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Effects of Age on Contextually Mediated Associations in Paired Associate Learning

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Abstract

Older adults demonstrate an associative memory deficit that has been attributed to difficulty binding item information to contextual information (Naveh-Benjamin, 2000). Accounts of temporally-defined episodic associations that depend upon contextual retrieval (TCM Howard & Kahana, 2002) predict that a deficit in item-to-context binding will result in fewer backward (B-A) and transitive (A-C) associations. To measure group differences in backward and transitive associations, younger and older participants learned single function lists of paired associates with no contextual overlap (e.g., J-K, L-M) and double-function lists of paired associates consisting of chains of pairs (e.g., A-B, B-C). Although younger adults out-performed older adults on both pair types, there was a robust pair-type by age interaction. We suggest the older adults performed better than would be expected on the contextually overlapping double-function pairs due to an associative deficit in item-to-context binding, which resulted in the generation of fewer competing responses. Relative to younger adults, older adults made significantly more intrusions. Intrusion levels were normalized to equate for group differences and subsequent analysis indicated that younger adults made a larger proportion of associative intrusions to double-function probes than did older adults. The propensity of older adults to make fewer associative intrusions to double-function pairs suggests that older adults did not generate these associations. Thus, group differences in both correct recall probabilities and intrusion analysis suggest that backward and transitive associations are sensitive to aging. The results are discussed within the theoretical framework of the temporal context model and the hypothesis that older adults are impaired at forming new item-to-context associations.

EFFECTS OF AGE ON CONTEXTUALLY MEDIATED ASSOCIATIONS IN PAIRED ASSOCIATE LEARNING

by

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Introduction

Paired-associate learning (PAL) is an episodic memory task in which pairs of unrelated items, e.g. ABSENCE-HOLLOW, are presented. At test the first item is presented as a cue for response of the second item. Importantly, memory for test items individually is insufficient to support accurate PAL memory performance. Instead, PAL tests whether items have been associated, or bound together in memory. PAL is particularly vulnerable to the effects of aging (Light, 1991). Older adults consistently demonstrate an associative deficit across study material and test paradigms, including word-word tests (Naveh-Benjamin, 2000; Naveh-Benjamin, Hussain, Guez, & Bar-On, 2003), word-context tests (Naveh-Benjamin, 2000; Naveh-Benjamin et al., 2003), picture-picture tests (Naveh-Benjamin et al., 2003), pattern-location tests (Collie, Myers, Schnirman, Wood, & Maruff, 2002), and name-face tests (Naveh-Benjamin, Guez, Kilb, & Reedy, 2004). An age-related associative deficit has also been observed across testing methodologies, including tests of cued-recall (Naveh-Benjamin, 2000; Kliegl & Lindenberger, 1993), yes-no recognition (Naveh-Benjamin, 2000), forced-choice recognition (Naveh-Benjamin et al., 2004), and associative recognition (Bastin & Van der Linden, 2006; Castel & Craik, 2003; Light, Patterson, Chung, & Healy, 2004; Healy, Light, & Chung, 2005; Prull, Dawes, Martin, Rosenberg, & Light, 2006). Additionally, in delayed and immediate free recall the temporal contiguity of study items exerted a weaker influence on older adults' recall transitions (Kahana, Howard, Zaromb, & Wingfield, 2002), suggesting that associations formed between nearby list items were weaker for older adults.

A

Double-function

ABSENCE	HOLLOW	PUPIL	RIVER	DARLING	

Single-function

ANGLE	ECHO	WRINKLE	ERROR	CLIMATE	NEPHEW

B

RIVER	DARLING
ANGLE	ECHO
HOLLOW	PUPIL
WRINKLE	ERROR
PUPIL	RIVER
ABSENCE	HOLLOW
CLIMATE	NEPHEW
DARLING	ABSENCE

Figure 1: **Single- and double-function pair schematics. A.** Randomly sampled word lists from which the single- and double-function pairs were composed. **B.** Mixed presentation of assembled single- and double-function pairs. Word were presented individually with a longer delay period between-pairs than within-pairs.

Associative Deficit

The associative deficit observed in cognitive aging has been hypothesized to arise from age compromised mechanisms for binding together multiple aspects of a memory episode (Chalfonte & Johnson, 1996; Mitchell, Johnson, Raye, Mather, & D'Esposito, 2000). Naveh-Benjamin (2000) specifically proposed the associative deficit hypothesis (ADH), which suggests that aging is associated with a deficiency in creating and retrieving links between single units of information, such as content and context, or between stimuli. Although item information remains relatively intact with age, the ADH predicts that the strength of associations between items is reduced. A specific quantification of the ADH, the temporal context model (TCM) provides convergent evidence that normal aging is associated with a decreased ability to bind item information to encoding context. By selectively disrupting a parameter that controls item-to-context learning, TCM can accurately model the associative deficit found with aging (Howard, Kahana, & Wingfield, 2006; Kahana et al., 2002).

The principle of contiguity (items presented together in time become associated to each other) is often used to account for associations between PAL items. The temporal context model (TCM Howard & Kahana, 2002) extends the principle of contiguity with the postulate that items presented close together in time also share overlapping contexts. For example, consider the pair ABSENCE-HOLLOW from Figure 1. The item representation for HOLLOW is associated with the encoding context. According to TCM, this same context will include elements retrieved by previous items, including ABSENCE. When ABSENCE is later repeated as a cue, the encoding context of the pair ABSENCE-HOLLOW can be recovered. In other words, the context retrieved by ABSENCE overlaps with the encoding context of HOLLOW, thereby allowing for the recall of HOLLOW.

TCM uses this contextual retrieval hypothesis, or the idea that associative effects in memory can arise because the retrieved contextual states overlap with the encoding contexts of nearby items, to describe the formation of transitive associations. The contextual retrieval hypothesis predicts that items that do not occur together in time should become associated together if they share similar temporal contexts. Double-function lists of paired-associates, in which each item serves as both a stimulus in one pair and a response in another pair (e.g., ABSENCE-HOLLOW, HOLLOW-PUPIL), share overlapping elements and provide an opportunity to test associations made between items in different pairs (Primoff, 1938). Figure 1 is an example of a randomly generated list of words (1A) with both traditional PAL pairs (single-function pairs) and double-function pairs composed from the word list (1B). Again, consider the pair ABSENCE-HOLLOW and the pair HOLLOW-PUPIL. In this example ABSENCE and PUPIL are never presented together in time, however, both words are presented in the context of HOLLOW. The contextual retrieval hypothesis predicts that ABSENCE and PUPIL should become associated together by virtue of having been encoded in similar temporal contexts (Howard, Jing, Rao, Provyn, & Datey, Revised).

