test probe. The correct response for each type of test probe is indicated in bold font. Note that for item word pairs, the correct response was either *Old-New* or *New-Old* depending on whether the reinstated word was on the left or the right. An alpha level of .05 was used for all significant tests, unless otherwise noted.

The first step in the analysis was to determine whether there were age-related differences in the distribution of responses to novel word pairs—the baseline condition. This was established with multiple pairwise comparisons of the responses to novel word pairs from Table 3 (older adults) to those in Table 2 (young adults), using the Tukey-Kramer correction (Kramer, 1956; Tukey, 1953). No value in Table 3 was significantly different from its corresponding value in Table 2. Thus, there were no age-related differences in responding to novel word pairs. It is common practice when comparing across age groups to correct associative recogni-

tion memory data by subtracting out baseline errors on new lure pairs. However, given the absence of age differences on these pairs, we carried out the remaining analyses on uncorrected proportions to simplify the exposition.

Visual inspection of the bolded correct responses in Tables 2 and 3 strongly suggests that young and older subjects alike were able to correctly identify each type of test probe with better than chance accuracy (see 95% confidence intervals in parentheses). We applied the analytic strategy used in Buchler et al. (2008, Experiment 1) to provide statistical support for this claim. If subjects can distinguish among the various word-pair types then the proportion of correct responses should differ reliably from the proportion of responses to novel word pairs for any given response category. We compared the proportions of correct and incorrect responses for stimuli in which words were studied once—the intact (Fan 1-1), rearranged (Fan 1-1), and item (Fan 1-New, New-Fan 1) word-pair types—to novel (New-New) word pairs. Multiple pairwise comparisons, using the Dunnett (1955) procedure, established that the proportion of correct responses for each type of word-pair was significantly different from responses to novel word pairs for both young and older adults ( $p < .001$ ). For example, the proportion of correct older adult *Old-Old (original)* responses to intact (Fan 1-1) word pairs ( $M = .28$ ) differed from the proportion of incorrect *Old-Old (original)* responses to novel (New-New) word pairs ( $M = .02$ ). Just as the correct responses were reliably different from the response proportions to novel pairs, the incorrect responses (unbolded cells) generally were not different from the novel pairs ( $p < .05$ ). In our older adult data, for example, the proportion of incorrect *Old-Old (original)* responses to rearranged (Fan 1-1) word pairs ( $M = .05$ ) did not differ from those to novel

Table 2  
Young Adult Mean Proportion of Responses to Each of the Four Word-Pair Types in the Word Pair Recognition Test as a Function of the Number of Associates (Fan) for Word 1 and Word 2

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

Note. Correct responses are shown in bold. Variability is given in parentheses as 95% confidence intervals. From "Memory for items and associations: Distinct representations and processes in associative recognition," by N. E. G. Buchler, L. L. Light, & L. M. Reder, 2008, *Journal of Memory and Language*, 59, 183–199. Copyright 2008 by Elsevier. Reprinted with permission.

Table 3

*Older Adult Mean Proportion of Responses to Each of the Four Word-Pair Types in the Word Pair Recognition Test as a Function of the Number of Associates (Fan) for Word 1 and Word 2*

Word pair	Response				
	Old-Old (original)	Old-Old (rearranged)	Old-New	New-Old	New-New
Intact pair					
Fan 1-1	<b>.28</b> (.07)	.14 (.04)	.12 (.04)	.10 (.03)	.36 (.09)
Fan 1-5	<b>.31</b> (.07)	.27 (.07)	.03 (.02)	.30 (.07)	.09 (.04)
Fan 5-1	<b>.26</b> (.07)	.30 (.05)	.32 (.06)	.03 (.02)	.09 (.04)
Fan 5-5	<b>.45</b> (.08)	.42 (.07)	.07 (.04)	.03 (.03)	.03 (.03)
Rep × 5	<b>.75</b> (.09)	.15 (.06)	.03 (.02)	.03 (.02)	.04 (.02)
Rearranged pair					
Fan 1-1	.05 (.03)	<b>.18</b> (.05)	.15 (.05)	.15 (.04)	.47 (.10)
Fan 1-5	.16 (.06)	<b>.29</b> (.07)	.07 (.03)	.39 (.07)	.09 (.04)
Fan 5-1	.09 (.04)	<b>.35</b> (.07)	.44 (.06)	.04 (.02)	.07 (.03)
Fan 5-5	.24 (.08)	<b>.62</b> (.07)	.04 (.03)	.09 (.04)	.01 (.01)
Rep × 5	.17 (.06)	<b>.48</b> (.08)	.16 (.05)	.14 (.04)	.05 (.03)
Item pair					
Fan 1-New	.04 (.03)	.08 (.04)	<b>.24</b> (.05)	.10 (.04)	.53 (.08)
New-Fan 1	.03 (.02)	.07 (.03)	.10 (.05)	<b>.19</b> (.06)	.61 (.10)
Fan 5-New	.06 (.03)	.23 (.07)	<b>.57</b> (.08)	.02 (.01)	.13 (.05)
New-Fan 5	.11 (.05)	.18 (.06)	.04 (.02)	<b>.59</b> (.09)	.07 (.05)
Novel pair					
New-New	.02 (.01)	.07 (.03)	.12 (.03)	.11 (.03)	<b>.69</b> (.08)

*Note.* Correct responses are shown in bold. Variability is given in parentheses as 95% confidence intervals.

(New-New) word pairs ( $M = .02$ ). There were two exceptions to this generalization, both in the young adult data; the proportion of *Old-New* ( $M = .19$ ) and *New-Old* ( $M = .20$ ) responses to rearranged word pairs were both significantly different from the response proportion to novel word pairs (*Old-New*  $M = .10$ , *New-Old*  $M = .10$ ), but only at a relaxed alpha level of  $p = .01$ .

In summary, both young and older adults could calibrate responses to the various stimuli. The proportions of correct responses given by young and older adults were significantly different from baseline for each type of word-pair, whereas the proportions of incorrect responses typically were not, demonstrating subjects' ability to distinguish among all five word-pair stimulus-types on the recognition test. Below, we examine the roles of other factors in the study, specifically the effects of repetition strengthening of study pairs and associative interference on associative recognition for the two age groups.

