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Implicit associative memory remains intact with age and extends to target-distractor pairs

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Abstract

Past research has shown that older adults' reduced inhibitory control causes them to *hyper-bind*, or form erroneous associations between task-relevant and -irrelevant information. In the current study, we aimed to extend hyper-binding to a novel, implicit memory paradigm. In two experiments, participants viewed pictures of objects superimposed with text and their task was to make speeded categorization judgments about the objects. The encoding phase contained three blocks that varied the potential for binding: no-binding, some-binding, and full-binding. During the no/some-binding blocks, participants decided if the pictured object alone could fit inside a common desk drawer while ignoring the superimposed text. In the no-binding block, the text was a nonword; in the some-binding block, it was an object word. During the full-binding block, participants attended to both the picture and word and decided if both items could fit inside a drawer together. After a delay, participants completed the test phase during which they viewed intact and rearranged pairs from the three encoding blocks and decided if both items could fit in a drawer together. In both experiments, older adults responded faster to intact than rearranged pairs from both the some- and full-binding blocks, suggesting that they had learned both target-target and target-distractor pairs. Young adults showed no difference in RTs to pairs from either block. These findings suggest that the binding mechanism itself is spared with age; what declines instead is inhibitory control, which serves to limit attention, and ergo binding, to task-relevant information.

Keywords: Implicit Memory, Associative Memory, Aging, Inhibitory Control, Hyper-binding

Previous research has shown that associative memory (i.e., memory for how different units of information are related) declines more with age than item memory (Chalfont & Johnson, 1996). This has been shown across various methods and materials, such as person-action pairs (Old & Naveh-Benjamin, 2008a), word pairs (Naveh-Benjamin, 2000), and picture pairs (Guez & Lev, 2016). According to the Associative Deficit Hypothesis (ADH; Naveh-Benjamin, 2000), older adults are particularly impaired on tests of associative memory because the mechanism that binds individual items into pairs at encoding declines with age (Old & Naveh-Benjamin, 2008b). While age differences in strategy (Naveh-Benjamin, Brav, & Levy, 2007) and attention (Castel & Craik, 2003) may also play a role, the primary cause of age differences in associative memory, according to the ADH, is an age-related decline in the binding mechanism itself (Naveh-Benjamin, & Mayr, 2018).

However, another potential contributor to age differences in associative memory is suggested by inhibitory deficit theory (Hasher & Zacks, 1988, Lustig, Hasher, & Zacks, 2007). Inhibitory deficit theory posits that older adults have difficulty limiting attention to goal-relevant information and blocking out irrelevant distraction. Once information has entered the focus of attention, older adults also have trouble deleting that information or putting it out of mind (Hasher, Zacks, & May, 1999). While some studies suggest that young adults also encode irrelevant information and use it in certain circumstances (e.g., Thomas & Hasher, 2012; Gopie, Craik, & Hasher, 2011; Mitchell & Perlmutter, 1986), younger adults' memory for distraction seems less robust than that of older adults (e.g., see Amer, Anderson, & Hasher, 2018, for a failed replication of the Gopie et al. findings and a demonstration of older adults' conceptual knowledge of previous distractors). Thus, older adults' inhibitory deficit often leads them to have more information within the focus of attention than young adults.

Campbell, Hasher, and colleagues have argued that this co-attended information becomes automatically bound into associations (many of which are irrelevant to the task at hand), an effect they termed “hyper-binding” (Campbell, Hasher, & Thomas, 2010; Campbell, Zimerman, Healey, Lee, & Hasher, 2012; Campbell, Trelle, & Hasher, 2014). There are instances in which access to these irrelevant associations may actually benefit older adults’ memory (Campbell et al., 2010; Weeks, Biss, Murphy, & Hasher, 2016; Amer, Campbell, & Hasher, 2016), but more often these associations likely result in increased competition during effortful retrieval and cause forgetting (e.g. Postman & Hasher, 1972; Gerard, Zacks, Hasher, & Radvansky, 1991; Biss, Campbell, & Hasher, 2012). Thus, it is possible that older adults’ poorer performance on associative memory tasks is not entirely caused by a lessened ability to bind, but also by their tendency to bind too much.