Backward Associations

There is a robust effect of pair-type on PAL recall: double-function pairs are markedly more difficult than single-function pairs (Primoff, 1938; Slamecka, 1976; Umemoto & Hilgard, 1961; Young, 1959, 1961; Young & Jennings, 1964; Howard et al., Revised). This difficulty for double-function pairs has often been attributed to response competition from the backward associate (Primoff, 1938; Slamecka, 1976; Umemoto & Hilgard, 1961; Young, 1961; Howard et al., Revised). For example, consider the pairs ABSENCE-HOLLOW and HOLLOW-PUPIL from Figure 1. When cued with HOLLOW the correct response is PUPIL and the backward associate is ABSENCE. This backward association may compete with the correct response, which can create associative response interference. Because single-function lists do not contain pairs with overlapping items there is no source of associative interference.

Transitive Associations

TCM predicts that associations can form between items presented together in time. The backward associate is presented in time with the target item and, correspondingly, provides the greatest amount of associative interference. TCM also predicts that remote bridging associations between items never presented together in time, or transitive associations, may also provide a source of associative interference (Popper, 1959; Slamecka, 1976; Bunsey & Eichenbaum, 1996; Howard et al., Revised). Howard, Jing, and Provyn (submitted) examined cued and free recall trends of pairs with overlapping temporal contexts. They tested the associative structure induced by mixed single- and double-function lists of paired associates and found evidence from cued-recall intrusion (i.e., incorrect recall) probabilities and final free recall transitions for both backward and transitive associations among the double-function pairs. The strength of the associations between items presented together in time in the forward direction were greatest, followed by the strength of the associations of items presented together in time in the backward direction. The strength of the associations between items never presented together in time, but which were presented in similar temporal contexts (i.e., the transitive associations), decreased as a function of list lag, or distance in the original list. Importantly, the backward and transitive associations were stronger than associations between items on different lists (i.e., associations between single- and double-function words).

The use of contextually-unrelated single-function and contextually-related double-function pairs enables us to examine backward and transitive associations as a source of associative interference in a cued-recall task. If aging is associated with reduced item-to-context binding (Naveh-Benjamin, 2000; Howard et al., 2006), then we would expect older adults to have less associative interference. Less associative interference would result in less response competition, which should be manifest in an interaction of pair type and age, such that older adults perform better than expected on double-function pairs. Additionally, if older adults make fewer backward and transitive associations then they should demonstrate fewer backward and transitive intrusions. Prior literature (Naveh-Benjamin, 2000) has demonstrated older adults perform disproportionately poorer than younger adults on cued-recall tasks of unrelated pairs. Therefore, overall recall output should be normalized for each age group to circumvent multiplicative age effects.

Experiment

To test the hypothesis that older adults are impaired at forming new item-to-context associations we conducted a PAL experiment with younger and older adults. Subjects were presented with a list of paired associates composed of both single-function pairs with no contextual overlap (e.g., J-K, L-M), and double-function pairs consisting of chains of pairs (e.g., A-B, B-C) (Fig. 1B). The double-function pairs were arranged in a circular linked-list so that the stimulus of the first pair and the response of the last pair were joined into another pair, e.g., DARLING-ABSENCE in Fig. 1B.

Method

Participants

A total of 67 younger adults and 70 older adults participated. Younger adults were recruited from the Syracuse community area and consisted of a combination of Syracuse University undergraduate and graduate students. Older adults were recruited through a registry of subjects from the CHAP longitudinal study run by Syracuse University and based at the Nottingham Adult Community Center. The younger adult group was constrained to an age range of 18 to 40 years. Mean age for the older adult group was 80.8 (SD = 5.5), with mean years of education 15.3(SD = 2.4). Both older and younger adults performed a battery of standard cognitive tests (operation span task, numbering matching task, and a mental count/keep track task). All of the older subjects were concurrently participating in cognitive experiments at the Nottingham Community Center. None of these experiments, however, involved PAL. Younger adults had not previously participated in any cognitive experiments conducted in our laboratories.

Materials

Study lists were composed of 8 double-function pairs consisting of 8 distinct words and 7 single-function pairs consisting of 14 distinct words. The double-function pairs were formed for each subject by randomly sampling 8 words without replacement from the noun subset of the Toronto word pool (Friendly, Franklin, Hoffman, & Rubin, 1982). The first two words were assigned to the first pair, the second and third word the second pair, etc., through the seventh pair. The eighth pair was formed by pairing the eighth word with the first word, thereby creating a circular list. Prior to shuffling, the underlying associative structure of the ordered pairs was established. For example, consider the pairs A-B, B-C. The correct response to item B was determined to be item C and the backward associate of item B was determined to be item A. Single-function pairs were formed for each subject by randomly sampling 14 distinct words without replacement from the Toronto word pool. The first two words were assigned to the first pair, the third and fourth word to the second pair, etc., until the 13th and 14th words were assigned to the seventh pair. Prior to shuffling, the pairs were ordered into a non-linked list (e.g, J-K, L-M). For the purposes of control in the analysis, each single-function pair's backward associate was an item assigned from the list of ordered pairs (e.g, the backward associate for L would be K). Single-function pair remote associations were assembled in the same manner (e.g., a remote associate for L would be J). Due to the lack of an underlying associative structure in the single-function pairs, backward and remote associations were not a consequence of associative learning.

Procedure

Participants were given a paired-associate learning task, followed by a 20s distractor task, and a cued-recall test over three separate testing sessions. Each pair was presented once per trial for five consecutive trials. Stimuli were presented visually and subjects were instructed to read each word aloud at presentation. The order of pair presentation was randomized. The testing format followed a study list, distractor task, cued-recall test design.

Each word was displayed in capital letters for 1000ms, followed by 100ms blank interval. Following the presentation of a pair there was an additional 2000ms blank screen interval before the next pair presentation.

Immediately following the study list participants were given a 20s arithmetic distractor task. The distractor task consisted of individually presented arithmetic problems of the form "A+B+C=?", where A, B and C were positive, single-digit, integers. Participants were required to read each equation aloud and state the answer aloud. Younger subjects typed the answer using the computer keyboard while older subjects had an experimenter present who typed the stated answer for them. Subjects were allotted as much time as necessary on each arithmetic problem for the duration of the 20s task.

After the distractor task the cue word from each pair was presented individually on the screen for 1000ms. The stimulus was followed by the simultaneous presentation of a row of asterisks and an auditory tone that signaled participants to recall the correct response word. Subjects were instructed to read each cue word aloud and recall the correct response to the stimulus. Subjects were encouraged to respond with the correct pair item, however, they were also encouraged to respond even if they were not completely certain of the correct response. Subjects had 7s for recall in response to each cue word. The order of test cue presentation was randomized.

The second and third experimental sessions were conducted at least one day after the previous session. The three sessions were identical in procedure with the exception that younger participants completed a consent form and a demographic measure at the beginning of session one and did not for sessions two and three. Older participants had already completed consent and demographic forms for prior testing so were not required to re-complete these forms.