### Does Pair Repetition Affect Associative Recognition in the Same Way for Young and Old Adults?

Hits were defined as *Old-Old (original)* responses to intact word pairs and false alarms were defined as *Old-Old (original)* responses to rearranged word pairs. Hit rates for young and older adults (see Figure 2, Panel A) were examined in the intact Fan 1-1 and Rep × 5 word pair conditions. A 2 (Age) × 2 (Repetition) ANOVA yielded significant main effects of both Age,  $F(1, 116) = 10.39$ ,  $p < .005$ ,  $\eta_p^2 = .08$ , and Repetition,  $F(1, 116) = 109.99$ ,  $p < .001$ ,  $\eta_p^2 = .49$ , but no interaction,  $F(1, 116) = 0.73$ ,  $p = .39$ ,  $\eta_p^2 = .006$ . Thus, there was an age-related associative memory deficit, but older adults benefited from the five-fold repetition of word pairs to an extent similar to that of young adults.

We also examined the degree to which repeating a word pair five times increased false alarms to rearranged lures for both

young and older adults. The false alarm rates for young and older adults were examined in the rearranged Fan 1-1 and Rep × 5 word pair conditions. A 2 (Age) × 2 (Repetition) ANOVA established a significant main effect of Repetition,  $F(1, 116) = 14.40$ ,  $p < .001$ ,  $\eta_p^2 = .11$ . Neither Age,  $F(1, 116) = 0.77$ ,  $p = .38$ ,  $\eta_p^2 = .007$ , nor the interaction of Age × Repetition,  $F(1, 116) = 1.73$ ,  $p = .19$ ,  $\eta_p^2 = .015$ , was significant. The lack of an Age × Repetition interaction was unexpected as repetition has been shown to increase false alarms to rearranged lures in older adults in a number of other studies (Light et al., 2004; Rhodes et al., 2008; Van Ocker et al., 2009). To further explore this matter, we carried out planned comparisons in young and older adults separately. We found a significant increase in associative false alarms with the five-fold word pair repetition for older adults,  $F(1, 30) = 7.42$ ,  $p = .007$ ,  $\eta_p^2 = .15$ , but not for young adults,  $F(1, 30) = 2.10$ ,  $p = .15$ ,  $\eta_p^2 = .07$ . Thus, the effects of pair strengthening on rearranged lures in the present study are consistent with prior results.

To provide a measure of the sensitivity of correctly identifying associated word pairs, we calculated  $d'$  scores (Swets, 1961; Tanner & Swets, 1954) in the Fan 1-1 and Rep × 5 word pair conditions. The  $d'$  scores increased with five-fold repetition in both the young,  $M = 1.27$  ( $SE = 0.12$ ) to  $M = 2.29$  ( $SE = 0.15$ ), and the older adults,  $M = 0.78$  ( $SE = 0.14$ ) to  $M = 1.82$  ( $SE = 0.19$ ) for the Fan 1-1 and Rep × 5 word pairs, respectively. A 2 (Age) × 2 (Repetition) ANOVA established significant main effects of Repetition,  $F(1, 116) = 45.90$ ,  $p < .0001$ ,  $\eta_p^2 = .28$ , and Age,  $F(1, 116) = 9.93$ ,  $p = .002$ ,  $\eta_p^2 = .08$ , but no interaction between age and repetition,  $F(1, 116) = 0.001$ ,  $p = .97$ ,  $\eta_p^2 < .001$ . Thus, repetition increased recognition sensitivity for both age groups equivalently even though young adults were generally better able to discriminate previously associated word pairs.

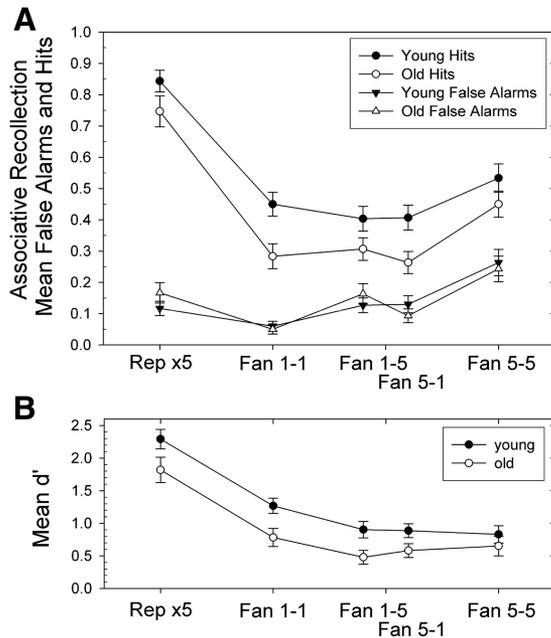


Figure 2. Panel A. Young (closed symbol) and older adult (open symbol) proportions of ‘Old-Old (original)’ hit responses to intact word pairs and ‘Old-Old (original)’ false alarm responses to rearranged word pairs as a function of increasing associative interference (Rep  $\times$  5, Fan 1-1, [Fan 1-5, Fan 5-1], Fan 5-5). Panel B. Mean  $d'$  statistic as a function of associative interference. The error bars are  $SEM$ .

### Are the Effects of Repetition in Strengthening Single Items and Pairs Similar Across Age?

Next, we compared the effects of repetition on the strengthening of item and associative information in young and older adults. By examining the proportions of hits and false alarms in the recognition of Rep  $\times$  5 and Fan 5-5 word pairs, we can separate the effects of strengthening the association between words in a pair from the strengthening of the individual words in the pair (see Figure 2, Panel A).<sup>1</sup> This was assessed by means of separate 2 (Age)  $\times$  2 (Condition) ANOVAs on the hit and false alarm rates. The fivefold repetition of an intact word pair (Rep  $\times$  5 condition) resulted in a significantly higher proportion of hits [*Old-Old (original)* responses] than in the intact Fan 5-5 condition,  $F(1, 116) = 49.49$ ,  $p < .0001$ ,  $\eta_p^2 = .04$ . Although young adults were more accurate than older adults,  $F(1, 116) = 4.36$ ,  $p < .05$ ,  $\eta_p^2 = .30$ , there was no interaction of age with pair type,  $F(1, 116) = 0.02$ ,  $p = .88$ ,  $\eta_p^2 < .001$ .

Turning to an analysis of false alarms, the five-fold repetition of a word pair (Rep  $\times$  5 condition) resulted in significantly fewer false alarms [*Old-Old (original)* responses to rearranged word pairs] than did repetition of individual words in the Fan 5-5 condition,  $F(1, 116) = 9.84$ ,  $p = .002$ ,  $\eta_p^2 = .08$ . There were no age-related differences in the false alarm rate,  $F(1, 113) = 0.18$ ,  $p = .67$ ,  $\eta_p^2 = .002$ , nor was there interaction of age and condition,  $F(1, 113) = 0.97$ ,  $p = .33$ ,  $\eta_p^2 = .008$ . This latter finding is surprising since we expected that older adults would be more susceptible to memory errors with the high levels of associative interference in the Fan 5-5 condition (Cohen, 1990; Gerard, Zacks, Hasher, & Radvansky, 1991).