In the first study on hyper-binding, Campbell, Hasher, & Thomas (2010) showed that older adults form erroneous associations between co-occurring target and distractor stimuli. In that study, older and younger adults performed a 1-back task in which pictures were shown with superimposed words as distractors. Following a delay, participants were asked to study several picture-word pairs for an upcoming memory test. Unbeknown to the participants, some of the pairs in the study list were presented during the 1-back task and were either intact (original pairing), rearranged (items were previously presented, but not together), or new (not seen before). The cued recall results showed that older adults’ memory performance was boosted for intact pairs and disrupted for rearranged pairs relative to new pairs, suggesting that they had formed associations between the target pictures and distracting words during the 1-back task. Younger adults did not show any benefit or disadvantage for the two pair types, suggesting that they did not form irrelevant associations during the 1-back task. Other studies have provided converging evidence for the hyper-binding effect (e.g., Campbell, et al., 2012; Campbell, et al., 2014; James, Strunk, Arndt, & Duarte, 2016; Pehlivanoglu, Jain, Ariel, & Verhaeghen, 2014; Weeks, Biss, Murphy, & Hasher, 2016), though recent work suggests that it may be a purely implicit phenomenon. When older adults are informed of a connection between the encoding and test tasks at retrieval, the memory benefit for intact pairs disappears (Campbell & Hasher, 2018). These findings suggest that older adults can encode associations, but they are less able to access them through effortful retrieval (c.f., Cohn, Emrich, & Moscovitch, 2008). Thus, implicit memory paradigms may offer a more sensitive measure of age differences in binding, independent of retrieval.

Further evidence of older adults' intact implicit associative memory comes from a study by Dew and Giovanello (2010). In that study, older and younger adults were shown picture pairs of everyday objects and asked to decide if the objects would fit together inside a common desk drawer, without forfeiting speed and accuracy. Following a delay, participants performed the same object categorization task, but now the pairs of stimuli were either kept intact from the encoding phase, rearranged, or new. Reaction times (RTs) during the test phase were used to measure memory, such that slower RTs for rearranged pairs compared to intact pairs was indicative of implicit associative memory. The researchers found that young and older adults were similarly slowed to rearranged pairs relative to intact pairs, suggesting that when tested implicitly, older adults' associative memory appears intact.

In the current study, we aimed to extend the hyper-binding effect to this fully implicit associative memory paradigm and conceptually replicate the findings of Dew and Giovanello (2010). Our primary goal was to further test the notion that the binding mechanism itself is preserved with age (a mechanism that underlies a number of important everyday functions, such as learning people's names, remembering where you put your keys, or who is allergic to what). Across two experiments, we modified the Dew and Giovanello paradigm to use picture-word pairs, similar to the original hyper-binding paradigm (Campbell et al., 2010), and to include three encoding blocks with varying potential for binding: a no-binding block, some-binding block, and full-binding block. The 'full-binding' block was closest to the encoding phase of Dew and Giovanello (2010) because participants were asked to attend to both the word and picture and decide if they could fit together inside a common desk drawer. Thus, it was expected that both age groups would attend to both items and incidentally encode the pairs. During the 'some-binding' block, participants were asked to ignore the word and make the categorization judgement on the picture alone. It was expected that because older adults have reduced inhibitory control, they would inadvertently attend to the word and bind it to the target picture. Young adults were expected to ignore the distracting words during the some-binding block and as a result, not show implicit memory for the pairs from this block. Finally, the 'no-binding' block was used as a baseline condition in which the distraction at encoding was random letter strings and the pictures were later paired with new words during the test phase. It was hypothesized that older adults would show faster RTs to intact than rearranged pairs from both the some-binding and full-binding blocks. In contrast, young adults were expected to show intact < rearranged only for pairs from the full-binding block because they should be proficient at ignoring the distracting words during the some-binding block.

Experiment 1

Methods

Participants.