There were three, presumably minor, procedural differences between the age groups. First, the experimenter accompanied the older subjects the entire testing session across all three sessions. Younger subjects were accompanied by the experimenter only during the instructions and first trial of session one. Second, the groups had different experimenters and some of the older subjects were familiar with the experimenters from previous testing, while the younger subjects had no previous experience with the experimenters. Finally, the groups were tested in different locations. The older subjects were tested at an assisted living community center in Syracuse and the younger subjects were tested in a lab at Syracuse University.

Results and Discussion

We examine the results of correct recall from the paired associate cued-recall data, followed by intrusion analyses.

Correct-recall Analysis

Figure 2A plots the probability of correct recalls for both age groups on single- and double-function pairs across trials. Examination of this figure demonstrates that single-function pairs were learned better than double-function pairs for both age groups. In addition, younger subjects outperformed older subjects across all trials on both pair types.

An ANOVA with probability of correct-recall as the dependent measure, and age (younger or older) and pair-type (single- vs. double-function) as factors, and trial (1-5) as a regressor, showed main effects of age, $F(1, 1362) = 930.1$, MSe = 27.9, $p < .001$; pair-type, $F(1, 1362) = 307.8$, MSe = 9.2, $p < .001$; and trial, $F(1, 1362) = 754.8$, MSe = 22.6, $p <$

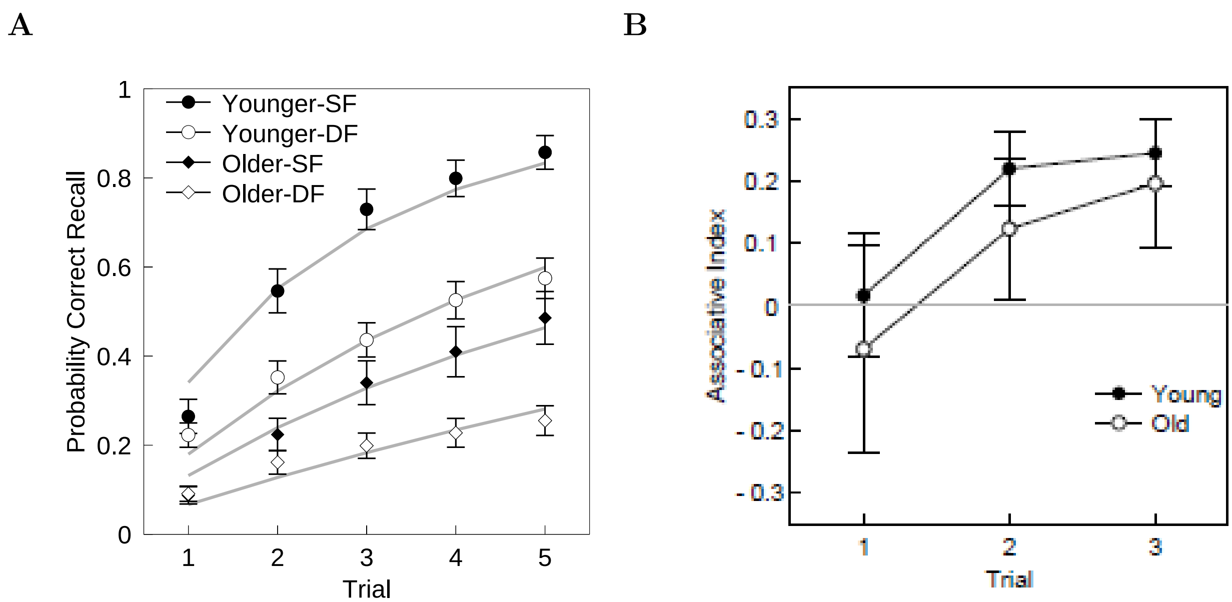

Figure 2: **Correct recall analysis.** Error bars are 95% confidence intervals. **A.** Probability of correct recall for double-function pairs is lower than probability of correct recall for single-function pairs across age groups. There is an interaction of pair-type and age. **B.** Associative index plotted as a function of trial and separated by age. Positive numbers indicate an advantage for single-function pairs with a maximum score of +1. Negative numbers indicate an advantage for double-function pairs with a maximum score of -1. Only the first 3 trials were used to eliminate ceiling affects. The grey line indicates an equivalent proportion of correctly recalled single- and double-function pairs.

.001. There were also significant interactions of pair-type with trial, $F(1, 1362) = 80.2$, MSe $= 2.4$, $p < .001$; of trial with age, $F(1, 1362) = 53.8$, MSe $= 1.6$, $p < .001$; and of pair-type with age, $F(1, 1362) = 26.4$, MSe $= .8$, $p < .001$. A three way interaction of pair-type by age by trial was not significant, $F(1, 1362) = .2$, MSe $= .01$, $p = .7$.

The main effect of age demonstrates that age influenced the overall magnitude of correct recalls. Younger adults had higher levels of correct recall across both pair types. The main effect of pair-type shows the probability of correct recall was higher for single-function pairs. In other words, the contextually-related double-function pairs were more difficult to recall than the non-overlapping single-function pairs. The main effect of trial indicates the probability of correct recall for both pair types increased with each trial. The pair-type by trial interaction demonstrates that probability of correct recall of single-function pairs increased more rapidly across the trials than probability correct recall of double-function pairs. The trial by age interaction shows that younger adults had greater increases in probability correct recall rates across the trials.

Importantly, though the older adults had lower overall correct recall probabilities, the pair-type by age interaction suggests that the older adults performed better on double-function pairs than would be predicted from their single-function pair performance. Conversely, the younger adults' probability of correct recall for double-function pairs was lower than would be expected given their overall probability of correct recalls. This could be indicative of increased associative interference for younger adults as a result of backward and transitive associations. But, because older adults had lower overall probabilities of correct recall it is also possible that the pair-type by age interaction is simply due to a multiplicative effect of age on probability of correct recall. For example, Cerella and Hale (1994) were able to describe an array of measurements using a two-dimensional function that combined the multiplicative effect of process-duration and the exponential effects of age. Therefore a global increase in processing demands with age, rather than an associative deficit, could be the source of the pair type by age interaction in this data. For a numerical example, consider two groups with different recall probabilities on a given trial for single and double-function pairs. Group 1 has single-function probability correct recall = .6 and double-function probability correct recall = .4; Group 2 has single-function probability correct recall = .3 and double-function probability correct recall = .2. Though the probability of correct recall for each pair type differs in magnitude between the groups, the relationship between the recall probabilities is the same: single-function recall probability is 1.5 times larger than double-function recall probability. An ANOVA would demonstrate an interaction of pair-type and group, though this would be attributable to the differences in the magnitudes of the values between the groups.