Turning now to sensitivity, repeating the same word pair five times increased  $d'$  scores in both the young, from  $M = 0.83$  ( $SE = 0.13$ ) to  $M = 2.29$  ( $SE = 0.15$ ), and the older adults, from  $M = 0.65$  ( $SE = 0.15$ ) to  $M = 1.82$  ( $SE = 0.19$ ), for Fan 5-5 and Rep  $\times$  5 word pairs, respectively. A 2 (Age)  $\times$  2 (Repetition) ANOVA established significant main effects of Repetition,  $F(1, 116) = 68.70$ ,  $p < .0001$ ,  $\eta_p^2 = .37$ , and Age,  $F(1, 116) = 4.23$ ,  $p = .04$ ,  $\eta_p^2 = .04$ , but no interaction between age and repetition,  $F(1, 116) = 0.86$ ,  $p = .35$ ,  $\eta_p^2 = .01$ . Thus, repeating the same association—and not just the constituent words in the pair—is key to improving associative recognition in both young and older adults.

In summary, older adults benefited from both repetition strengthening (i.e., Rep  $\times$  5 vs. Fan 1-1) and associative strengthening (i.e., Rep  $\times$  5 vs. Fan 5-5) to the same degree as young adults as evidenced by a lack of age-related interactions in recognition sensitivity. A focal comparison demonstrated an age-related deficit in the hit rate when comparing Rep  $\times$  5 performance to Fan 5-5 word pairs. Taken together, these results suggest that older adults initially have a weaker associative memory representation than young adults, but that this weak association can be strengthened through repeated exposure to an extent similar to that of younger adults.

### Does Associative Interference Have a Larger Negative Impact on Associative Recognition in Older Adults Than in Young Adults?

Here, we focused on the effects of interference on associative recognition in young and older adults. As above, we compared *Old-Old (original)* responses to intact word pairs (hits) and rearranged word pairs (false alarms). Hits and false alarms were examined as a function of Age and increasing associative interference (i.e., Fan, the number of overlapping word pairs)—Fan 1-1, (Fan 1-5, Fan 5-1), and Fan 5-5. Young adults had a consistently higher hit rate than older adults,  $F(1, 234) = 17.60$ ,  $p < .001$ ,  $\eta_p^2 = .08$ , and there was a main effect of Fan,  $F(2, 234) = 9.57$ ,  $p < .001$ ,  $\eta_p^2 = .08$ , but no Age  $\times$  Fan interaction,  $F(2, 234) = 0.56$ ,  $p = .57$ ,  $\eta_p^2 = .005$  (see Figure 2, Panel A). A series of planned contrasts indicated that between the first two levels of the fan manipulation—Fan 1-1 and (Fan 1-5, Fan 5-1)—hits did not increase for either the young,  $F(1, 119) = 0.82$ ,  $p = .37$ ,  $\eta_p^2 = .01$ , nor the older adults,  $F(1, 119) = 0.002$ ,  $p = .97$ ,  $\eta_p^2 < 0.001$ . However, between the last two levels of the fan manipulation—(Fan 1-5, Fan 5-1) and Fan 5-5—significant increases were observed for the hits, both for young,  $F(1, 119) = 6.68$ ,  $p = .01$ ,  $\eta_p^2 = .07$ , and older adults  $F(1, 119) = 12.36$ ,  $p < .001$ ,  $\eta_p^2 = .13$ . This finding is not entirely unexpected as presenting multiple overlapping word pairs improves retrieval of item information but

<sup>1</sup> Differences in performance between Fan 5-5 and Rep  $\times$  5 could be due not only to differential strengthening of items and associations, but also to increased associative interference in the former condition. There is evidence, however, to discount associative contextual interference as a weaker influence. Hockley and Cristi (1996) found that participants are able to accurately make frequency judgments (zero to four repetitions) for words and word pairs irrespective of whether the words and word pairs are studied in a mixed condition (comprised of singletons and pairs) or whether they are studied in a pure unmixed repetition condition.

impairs retrieval of associative information, leading to mixed results (for a discussion, see Buchler et al., 2008).

Figure 2 (Panel A) also shows a systematic increase in the proportion of false alarms for both age groups with increases in fan. False alarms to rearranged pairs increased with interference (Fan),  $F(2, 234) = 23.98, p < .001, \eta_p^2 = .17$ , but there was no main effect of age or interaction of fan with age, with  $F(1, 234) = 0.21, p = .65, \eta_p^2 = 0.001$ , and  $F(2, 234) = 0.08, p = .92, \eta_p^2 = 0.001$ , respectively. A series of contrasts indicated that between the first two levels of the fan manipulation—Fan 1-1 and (Fan 1-5, Fan 5-1)—false alarms increased significantly for both the young,  $F(1, 119) = 3.79, p < .05, \eta_p^2 = .07$ , and older adults,  $F(1, 119) = 4.68, p < .05, \eta_p^2 = .07$ . Between the last two levels of the fan manipulation—(Fan 1-5, Fan 5-1) and Fan 5-5—significant increases in false associative recollection were also observed for both young,  $F(1, 119) = 14.79, p < .001, \eta_p^2 = .12$ , and older adults  $F(1, 119) = 10.08, p < .01, \eta_p^2 = .08$ . Thus, older adults were not more susceptible to false recollection than young adults in response to increased fan. As noted earlier, this was a surprising result as we expected older adults to make more false recollection errors, particularly in response to the interference manipulation.

As seen in Figure 2 (Panel B),  $d'$  declined monotonically as a function of increasing associative interference—Fan 1-1, (Fan 1-5, Fan 5-1), Fan 5-5—for both age groups and older adults exhibited generally lower sensitivity. A 2 (Age)  $\times$  3 (Fan) ANOVA confirmed these visual impressions— $d'$  decreased significantly across fan manipulation,  $F(2, 234) = 4.56, p < .05, \eta_p^2 = .04$ , as well as across age,  $F(2, 234) = 13.88, p < .001, \eta_p^2 = .06$ . There was no Age  $\times$  Fan interaction,  $F(2, 234) = 0.79, p = .46, \eta_p^2 = .007$ . The contrast between Fan 1-1 and (Fan 1-5, Fan 5-1) was significant for the young,  $F(1, 119) = 6.38, p < .05, \eta_p^2 = .07$ , and marginally significant for older adults,  $F(1, 119) = 2.67, p = .10, \eta_p^2 = .03$ . The contrast between (Fan 1-5, Fan 5-1) and Fan 5-5 was not significant for either young,  $F(1, 119) = 0.19, p = .67, \eta_p^2 = .002$ , nor older adults,  $F(1, 119) = 0.62, p = .43, \eta_p^2 = .007$ . In summary, retrieval sensitivity was generally lower in older adults and—to a similar extent in both age-groups—declined with increasing levels of associative interference.