To construct a measure of associative interference insensitive to multiplicative effects, we calculated an associative index. This index takes the difference between the non-associative (single-function) and associative (double-function) probabilities divided by the total probabilities of all correct recalls:

$$\text{associative index} = \frac{C_S - C_D}{C_S + C_D}$$

where C_S is the average probability of correct recall of single-function pairs (across lists) and C_D is the average probability of correct recall of double-function pairs (across lists). The associative index can take values from -1 to +1. An index value of -1 would indicate that all of the pairs that were correctly recalled were double-function. An index of 0 would indicate that the same proportion of single- and double-function pairs were correctly recalled. An index value of +1 would indicate that all of the pairs correctly recalled were single-function. Returning to our hypothetical example, we calculate the associative index and find there is no difference in the associative indexes (i.e., Group 1 = (.6 - .4)/(.6 + .4) = .2; Group 2 = (.3 - .2)/(.3 + .2) = .2). This example demonstrates that the associative index is immune to differences in probability of correct recall across groups that is an artifact of a multiplicative effect.

A limitation of the associative index is that it is sensitive to ceiling and floor effects. The associative index starts at zero, indicating none of the pairs have been learned, and ends at zero, indicating all of the pairs have been learned. If performance on single-function pairs reaches ceiling prior to performance on double-function pairs, then the associative index will start to bend down toward zero. The ceiling effect of one pair-type could produce an erroneous interaction in the associative index. Inspection of Fig. 2A shows younger adults' single-function pair performance was approaching ceiling on trials four and five. Specifically, 12% of younger adults performed at ceiling for single-function pairs on trial four, and 22% of younger adults demonstrated ceiling performance for single-function pairs by trial five. To control for false interactions resulting from ceiling effects only the first 3 trials were used. In addition to controlling for ceiling effects, to control for floor effects only subjects that had probability of correct recall greater than zero for either pair type by the third trial were included in the analysis.

Figure 2B illustrates that the associative index increases with trial across groups. Across all three trials, relative to older adults, younger adults had a higher associative index. This indicates younger adults consistently correctly recalled more single- than double-function pairs. An ANOVA with the associative index as the dependent measure, age as a factor, and trial as a linear regressor, showed main effects of trial, $F(1, 398) = 23.3$, MSe = 4.1, $p < .001$; and age, $F(1, 398) = 4.3$, MSe = .76, $p < .05$. The age by trial interaction was not significant, $F(1,398) = .1$, MSe = .02, p = .7. The main effect of trial confirms that differences in pair-type recall trends increased with trial. The main effect of age indicates a difference above and beyond a multiplicative effect. Specifically, after overall levels of recall were controlled for, younger adults were disproportionately decremented on double-function pairs.

The theoretical framework of an overlapping context hypothesis (Howard & Kahana, 1999, TCM) predicts that an intact associative memory leads to greater response competition in a cued-recall task. We suggest younger adults, who are presumably not subject to age-mediated associative deficits, made backward and transitive associations that contributed to response competition, or associative interference, on double-function pairs. Relative to younger adults, older adults did not demonstrate such a pronounced difference in probability of correct recall of the different pair types. The overlapping context hypothesis suggests that a decreased ability to bind temporal contextual states would result in less associative interference for the contextually-related, highly associative, double-function pairs. We suggest older adults, who are presumably subject to age-mediated associative deficits, made fewer backward and transitive associations which resulted in less associative interference on double-function pairs. If there were fewer competing responses then, perhaps paradoxically, this associative deficit actually facilitated double-function correct recall rates.

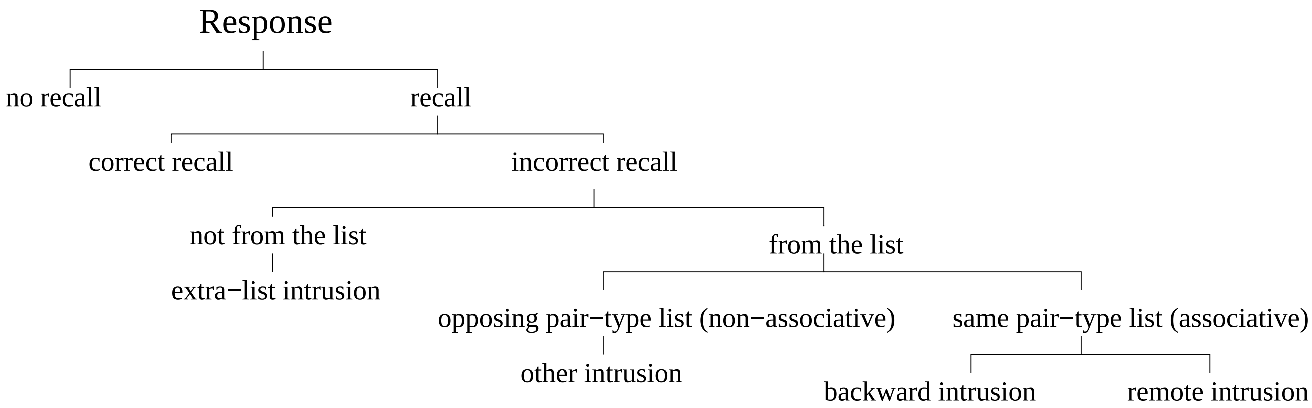

Figure 3: **Response-tree diagram.** The rational behind each response category is broken down in diagram format.

Despite measures to control for bias resulting from between-group performance differences, the associative index is not completely immune to the possibility of floor effects. There is a non-zero probability that the correct recall analysis could be subject to skew resulting from the overall decremented performance of older adults. However, the fact that older adults made fewer correct recalls necessitates they made correspondingly more incorrect recalls (intrusions). Intrusion analysis may provide a measure of associative performance that circumvents possible floor effects. If the older adults had reduced response interference due to a decrement in item-to-context binding, then these associations should be absent in the intrusions; associations that were never formed cannot provide a source of interference. Conversely, if younger adults had highly functioning associative memory, manifest as increased response competition among contextually related items, then intrusion analysis should yield a greater proportion of backward and transitive intrusions.

Intrusion Analysis

The associative index suggests the absence of backward and transitive associations in older adults, however, it does not directly measure them. Intrusion analysis addresses the presence or absence of associative intrusions as well as circumvents the lower overall correct

A

(Cue word = PUPIL)

Response	Recall Category	
——	No-Response	N
RIVER	Correct Recall	C
MUSEUM	Extra-List Intrusion	X
CLIMATE	Single-Function Intrusion	O
HOLLOW	Backward Intrusion	B
ABSENCE	Remote Intrusion	R

B

(Cue word = CLIMATE)

Response	Recall Category	
——	No-Response	N
NEPHEW	Correct Recall	C
BAMBOO	Extra-List Intrusion	X
PUPIL	Double-Function Intrusion	O
ERROR	Backward Intrusion	B
ANGLE	Remote Intrusion	R

Figure 4: **Recall categories.** Example of the recall categories for a given cue word. The pairs refer to those listed in Figure 1. **A.** Double-function. **B.** Single-function.

recall performance of older adults.

Responses to a cue word can be divided into 6 exhaustive non-overlapping categories (see Fig. 3 for a diagram). Figure 4 illustrates an example of recall categorization using the pairs constructed in Fig. 1. A subject could either not respond (N) or respond to a cue. Given that there was a response, the response could either be a correct recall (C) or an incorrect recall (intrusion). An intrusion could have been a word that was not presented at study or a word that was presented at study. Words recalled that were not on the list were extra-list intrusions (X). Intrusions that were on the list could have come from the opposing pair-type list (non-associative) or the same pair-type list (associative). For example, a non-associative intrusion (other intrusion (O)) for a double-function cue was a single-function word, and vice versa (see Fig. 4 for a concrete example). O intrusions were non-associative because they did not represent associations made between the same pair-type list items.

Intrusions from the same pair-type list as the cue word were associative intrusions. There were two types of associative intrusions: backward (B) and remote (R). For double-function pairs, a B intrusion was the stimulus in a study-pair in which the test-word was the response For example, the B associate for D from the list C-D, D-E would be C. Single-function pairs do not overlap, therefore, B associations were assigned prior to shuffling and so were not a consequence of associative learning. For example, the B associate for L from the list J-K, L-M, N-O would be item K. Remote intrusions (R) were those words which originated from the pair-type study list, but were not the correct response (C) or the backward response (B). Examples of double-function remote intrusions to the cue C from the list A-B, B-C, C-D, D-E would be items A and E. Examples of single-function remote intrusions to the cue L from the list J-K, L-M, N-O would be items J, N, and O. In analyzing associative learning between age groups, associative intrusions were calculated as the sum of B and R intrusions, while non-associative intrusions were O intrusions. Thus, all associative and non-associative intrusions were constrained to come from the study list.

Table 1 displays response probabilities for each category. Each row of the table sums to 1 (up to rounding error). With respect to the intrusions for both pair-types, initial inspection of the tables indicates younger adults made far fewer extra-list (X) intrusions than older adults. It is possible that methodological differences between the groups could have influenced group differences in X intrusions. That is, older adults had an experimenter sitting with them through the experiment across all sessions, who reminded them of the instructions to guess if there were not sure of a response. The younger adults received the same instructions for recall but did not have an experimenter sitting with them after the instructions on the first session. However, the trend for older adults to produce more errors in the form of X intrusions is consistent with other episodic recall data (Kahana, Dolan, Sauder, & Wingfield, 2005; Kahana et al., 2002).

Another notable difference between the groups, with respect to intrusion trends, is the proportion of associative (B and R) to non-associative (O) errors made on double-function pairs. Across trials, younger adults made a larger proportion of B and R intrusions relative to O intrusions. More specifically, by trial five younger adults made about three times more B than O intrusions, and about two times more R than O intrusions. This trend does not follow suit for older adults. By trial five older adults had equivalent performance on B and O intrusions, and the probability of making an O intrusion was actually higher than the probability of making a R intrusion. The high

Table 1: **Response Probabilities.** Raw probabilities for the different types of responses to probes across trials. The column labeled "N" gives the probability of no responses. "C" gives the probability of correct recalls. "X" gives the probability of an extra-list intrusion–a word that was not presented during study of either list. "O" gives the probability of reporting an intrusion from the list opposite the cue-word list. "B" gives the probability of a backward intrusion."R" gives the probability of a remote intrusion (see text for details). The numbers in parentheses are 95% confidence intervals.

				Double-function			
	Trial	N	C	X	O	B	R
Young	1	.15 (.04)	.23 (.03)	.11 (.03)	.17 (.03)	.17 (.02)	.16 (.03)
	2	.08 (.03)	.35 (.04)	.06 (.02)	.15 (.03)	.19 (.02)	.15 (.03)
	3	.06 (.02)	.44 (.04)	.05 (.02)	.11 (.02)	.21 (.03)	.13 (.02)
	4	.03 (.01)	.53 (.05)	.04 (.01)	.08 (.03)	.20 (.03)	.11 (.02)
	5	.03 (.01)	.56 (.05)	.04 (.02)	.06 (.02)	.19 (.03)	.11 (.02)
Old	1	.18 (.05)	.09 (.02)	.29 (.05)	.16 (.03)	.09 (.02)	.17 (.03)
	2	.10 (.04)	.16 (.03)	.19 (.05)	.22 (.03)	.13 (.02)	.19 (.03)
	3	.10 (.03)	.20 (.03)	.15 (.04)	.20 (.03)	.16 (.02)	.18 (.03)
	4	.08 (.03)	.22 (.03)	.17 (.04)	.18 (.03)	.19 (.03)	.16 (.02)
	5	.06 (.03)	.25 (.03)	.13 (.04)	.19 (.03)	.19 (.03)	.16 (.02)
				Single-function			
Young	1	.19 (.05)	.26 (.04)	.11 (.03)	.25 (.04)	.01 (.006)	.16 (.03)
	2	.10 (.03)	.54 (.05)	.06 (.02)	.16 (.03)	.006 (.005)	.13 (.03)
	3	.05 (.02)	.72 (.05)	.04 (.01)	.10 (.02)	.01 (.006)	.07 (.02)
	4	.03 (.01)	.80 (.04)	.04 (.01)	.06 (.02)	.004 (.003)	.06 (.02)
	5	.02 (.01)	.86 (.05)	.03 (.01)	.05 (.02)	.005 (.005)	.03 (.01)
Old	1	.18 (.05)	.09 (.02)	.32 (.05)	.26 (.04)	.007 (.004)	.13 (.02)
	2	.11 (.03)	.21 (.04)	.22 (.04)	.25 (.04)	.01 (.006)	.18 (.03)
	3	.09 (.03)	.33 (.05)	.16 (.04)	.23 (.03)	.02 (.007)	.16 (.03)
	4	.08 (.03)	.40 (.06)	.16 (.04)	.17 (.03)	.02 (.008)	.16 (.03)
	5	.06 (.02)	.47 (.06)	.14 (.04)	.16 (.03)	.01 (.006)	.15 (.03)

probability of B intrusions across groups may be because B intrusions occur in the same temporal context as the cue item. For example, if the cue item is D from the list C-D, D-E, the B associate, C, was presented in the same temporal context as D. The older adults made a significantly greater proportion of O intrusions than younger adults, and these O intrusions may be a consequence of guessing words from the experiment.

Given a double-function cue there were 14 possible words that comprised the single-function list. However, given the same double-function cue, there were only four remote items left from which to guess from the double-function list. For example, consider the list A-B, B-C, C-D, D-E, E-F, F-G, G-H, H-A. If the cue item was B, an R intrusion by definition excludes the item itself (B), the C (C), and the B associate (A). The low probability of R intrusions for older adults on double-function pairs fits with a guessing hypothesis because there were more O response options. The higher probability of R than O intrusions for younger adults, however, does not fit with a guessing hypothesis. Instead, we suggest younger adults made significantly more R intrusions than O intrusions due an intact associative mechanism that allowed item-to-context binding among items not presented together in time.

The raw intrusion data indicates younger adults made more associative intrusions than older adults, despite the fact that the raw probabilities are biased against the younger adults. Each row of the table is constrained to sum to one, such that an increase in one category of the table necessarily means decreases in all other categories. For example, younger adults made substantially more correct recalls than older adults. Therefore a direct comparison of younger adult intrusion probabilities is negatively biased with respect to older adult intrusions.