### Is Use of Item Information in Associative Recognition Preserved in Old Age?

We approached the question of preserved familiarity in old age in two ways. Our first analysis compared the proportions of familiarity of item-based responses (i.e., *Old-Old (rearranged)*, *Old-New*, *New-Old*, *New-New*) across the two age-groups. Multiple pairwise comparisons with the Tukey-Kramer correction were used to compare the matching proportions of five-choice responses for each lure type from Table 3 (older adults) to those in Table 2 (young adults). The older adult responses in Table 3 closely matched those of the young adults in Table 2 across all four item-based responses and memory probe conditions. No value in Table 3 was significantly different (all  $ps > .05$ ) from its corresponding value listed in Table 2. Thus, there were no specific age-related differences in familiarity-based responding.

Our second approach capitalized on the response specificity required by the 5-PAR recognition task. In the 5-PAR task, if a subject fails to retrieve the relevant association from memory when an intact pair is presented and therefore does not produce an

*Old-Old (intact)* response, the word pair may nonetheless be judged as consisting of two previously studied elements by making an *Old-Old (rearranged)* response. In comparing Tables 2 and 3, it is evident that the summed proportion of responses to intact word pairs across the first two response categories [*Old-Old (original)* + *Old-Old (rearranged)*] were virtually identical in young and older adults for each level of the fan manipulation for intact word pairs. This suggests that although older adults are less likely to recollect the association—as described in our earlier analysis of correct responses to intact pairs—they make more responses based on pair familiarity when they fail to recollect the association. The sole exception was for intact Fan 1-1 word pairs where there was a significant age-related difference in the summed response proportions,  $F(1, 60) = 5.92, p = .02, \eta_p^2 = .09$ . Thus, for word pairs studied only once, our results also suggest that item memory is impaired in old age.

We tested the hypothesis that older adults are more likely to use familiarity-based responding when they cannot retrieve the correct association for intact pairs by examining *Old-Old (original)* and *Old-Old (rearranged)* response proportions in a 2 (Age)  $\times$  3 (Fan Repetition: [Fan 1-5, Fan 5-1], Fan 5-5, Rep  $\times$  5)  $\times$  2 (Response) ANOVA. Older adults did indeed respond *Old-Old (rearranged)* rather than *Old-Old (original)* as indicated by a significant Age  $\times$  Response interaction,  $F(1, 468) = 21.84, p < .0001, \eta_p^2 = .05$ , together with a non-significant main effect of Age,  $F(1, 468) = 0.30, p = .58, \eta_p^2 = .00$ , and nonsignificant interactions of Age  $\times$  Fan,  $F(1, 468) = 0.03, p = .97, \eta_p^2 = .00$ , and Age  $\times$  Fan  $\times$  Response,  $F(1, 468) = 0.37, p = .69, \eta_p^2 = .00$ . In summary, older adults give more weight to item information in making a recognition response in the face of age-related failure to retrieve associative memories.

### Testing the Adequacy of the WM Deficit Model

We used a third converging method to help disentangle the differential contributions of familiarity and recollection when comparing memory in younger and older adults. We used the SAC dual process model of memory (e.g., Diana et al., 2006; Reder et al., 2002; Reder et al., 2000; Reder et al., 2007; Reder et al., 2008). The classic SAC assumptions can explain the effects of strengthening and fan quite easily and have been used to fit many similar datasets, holding almost all parameter values constant across groups. Recently, Reder et al. (2008) have elaborated the SAC model to incorporate assumptions about the role of WM in the probability of forming an association. Of special interest in the present context was whether the newer assumptions would be adequate to account for the age differences in the 5-PAR paradigm. We tested whether our model could fit the 75 data points for each age group by varying only a single parameter—WM capacity—between the two age groups. Below we briefly describe the model assumptions and explain how we fit the data. The results of the model fitting are given in Table 4 (young) and Table 5 (older adults).

**Representation and retrieval assumptions.** SAC is an experience/history sensitive model that represents information as a set of interconnected nodes. Concept nodes are linked to semantically related nodes as well as nodes representing the constituent features of the concept (e.g., phonemic and lexical features, semantic features, perceptual features). Episode nodes are new mem-

Table 4  
*Limited Resource Model Fits to the Young Adult Data*

Word pair	Response				
	Old-Old (original)	Old-Old (rearranged)	Old-New	New-Old	New-New
	Data [model]	Data [model]	Data [model]	Data [model]	Data [model]
Intact pair					
Fan 1-1	.45 [.32]	11 [.03]	.06 [.24]	10 [16]	.28 [.31]
Fan 1-5	.40 [.47]	19 [.09]	.04 [.07]	.29 [.34]	.07 [.05]
Fan 5-1	.40 [.48]	19 [.09]	.31 [.33]	.02 [.07]	.08 [.05]
Fan 5-5	.53 [.54]	.37 [.22]	.04 [.12]	.05 [.11]	.01 [.02]
Rep × 5	.84 [.87]	.06 [.06]	.04 [.04]	.03 [.04]	.03 [.00]
Rearranged pair					
Fan 1-1	.06 [.02]	.20 [.11]	19 [.29]	.20 [.19]	.35 [.34]
Fan 1-5	13 [.05]	.35 [.27]	.04 [.08]	.42 [.41]	.07 [.08]
Fan 5-1	13 [.05]	.32 [.26]	.45 [.42]	.02 [.08]	.07 [.08]
Fan 5-5	.26 [.11]	.61 [.54]	.05 [.14]	.06 [.14]	.01 [.03]
Rep × 5	12 [.14]	.53 [.66]	14 [.06]	14 [.06]	.08 [.00]
Item pair					
Fan 1-New	.02 [.01]	.08 [.04]	.29 [.40]	.08 [.06]	.53 [.47]
New-Fan 1	.04 [.00]	.07 [.04]	.06 [.13]	.31 [.26]	.52 [.55]
Fan 5-New	.04 [.02]	17 [.15]	.69 [.66]	.02 [.03]	.08 [.13]
New-Fans	.07 [.02]	.10 [.15]	.02 [.03]	.72 [.66]	.09 [.13]
Novel pair					
New-New	.01 [.00]	.05 [.02]	10 [17]	10 [.08]	.74 [.72]