Simplex

To compare associative and non-associative intrusions and control for differences in the magnitude of intrusions across age groups we employed a simplex method. The simplex

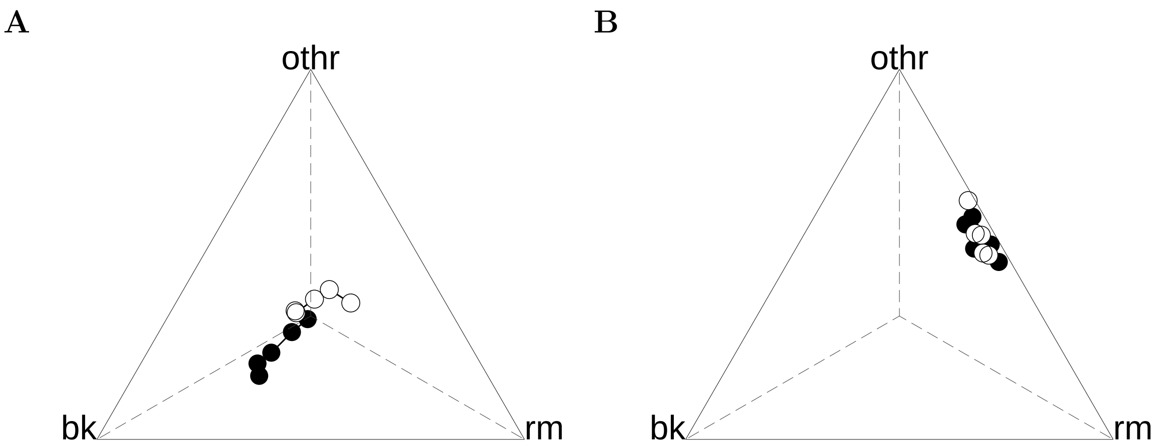

Figure 5: **Intrusion Simplexes.** Younger adults are represented by the filled circles and older adults are represented by the open circles. The center of the simplex figure represents equal probabilities for the three vertices. Each vertex represents a specific intrusion. The "B" vertex is the probability of backward intrusions, the "R" vertex the probability of remote intrusions, and the "O" vertex the probability of intrusions from the non-cue-word list. Each point represents a trial. **A.** Double-function intrusion simplex. Trial 1 is represented by the right-most point for each group. **B.** Single-function intrusion simplex.

method takes as inputs three probabilities–A, B, and C–and normalizes them (Hamm, 2006). Each intrusion probability was calculated by subject across pair-type and trial. The normalized intrusion proportions were calculated by dividing each proportion by the sum of the B, R, and O intrusion probabilities. For instance, the normalized rate of B intrusions, B', is the proportion of B intrusions given all B, R, and O intrusions. This method ensured the intrusion analysis included only study list items (i.e., associative or non-associative). Because $B' + R' + O' = 1$, the simplex method controls for differences in overall intrusion magnitudes across groups. Also, due to the property that the proportions sum to one, each proportion can be plotted on a plane.

Figure 5 plots each intrusion proportion for both age groups across trials for double-function (5A) and single-function (5B) pairs. The center of the simplex figure represents equal proportions of each intrusion type–i.e., $\frac{1}{3}, \frac{1}{3}, \frac{1}{3}$. A point in the center of the simplex figure would indicate that B', R', and O' intrusions were made equally often. A point at a vertex of the simplex figure would indicate that all of the intrusions of list items were of a particular type. For instance, a point at the B axis would indicate, given an intrusion was made and it was either a B', R', or O' intrusion, it was always a B' intrusion (i.e., $B' = 1$, $R' = 0$, and $O' = 0$).

Figure 5A illustrates the normalized double-function intrusion trends for both age groups. Trial one is represented by the right-most point for each group and trial 5 is represented by the left-most point for each group. Importantly, the associative (B' and R') and non-associative (O') intrusion trends differed significantly as a function of age group. The younger adults made a greater proportion of associative intrusions across trials. This is illustrated by the south-westerly trajectory of the filled circles in the associative (B' and R') quadrant. Additionally, of the associative intrusions, younger adults were particularly subject to B' intrusions. In contrast to the younger adults, older adults made a larger proportion of non-associative intrusions. This is indicated by the trend that the open circles remain in the non-associative (O') quadrant across trials.

The propensity for younger adults to have made more associative intrusions to double-function cues than older adults could be argued to be due to an item repetition effect. Although both pair types were presented an equal number of times, the double-function words were presented in two different pairs so received twice as much as exposure as the single-function words. If younger adults benefited from extra presentations of the double-function words, then they would also be more likely to make double-function intrusion errors in response to single-function probes. The standard non-overlapping single-function pairs provide a control measure against which to compare the double-function pairs. The item repetition effect hypothesis would be supported if younger adults made a greater proportion of O' intrusions in response to single-function probes.

The single-function simplex figure (Fig. 5B) illustrates that both the younger and older adults made approximately equivalent proportions of associative and non-associative intrusions on single-function pairs across all five trials. Therefore, the younger adults' propensity to have made a greater proportion of associative intrusions to double-function cues is not accounted for by an item repetition effect.

In addition to providing a control measure for the item repetition effect, the single-function pairs also control for type selection effects. Suppose that subjects identified targeted words as a belonging to a particular pair-type (single- or double-function) and used that information to guess from the corresponding list. If younger adults were better at the targeting process, then this could account for the result that younger adults made more associative intrusions to double-function cues. If this were the case, however, then the younger adults should also have made more associative intrusions on the single-function pairs. Figure 5B demonstrates that younger adults did not make significantly more associative than non-associative intrusions to the single-function cues. This suggests type selection effects did not mediate the age differences in the double-function associative intrusion trends.

Associative Difference Index

To quantify the differences between associative and non-associative intrusions an associative difference index was calculated for each subject across trials. The associative difference index is the difference in the probability of making an associative vs. a non-associative intrusion, $B' + R' - O'$. The associative difference index can take values from -1 to +1. An index value of -1 would indicate that the intrusions were all non-associative (i.e., O'). A value of zero would indicate an equivalent proportion of non-associative and associative intrusions was made. An index value of +1 would indicate that the intrusions were all associative (i.e., B' and R').