*Note.* Young adult data and model fits [in brackets] shown as the mean proportion of responses to each of the four word-pair types in the word-pair recognition test as a function of the number of associates (fan) for word 1 and word 2. Correct responses are shown in bold. Overall model fit statistics for trend and deviations from data are,  $r^2 = .90$  and  $SSE = .31$ , respectively.  $SSE =$  sum squared error.

ory traces formed during the study phase that bind a concept (e.g., word) to the context in which it was experienced. An episode node can also represent the binding of two words that are experienced together in experiments like ours. There is also a node for the

general experimental context in the model that has features of the experiment bound to it and which is also linked to the episode nodes. It is the detailed specification of how representations change with experience and how activation values are interpreted

Table 5  
*Limited Resource Model Fits to the Older Adult Data*

Word pair	Response				
	Old-Old (original)	Old-Old (rearranged)	Old-New	New-Old	New-New
	Data [model]	Data [model]	Data [model]	Data [model]	Data [model]
Intact pair					
Fan 1-1	.28 [.25]	14 [.05]	12 [.25]	10 [.17]	.36 [.34]
Fan 1-5	.31 [.38]	.27 [.12]	.03 [.07]	.30 [.38]	.09 [.06]
Fan 5-1	.26 [.40]	.30 [.11]	.32 [.37]	.03 [.07]	.09 [.06]
Fan 5-5	.45 [.50]	.42 [.24]	.07 [.12]	.03 [.12]	.03 [.02]
Rep × 5	.75 [.85]	15 [.06]	.03 [.05]	.03 [.05]	.04 [.00]
Rearranged pair					
Fan 1-1	.05 [.01]	.18 [.09]	15 [.28]	15 [.18]	.47 [.40]
Fan 1-5	16 [.05]	.29 [.26]	.07 [.08]	.39 [.43]	.09 [.09]
Fan 5-1	.09 [.05]	.35 [.26]	.44 [.43]	.04 [.08]	.07 [.09]
Fan 5-5	.24 [.11]	.62 [.52]	.04 [.14]	.09 [.14]	.01 [.03]
Rep × 5	17 [.14]	.48 [.63]	16 [.07]	14 [.07]	.05 [.01]
Item pair					
Fan 1-New	.04 [.00]	.08 [.05]	.24 [.38]	10 [.08]	.53 [.48]
New-Fan 1	.03 [.00]	.07 [.05]	10 [.14]	.19 [.25]	.61 [.54]
Fans-New	.06 [.02]	.23 [.15]	.57 [.65]	.02 [.04]	.13 [.13]
New-Fans	11 [.02]	.18 [.15]	.04 [.04]	.59 [.65]	.07 [.14]
Novel pair					
New-New	.02 [.00]	.07 [.03]	12 [.18]	11 [.09]	.69 [.71]

*Note.* Older adult data and model fits [in brackets] shown as the mean proportion of responses to each of the four word-pair types in the word-pair recognition test as a function of the number of associates (fan) for word 1 and word 2. Correct responses are shown in bold. Overall model fit statistics for trend and deviations from data are  $r' = .88$  and  $SSE = .33$ , respectively, with only one parameter varied between the young and older adult models to account for 75 data points.  $SSE =$  sum squared error.

in particular situations that allows SAC to make specific, quantifiable predictions for many types of tasks.<sup>2</sup>

**1. Node strength.** The base-line strength of a concept (also known as resting level of activation) increases and decreases according to a power function, depending on how often and how recently it was last experienced:

$$B = c \sum t_i^{-d} \quad (1)$$

where  $B$  is the base level activation,  $c$  and  $d$  are constants, and  $t_i$  is the time since the  $i$ th presentation.

**2. Link strength.** Links connect concepts (nodes) that have been associated experienced at the same time. The strength of these links also varies with history of exposure:

$$S_{s,r} = \sum t_i^{-dL} \quad (2)$$

where  $S_{s,r}$  is the strength of the link from the node  $s$  to node  $r$ ,  $t_i$  is the time since the  $i$ th co-exposure, and  $d_L$  is the decay constant for links.

**3. Spread of activation.** The current activation level of a node can increase by receiving environmental stimulation directly or by receiving activation that has spread from another node in the network to which it is linked. The change in activation of some node  $r$  is computed by summing the spread of activation from all source nodes  $s$  connected to node  $r$  according to the equation:

$$\Delta A_r = \sum (A_s * S_{s,r} / \sum S_{s,i}) \quad (3)$$

where  $\Delta A_r$  is the change in activation of the receiving node  $r$ ,  $A_s$  is the activation of each source node  $s$ ,  $S_{s,r}$  is strength of the link between nodes  $s$  and  $r$ , and  $\sum S_{s,i}$  is sum of the strengths of all links emanating from node  $s$ . The effect of the ratio  $S_{s,r} / \sum S_{s,i}$  is to limit the total spread from a node  $s$  to all connected nodes such that it is equal to the node's current activation  $A_s$ . This feature gives the model the ability to simulate *fan effects* (e.g., Anderson, 1974; Reder & Ross, 1983). When the test probe words activate their corresponding concept nodes, activation will spread from both source nodes to all of their associated contexts. The activation spread to any given episode node will depend on the strength of that link and its strength *relative to all competing links*; the more competing links, the less activation that is sent down any one link.

**4. Current activation of a node.** The current level of activation of a node is distinguished from its baseline. The current level will be higher than the baseline whenever it receives stimulation from the environment, that is, when the concept is mentioned or perceived, or when the concept receives activation from other nodes. While baseline strength decays according to a power-function, current activation decays rapidly and exponentially towards its base level. Let  $A$  represent the current level of activation and  $B$  represent the base level of activation. Then, the decrease in *current* activation will be:

$$\Delta A = -\rho(A - B) \quad (4)$$

**Encoding assumptions.** We have previously implemented SAC models that vary the probability of encoding an event to explain aging effects (Reder, Park, & Kieffaber, 2009) and to simulate the effects of midazolam (Reder et al., 2007). We accomplished these effects by simply positing different probabilities of forming a link. Although those modifications worked well, they

were ad hoc. The addition of a WM component to the SAC architecture (Reder et al., 2008) enables the probability of encoding to vary in a more principled fashion (i.e., without merely fitting a parameter that varies the success of the binding).

We assume that the amount of WM varies among individuals (Daily, Lovett, & Reder, 2001; Lovett, Daily & Reder, 2000; Lovett, Reder & Lebiere, 1997), as well for a particular individual as a function of fatigue, etc.<sup>3</sup> This pool is depleted as resources are used and it returns to full capacity over time. Resources from this pool are used to enable a stimulus to be linked to another node. The amount of resources needed to enable the stimulus to be involved in a new memory structure (building a link between concepts) depends on the resting level of activation for that concept. That is, the more familiar a concept, the higher its resting level of activation and thus the less demand on the WM pool. Multiple concepts make larger demands on the WM pool. The amount of WM expended in encoding one concept is:

$$WM_{\text{encode}} = \tau - B \quad (5)$$

where  $\tau$  is the threshold and  $B$  is the node's base level activation (see Equation 1). The WM pool replenishes at a linear rate,  $r$ , such that the pool at time  $t$  is given by:

$$WM_t = \min(WM_{\text{max}}, WM_{t-1} + r) \quad (6)$$

At retrieval, the same assumptions hold in that there must be enough WM resources to get the concept up to threshold to spread activation to its associated nodes. Below, we provide a short description of the model as fit to our 5-PAR experimental paradigm.

**Fitting the model to the data.** The model simulated each study and test trial in the experiment, generating the complete set of 75 data points for each age group, and was fit to the behavioral data aggregated across subjects within age groups (see Tables 4 and 5). The memory representations of all the word stimuli were initialized using the metric of normative word frequency (occurrence per million in the lexicon) to estimate their pre-experimental base-level activation and number of associative links (i.e., fan) for each word. For each trial in the study phase of the experiment, the concept nodes—representing each word of the pair—were strengthened through practice. If there were enough WM resources available to boost these concept nodes above a threshold of activation from their current base-level strength, then an episode node that represented the studied word pair was created and linked to both concept nodes. Each time a node was boosted to threshold,

<sup>2</sup> The SAC model assumes that episodic (context node) information is stored separately from semantic item (concept node) information. This local model representation distinguishes it from global matching models, such as REM (Shiffrin & Steyvers, 1997), TODAM (Murdock, 1997), MINERVA II (Hintzman, 1988), and Matrix (Humphrey et al., 1989), that assume that item and associative information are inseparable and are stored as part of a common memory system. For a comparative analysis of these representational issues as they pertain to recognition decision-making in the current 5-PAR paradigm, see Buchler et al. (2008).

<sup>3</sup> Reder's previous work on individual differences in WM capacity used the ACT-R framework. In ACT-R, WM differences are assumed to only affect retrieval, not encoding. There are currently no assumptions about differential probability of binding in ACT-R.

the available pool of WM resources decreased by this amount and then was replenished gradually over time. If the WM resources were already depleted, then no episode node would be created and consequently the word pair was not encoded. Because base-level node strengths and link strengths both increase with experimental exposure and decrease over time, concepts that are repeated are stronger and require less WM resources to get over threshold. Thus, repeated word pairs were more likely to be encoded.

At test, when a tested word pair was shown, if enough WM resources were available to get one of the word concept nodes over threshold, then the activation was spread from that concept node to all of the nodes linked to it. If there was not enough WM available to get one or both of the concept nodes over threshold, then that node did not spread activation to any nodes linked to it. For intact trials, if the concept nodes were encoded, they were linked to the same episode node, making it more likely that the episode node would reach threshold. In swapped trials, each concept node—if encoded—was linked to a separate episode node. In foil trials, one or both of the presented words had not previously been studied and thus were not linked to an episode node.

The simulation produced the various probabilities of responding *Old-Old (original)*, *Old-Old (rearranged)*, *Old-New*, *New-Old*, or *New-New* for each condition. These probabilities were determined by the activation values of the episode nodes and concept nodes. For instance, the probability of generating a *New-New* response was contingent on neither episodic nor concept nodes being over threshold. The *Old-New* and *New-Old* responses were determined as the probability that an episode node or concept node for one word in the test pair was over threshold while neither was over threshold for the other word. The probability of an *Old-Old (original)* response required that the episodic node encoding the event that both test words were studied together was over threshold. An *Old-Old (rearranged)* response was contingent on both episodic nodes being over threshold as the two words did not share an episodic node and represented separately encoded events, or the

more likely scenario where no episodic nodes were over threshold but both concept nodes were. In addition, we included the possibility of spurious recollection. Spurious recollection occurs when the concept nodes for both words are over threshold, but only one event node is over threshold. The model predicts that half the time this case will result in an *Old-Old (rearranged)* response and the other half of the time will result in an *Old-Old (original)* response.

**Results of the model fitting.** The fixed parameter values used to model memory performance of the 5-PAR task for younger and older adults are given in Table 6. Two goodness-of-fit statistics are reported:  $r^2$  for trend relative magnitude and SSE for deviation of the model predictions from the actual data points. Both goodness-of-fit statistics are useful because it is possible for the model fit to capture one dimension of the data (the magnitude of the trend relative to one another) and not the other (deviation from exact data value), or vice-versa. The model determined the best fitting parameters by minimizing the SSE (sum squared error) between the simulated data and the actual data. The model provided good fits for the young adult data with  $r^2 = .90$  and SSE of .31. This fit used a WM parameter value of 84,  $T_E$  (threshold for the episode node) of 3.77 and  $T_W$  (threshold for the concept node) of 4.11, to model the young adults. In previous SAC model fits to data, we only allowed the threshold(s) for subjects to elicit a response to vary. In this case that would be  $T_E$  and  $T_W$  for recollection of the association and familiarity of the word, respectively. To test whether the only thing that differed between young and older subject was WM, we tried keeping constant the threshold parameter values used to fit the young data when modeling the older adult data and only letting the WM value vary. This resulted in a good fit with a diminished WM value of 70 ( $r^2 = .85$ , SSE = .42). As a baseline, the older adult model fit was poor when the same young adult WM value of 84 was applied ( $r^2 = .80$ , SSE = .57). Figure 3 provides a visualization of model fit across the range of response proportions. As evident, the model did a reasonable job of capturing the young and older adult data sets—each com-