Figure 6 illustrates the associative difference indexes for double- (Fig. 6A) and single-function (Fig. 6B) pairs. The younger adults made a greater proportion of associative than non-associative intrusions on the double-function cues and the proportion of associative intrusions increased with trial. The older adults made significantly fewer associative intrusions to double-function pairs than the younger adults, and the proportion

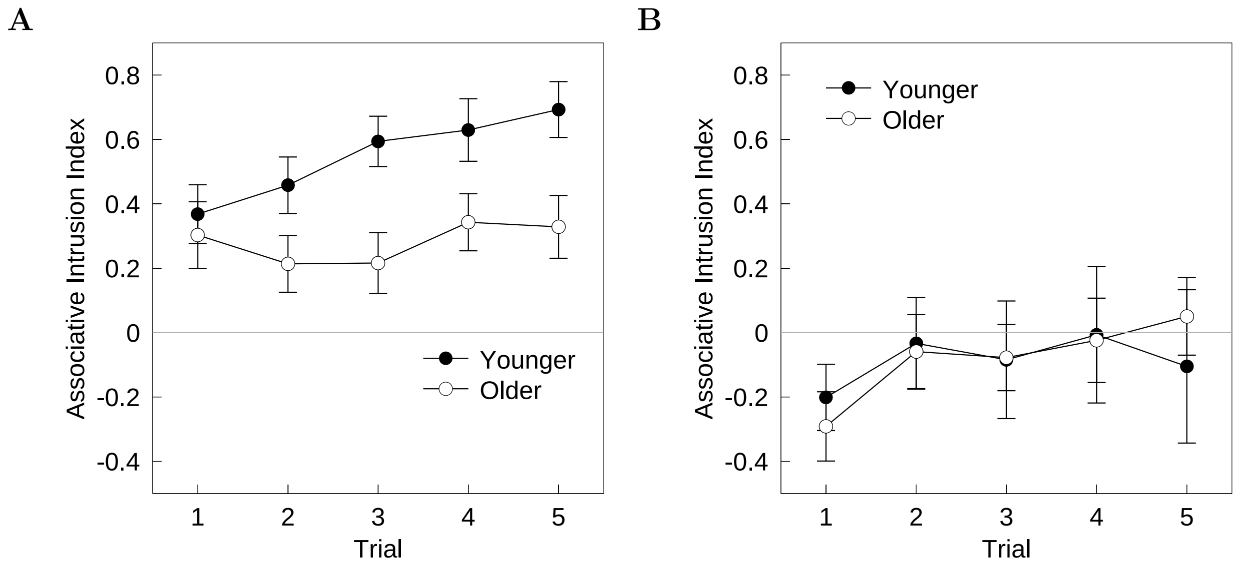

Figure 6: **Associative Intrusion Indexes.** Intrusion difference indexes plotted as a function of age across trial. Associative intrusions are responses from the same list as the cue word. Positive numbers indicate a higher probability of making an associative intrusion with a maximum score of +1. Non-associative intrusions are responses from the opposite list of the cue word. Negative numbers indicate a greater probability of making an non-associative intrusion with a maximum score of -1. The grey line indicates the probability of an equivalent proportion of associative and non-associative intrusions. Error bars are 95% confidence intervals. **A.** Double-function. **B.** Single-function.

of associative intrusions the older adults made did not significantly increase with trial. The single-function associative difference index (Fig. 6B) demonstrates that younger and older adults did not have significantly different intrusion trends for the non-overlapping pairs. Specifically, younger and older adults tended to make slightly more non-associative errors in response to single-function pairs, though the error bars indicate both groups had an index of approximately zero on trials two through five.

An ANOVA with the associative difference index as the dependent measure, age and pair-type as factors, and trial as a regressor, showed main effects of trial, $F(1, 1297) = 30.2$, MSe = 7.0, $p < .001$; pair-type, $F(1, 1297) = 336.6$, MSe = 78.3, $p < .001$; and age, $F(1, 1297) = 33.2$, MSe = 7.7, $p < .001$. Additionally there was an interaction of pair-type and age, $F(1, 1297), = 20.9$, MSe = 4.9, $p < .001$; and a three-way interaction of age by pair-type by trial, $F(1, 1297) = 8.0$, MSe = 1.9, $p < .005$. The main effects of trial, pair-type, and age indicate that the associative difference index changed significantly across trail, differed for the single- and double-function pairs, and was reliably different across the age groups. The interaction of pair-type and age confirms that the younger and older adults produced disproportionate amounts of associative and non-associative intrusions, such that younger adults made more associative intrusions to double-function cues than older adults. The pair-type by age by trail interaction demonstrates that older and younger adults not only differed with respect to the proportions of associative to non-associative intrusions to double-function cues, but that the older and younger adults' intrusion trends, across trials, followed different trajectories.

General Discussion

Consistent with previous literature, this paper demonstrates an age mediated associative deficit that is suggested to stem from a decreased ability to bind item information to contextual information (Naveh-Benjamin, 2000; Naveh-Benjamin et al., 2003, 2004; Chalfonte & Johnson, 1996; Howard et al., 2006; Murdock, 1962). We employed a paired-associate task to quantify age differences in the associative structure induced by standard paired-associate learning (PAL) pairs and pairs with overlapping contexts. Standard PAL single-function pairs with non-overlapping contexts (e.g., J-K, L-M) and double-function pairs with overlapping contexts (e.g., A-B, B-C) were randomly presented to groups of younger and older adults. Relative to older adults, younger adults demonstrated significantly higher probabilities of correct recall for both single- and double-function pairs. Therefore an associative index was created to equate correct recall performance between groups and to control for a multiplicative age effect.

Associative Indexes

The associative index was calculated by subject across pair-type and trials, as a normalized proportion of the difference between single- and double-function probabilities of correct recall given the total correct recall probability. The older adults had a lower associative index than younger adults, indicating they not only performed more equivalently on single- and double-function pairs, but that they also performed better on the double-function pairs than would be expected from their overall probability of correct recall. We suggest older adults, as the result of an associative age deficit, had less associatively-mediated response competition that could negatively affect performance on double-function pairs.

A possible confound with the associative index, however, is that it is not immune to extreme performance values. The older adults demonstrated comparatively lower overall correct recall rates. This tendency for older adults to perform closer to floor could have potentially masked the difference between the correct recall rates of the pair types. To circumvent disproportionate recall output between younger and older adults (Kahana et al., 2005, i.e., older adults make fewer correct recalls and more extra-list intrusions than younger adults) other studies of associative learning have employed recognition paradigms (Naveh-Benjamin, 2000; Naveh-Benjamin et al., 2003, 2004; Bastin & Van der Linden, 2006; Castel & Craik, 2003; Light et al., 2004; Healy et al., 2005; Prull et al., 2006). However, if older adults correctly recall fewer items, they necessarily have correspondingly elevated intrusion probabilities (Kliegl & Lindenberger, 1993; Balota et al., 1999; Kahana et al., 2002, 2005). We suggest that, in addition to the probability of correct recall, an age-related associative deficit is quantifiable via intrusion analysis. The PAL paradigm, in contrast to recognition methodologies, allows for direct measurement of intrusions.