Table 6  
*SAC Model Parameter Descriptions and Values*

Parameter name	Function	Value
Preword strength	Converts Kucera and Francis frequency to pre-existing baseline activation	0.4
Preword fan	Converts Kucera and Francis frequency to initialize pre-existing fan	0.7
Input activation	Input current activation for component nodes	50
$\rho$	Exponential decay constant for current activation	0.8
$C_N$	Power-law growth constant for base-level activation	5
$d_N$	Power-law decay constant for base-level activation	0.175
$C_L$	Power-law growth constant for link strength	25
$D_L$	Power-law decay constant for link strength	0.12
$T_E$	Study-episode node decision threshold	3.77
$E$	Study-episode node decision standard deviation	0.87
$T_W$	Word node decision threshold	4.11
$W$	Word node decision standard deviation	0.39
<b>WM<sub>young</sub></b>	Maximum pool size of WM resources in young adults	84
<b>WM<sub>old</sub></b>	Maximum pool size of WM resources in older adults	70
<b>WM<sub>refresh</sub></b>	Replenishment rate of WM resources over time	0.0001
<b>Encode threshold</b>	Activation threshold to create study-episode node	40

*Note.* The free model parameters fit to the young adult data are shown in bold. In our model fit to the older adult data, only one parameter  $WM_{old}$  was free to vary, also shown in bold. Constant model parameters (not bolded) were inherited from previous SAC models (see Reder et al., 2000, Table 2). SAC = Source of Activation Confusion; WM = working memory.

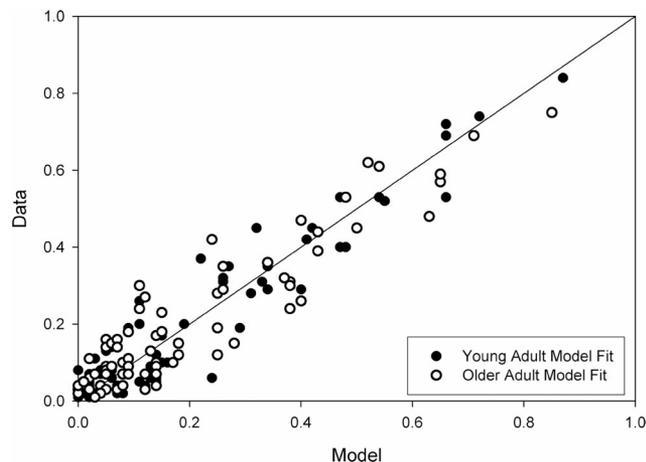


Figure 3. Overview of model fits to the young (closed symbol) and older adult (open symbol) data across the range of response proportions (unspecified) expressed as a function of model prediction versus actual data. The diagonal signifies a perfect fit of the model to the data; deviations above or below the diagonal reflect an under-fitting or over-fitting of the data, respectively. Refer to Tables 4 and 5 for a full account of the model fits specified by both response and condition.

prised of 75 data points—especially considering the parsimony of only one parameter (WM) varied between the young and older adult models. Thus, our model supports the theory that a diminished capacity of limited WM resources with age is necessary to capture age-related differences in memory.<sup>4</sup>

## Discussion

The current study yielded four main findings. First, we found results consistent with an associative deficit account of aging. Associative recognition was generally impaired in older adults across all of our memory conditions and no statistically significant age-related interactions were evident. Although we did not find the higher overall false alarm rate to rearranged lures for older adults that we expected for rearranged lures, we did find a pattern of increasing false alarms with repetition in older (but not in younger) adults, consistent with prior results (e.g., Kelley & Wixted, 2001; Light et al., 2004; for a review, see McCabe, Roediger, McDaniel, & Balota, 2009). We also expected older adults to be more susceptible to associative interference (i.e., fan effects) generated from studying multiple overlapping word pairs inasmuch as increased fan effects have been reported for older adults (Cohen, 1990; Gerard et al., 1991). However, greater interference in older adults relative to young adults is not always observed (e.g., Overman & Becker, 2009).

Our second finding was that older adults benefited from both item strengthening and associative strengthening as much as young adults. For instance, in the signal detection analysis of repetition strengthening—comparing Fan 1-1 and Rep  $\times$  5 word pairs—recognition sensitivity was greatly reduced in older adults with no age-related interaction. This suggests that although older adults initially have difficulty retrieving a memory trace for a weak association, they benefit from repetition strengthening as much as young adults do. Thus, repetition is an important mechanism for

both strengthening weak associative memory representations in older adults and lessening the retrieval demands of the task.

Third, an important result was our finding that older adults' recognition judgments depend more on familiarity-based (i.e., item retrieval) processes in the face of a recollection (i.e., associative retrieval) deficit, consistent with dual-process accounts of memory in old age. It may be that—faced with declining WM—older adults rely more heavily on less demanding processes (e.g., Reder, Wible & Martin, 1986). In this context, it is worth highlighting that the sum of the response proportions for the two decision categories of *Old-Old (original)* and *Old-Old (rearranged)* were equivalent across age-groups; however, older adults made significantly more *Old-Old (rearranged)* responses than *Old-Old (original)* responses. Given the age-related associative deficit, this suggests that older adults base their response decisions more squarely on the familiarity of the word pair.

Fourth, we were able to better fit the older adult data by reducing the WM resources available. According to SAC, this resource pool affects both the probability of encoding a new association and the ability to retrieve an association once formed. We did not constrain the model to give younger adults a larger pool but the best fit resulted in a higher level of WM for younger adults. The findings from the model fit are consistent with the divided attention study of Naveh-Benjamin, Craik, Guez, and Krueger (2005) that found that both encoding and retrieval operations place greater demands on the cognitive resources of older than younger adults. That is, the costs of dividing attention were disproportionately greater for older adults at both encoding and retrieval.

The successful fit of our computational model to such a rich dataset while varying the WM parameter suggests that older adults have diminished WM capacity that impacts their ability to engage in successful memory encoding and retrieval operations. This result provides additional support for prevailing hypotheses about the mechanisms responsible for deficits in memory performance as a function of age. The age-related associative memory deficit is sometimes viewed as a difficulty in binding information at encoding (Chalfonte & Johnson, 1996; Naveh-Benjamin, 2000). However, it is also clear that less effective retrieval processes contribute to associative memory deficits (Buchler & Reder, 2007; Cohn et al., 2008; Dunlosky, Hertzog, & Powell-Moman, 2005; Healy et al., 2005; Light et al., 2004; Luo & Craik, 2009). In this context, we note that the WM parameter modeled in SAC plays a role in both encoding and retrieval and thus nicely captures the pattern of findings in the aging literature. Furthermore, the computational mechanisms instantiated in the WM model constitute a broad theoretical framework that extends beyond the aging literature to formally describe encoding/retrieval tradeoffs with various experimental and quasi-experimental manipulations of stimulus expo-

<sup>4</sup> A slightly better fit to the older adult data was achieved by allowing even more parameters to vary, both of the threshold parameters and the WM parameter ( $r^2 = .88$ , SSE = .33). However, varying just the threshold parameters alone while holding WM constant at the young adult value of 84 ( $r^2 = .85$ , SSE = .38) does not improve the fit as much as varying the WM parameter alone. Thus, the WM parameter model achieves greatest parsimony.

sure; repetition, frequency, prior knowledge, contextual features, and associated information (for a review, Reder et al, 2008).