Intrusion Analysis

The PAL task specifically tests subjects' ability to verbally generate the correct responses to studied cues. Due to the generative nature of PAL tests, intrusions are subject to confounds specific to verbal stimuli. For example, lists of semantically or phonologically related verbal stimuli are vulnerable to the possibility of differential strategy production. Prior studies have demonstrated that differential strategy production, concordant with age, may unduly influence item encoding (Dunlosky & Hertzog, 1998; Kausler & Lair, 1966; Kausler, 1994). Because the present study examined age-related differences in temporally based associative processes, our findings are presumably unlikely to be attributable to differential strategy production, the role of semantic relatedness, or the role of phonological similarities between list items and subsequent intrusions (Deese, 1959; Roediger & McDermott, 1995, e.g., false memory paradigms).

Initial intrusion analysis of the present data indicated that older adults made more intrusions than younger adults (see table 1). Associative retrieval accounts of episodic memory characterize response generation as a process in which potential recalls are first sampled, followed by an editing process that should limit responses to those items that were part of the target list/pair (Raaijmakers & Shiffrin, 1981). The older adults' tendency to globally produce more intrusions than younger adults may be due to a reduced ability to recognize that a generated intrusion was not part of the target list/pair (Zaromb et al., 2005; Kahana et al., 2005). For example, older adults committed a greater proportion of non-list item, or extra-list (X), intrusions. Hasher and Zacks (1988) suggest this may reflect an inability to inhibit extraneous associations formed in previous contexts, and is consistent with prior research demonstrating an age-related deficit in the ability to inhibit non-list items generated at recall (Kahana et al., 2005).

To constrain intrusion analysis to only items that were presented at study, as well as control for differences in the magnitude of intrusions across age groups, we employed a simplex method. The simplex equation took as inputs the associative (i.e., from the probe item list) and non-associative (i.e., from the non-probe item list) intrusions and normalized them by subject across pair-type and trial. The single-function pairs lacked an underlying associative structure and therefore provided a control measure against which to compare double-function associative learning.

As predicted, neither younger nor older adults made a significant proportion of associative intrusions to single-function cues. A greater proportion of associative intrusions to double-function cues would provide evidence that backward and transitive associations were not only generated, but provided a significant source of response competition. Temporally based intrusion analysis of the double-function pairs showed that although both groups made associative intrusions, younger adults made a greater proportion of associative intrusions than older adults. This tendency for older adults to make fewer associative intrusions to items with overlapping contexts could be due to an impaired ability to remember an item's temporal context (Hultsch & Dixon, 1983; Tun, 1989; Howard & Kahana, 2002; Kliegl & Lindenberger, 1993; Naveh-Benjamin, 2000; Naveh-Benjamin et al., 2003, 2004). We suggest that an item-to-context binding deficit prevented older adults from generating the same magnitude of contextually-overlapping associative information as younger adults. This age-mediated associative deficit was quantified as fewer associative intrusions to double-function cues.

The finding that older adults generated a reduced proportion of associative intrusions to double-function cues could suggest the mechanism(s) that mediates the formation of associations undergoes damage with age. Gluck and Myers (1997) suggested the hippocampus is necessary for making arbitrary associations between abstract stimuli. Recent neurophysiological and neuroanatomical evidence from humans and nonhuman primates demonstrates that one role of the hippocampal formation is to facilitate such associative learning (Eichenbaum, 2000; Heckers, Zalesak, Weiss, Ditman, & Titone, 2004; Henke, Weber, Kneifel, Wieser, & Buck, 1999; Henke, Buck, Weber, & Wieser, 1997; Wallenstein, Eichenbaum, & Hasselmo, 1998; Squire & Zola-Morgan, 1991). If the hippocampus is suggested to mediate associative learning and associative learning is decremented with age, then the integrity of the hippocampus could be compromised with age. In fact, hippocampal dysfunction has been shown to contribute to the associative memory deficits observed during normal aging in old humans, monkeys, and rats (Erickson & Barnes, 2003).

Conclusions

We studied age differences in the associative structure induced by learning mixed lists of double-function and single-function pairs. We found evidence, from both correct recall probabilities and intrusion analysis, of age-mediated associative differences. Motivated by the theoretical framework of temporally-defined episodic associations that depend upon contextual retrieval (Howard & Kahana, 1999, TCM), we predicted that a high functioning associative memory would create response interference among items with overlapping contexts. Comparison of the correct recall probabilities, normalized by subject for overall levels of correct recall, indicated an interaction of probability of correct recall and age for double-function pairs. Older adults, who are subject to an age-mediated associative deficit, demonstrated comparatively better normalized double-function pair performance. We suggest older adults had better normalized double-function pair performance because they were subject to less associative interference. Correspondingly, we suggest that a high functioning associative memory enabled younger adults to retrieve additional contexts at test, and this resulted in increased associative interference on the double-function cues.

Consistent with prior literature, older adults made more incorrect recalls (intrusions) than younger adults (Kliegl & Lindenberger, 1993; Balota et al., 1999; Naveh-Benjamin, 2000; Kahana et al., 2002, 2005). We predicted that quantification of intrusion trends between the age groups could provide another instantiation of an associative age deficit. To directly measure associative interference the intrusion analysis was constrained to include only items that were presented at study. Specifically, intrusions were normalized to be a proportion of the total associative (i.e., from the cue word list) and non-associative (i.e., from the opposite list) intrusions. There were no significant age differences with respect to proportions of associative and non-associative intrusions to the single-function cues. However, younger adults made a greater proportion of associative intrusions to double-function cues than older adults. An age-mediated associative deficit may be due, at least in part, to an inability to generate item-to-context binding. This item-to-context binding deficit was manifest in fewer associative intrusions to highly associative cues. Thus, we provide evidence from intrusion analysis that contextually overlapping associations decrease as a function of age and suggest that in addition to traditional PAL correct recall analysis, intrusion analysis can contribute a novel analytic technique for studying the mechanisms suggested to account for age-related associative deficits.

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Working Papers
- Provyn, J. P., Sliwinski, M. J. and Howard, M. W. Effects of age on contextually mediated associations in paired-associate learning.
- Howard, M. W., Jing, Provyn, J. P. Bridging the gap: Transitive associations between items presented in similar temporal contexts.

Support/Awards
- 2007-2008 Eric F. Gardner Fellowship
- 2006 Syracuse University one-month summer fellowship: $700.00
- 2005 Syracuse University one-month summer fellowship: $700.00

Invited Talks
- "Effects of age on contextually mediated associations in paired-associate learning, Gardner Conference, (anticipated) September 2007, Auburn, NY.

Teaching and Mentoring
- Teaching Assistant: PSY 205, Foundations of Human Behavior, 2003-2005
- Instructor: PSY 332, Cognitive Psychology Lab, 2006-2009
- Guest lecturer for PSY 373 (Human Memory), Fall 2006
- Guest lecturer for PSY 373 (Human Memory), Spring 2008
- Teaching Assistant: PSY 323 Cognitive Psychology, 2007-2008
- Tutor: PSY 252, Statistical Methods II, 2008-2009

Presentations at Scientific Meetings
- Provyn, J. P., Sliwinski, M. J. and Howard, M. W. Age differences in transitive associations, Poster presented to the *Society of Mathematical Psychology*, Vancouver, BC, July 2006.