Our results comport well with recent aging neuroscience results suggesting that older adult cognitive deficits reflect a diminution of frontally mediated controlled processing. First, executive control processes are heavily dependent upon the integrity of prefrontal cortex (PFC) (Stuss & Knight, 2002) and the PFC is the locus of pronounced age-related atrophy in both cortical gray matter (Raz, 2005) and white-matter tracts (Davis, Dennis, Buchler, White, Madden, & Cabeza, 2009). Second, neuroimaging studies have consistently shown increased recruitment of medial and left PFC regions when retrieval is particularly demanding, for instance when recovering contextual associations (Buchler, Dobbins, & Cabeza, 2008; Dobbins, Foley, Schacter, & Wagner, 2002; Nolde, Johnson, & Raye, 1998; Rugg, Fletcher, Chua, & Dolan, 1999; Simons, Gilbert, Owen, Fletcher, & Burgess, 2005). Thus, converging evidence from neuroanatomical and neuroimaging studies highlights the vulnerability of certain PFC regions to age-related neurodegeneration, and further shows that the prescribed functions identified by those regions support controlled processes involved in effortful memory retrieval. From a systems neuroscience perspective, integrative models are needed to fully capture how the PFC operates in concert with other regions to support memory encoding and retrieval. For instance, distinct regions defined by the cytoarchitecture of the medial temporal lobe have been found to support the mnemonic processes of familiarity and recollection (Daselaar, Fleck, & Cabeza, 2006; Diana, Yonelinas, & Ranganath, 2007; Yonelinas, Otten, Shaw, & Rugg, 2005), and furthermore, recent evidence suggests an important role of parietal regions to attention on memory (Cabeza, Ciaramelli, Olson, & Moscovitch, 2008). In summary, recent neuroimaging results support the idea promoted by our model that older adults have a diminished capacity to engage in WM-intensive memory encoding and retrieval operations and suggest that this may reflect the age-related degradation of frontally mediated processes.

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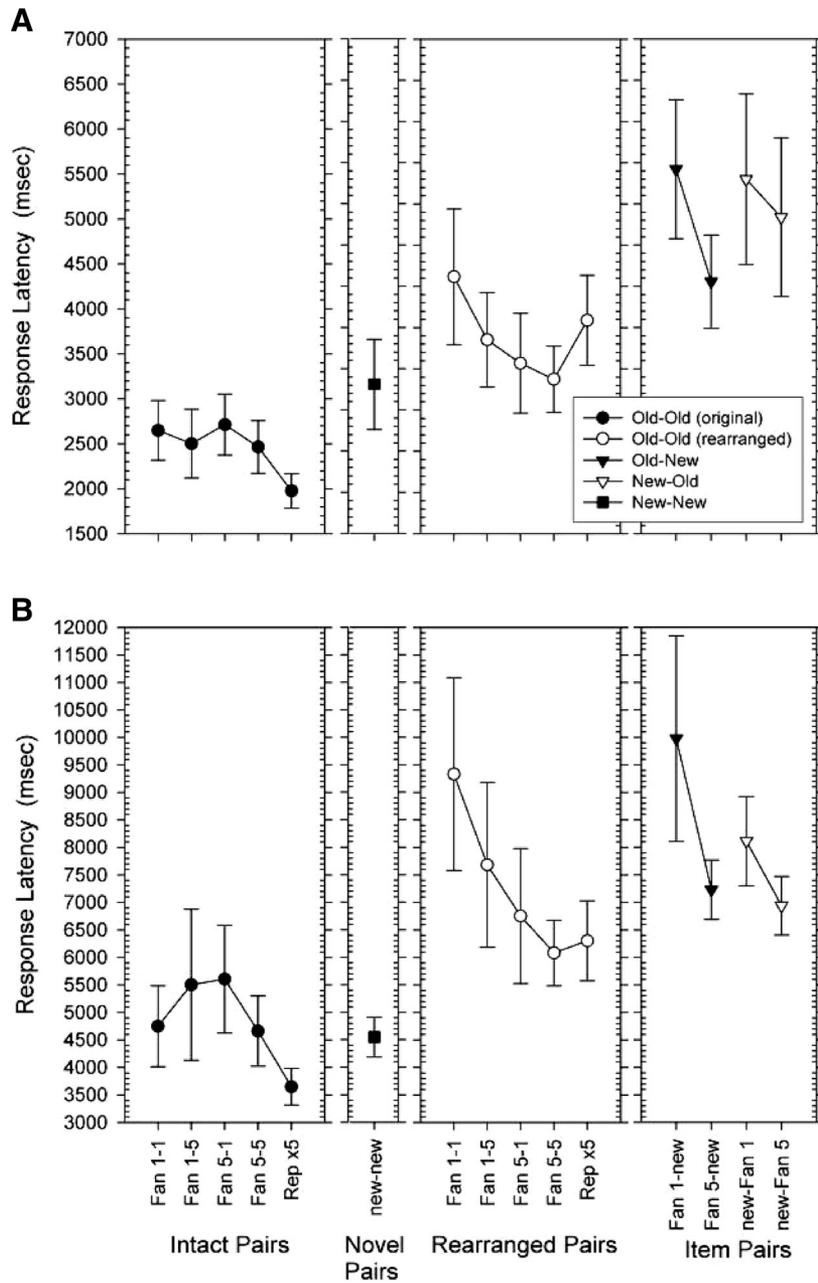
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(Appendix follows)

Appendix

Age-Related Decision Latency in Associative Recognition



Appendix Figure. Panel A. Young adult response latencies (mean of medians) for hit responses to intact pairs, novel pairs, rearranged pairs, and item pairs. Panel B. Older adult response latencies (mean of medians) for hit responses to intact pairs, novel pairs, rearranged pairs, and item pairs.