Data were collected from 30 younger and 30 older adults. A power analysis using Gpower software (Faul, Erdfelder, Lang, & Buchner, 2007) indicated that this sample was sufficient to detect a small effect with 96% power ($\alpha = .05$). The expected effect size used to calculate power was based on the original hyper-binding study, which showed a small effect size for the critical age x pair type interaction (Campbell, et al., 2010, Exp 1: $\eta_p^2 = .07$, and Exp 2: $\eta_p^2 = .10$). Young adults were recruited from Brock University and received partial course credit for their participation. Older adults were recruited from the community with the following inclusion criteria: aged 60+, normal or corrected-to-normal vision, and sufficient hand mobility to use a key board. Older adults received $10/hr in compensation. One young adult was excluded for reporting use of an explicit recall strategy during the implicit memory task and one was excluded for not meeting the young adult age criteria (i.e., 18-28 years old). One older adult was excluded for misunderstanding task instructions and two were excluded for having Montreal Cognitive Assessment (MoCA; Nasreddine et al., 2005) scores less than 23 (Carson, Leach & Murphy, 2018). These exclusions resulted in a final sample of 28 young adults, aged 18-27 (23 female; $M_{age} = 20.29$; $SD = 2.16$), and 27 older adults, aged 64-82 (20 female; $M_{age} = 71.44$; $SD = 4.78$). Demographic information for all participants is presented in Table 1. Most participants were tested in the afternoon, when older adults tend to be most distractible (e.g., May, 1999).

Older adults scored higher on the Shipley Vocabulary Test (Shipley, 1946), $t(53) = 11.20$, $p < .001$, $d = 1.51$, as would be expected (Verhaeghen, 2003), and had more years of education, $t(30.24) = 5.23$, $p < .001$, $d = .71$[1], than younger adults.

Materials.

Seventy-two words representing everyday objects (e.g. airplane, fence, owl) and 76 line-drawings (Snodgrass and Vanderwart, 1980) were selected. The average word length was 5.67 characters (min. 3, max. 12). Stimuli were the same or similar to the types of objects used by

[1] Adjusted for heterogeneity of variance. Levene's Test was significant ($F = 11.53$, $p = .001$)

Dew & Giovanello (2010; e.g., picture of couch becomes the word, "*couch*" or a Snodgrass image of a couch). Line drawings (e.g., church, elephant, kite) were colored red (in-line with Campbell et al., 2010) and divided into three lists of 24, plus another four for practice trials. One of the lists was paired with random six-character, letter strings (e.g. church - WZBLWY) to create the no-binding condition and two of the lists were paired with words (e.g., elephant – fence, kite – owl) to create the some- and full-binding conditions. The practice set was paired with letter strings. For the memory test (72 trials), pairs from the some- and full-binding blocks were evenly split into intact and rearranged pairs, and the no-binding pictures were paired with new words from the remaining word list.

All picture/word pairs were matched such that the correct response to both objects would be congruent (i.e., both objects either fit, or did not fit, inside a desk drawer), but participants were not made aware of this. Half of the trials required a "yes" response, and the other half required a "no" response. The picture and word lists were rotated through the different block types to create three counterbalance conditions, such that the stimuli pairs appeared in each block and pair type across counterbalances. Stimuli have been made available on Open Science Framework: https://osf.io/xfzsn/?view_only=50f287d4b31242f08365d1cf2acd13fc.

Procedure.

The study was approved by the Research Ethics Board at Brock University. The task was administered with E-Prime 3 (Psychology Software Tools, Pittsburgh, PA) on a 14-inch laptop (1366 x 786 px). The picture-word pairs were presented in the center of the screen. Word stimuli were presented in black, Consolas, size 24 font superimposed directly on the red Snodgrass images against a white background. For the encoding task, participants first performed the practice trials and were given the opportunity to repeat the practice if they were unclear about the instructions. Then for every participant, the conditions were presented in the following order: no-binding, some-binding, full-binding. In the no-binding condition, a picture with superimposed letters appeared in the center of the screen and participants were asked to ignore the letters and answer the question, “Does the object fit inside a common desk drawer?”, without sacrificing speed or accuracy. Participants were told that the objects on the screen represented real life objects and a real desk drawer was shown to them for reference. Yes/no responses were made using two keyboard options and RT was measured in milliseconds. Each trial cleared the display once a participant responded, or after eight seconds, and was followed by a fixation cross (500ms).

The some- and full-binding conditions used the same timing, except the pictures were superimposed with words instead of letter strings, and participants were given different instructions. In the some-binding condition, participants were asked to judge the object and ignore the word and answer the same question as the no-binding condition. In the full-binding condition, participants were asked to attend to both the picture and the word and to decide if the objects could fit *together* inside a desk drawer. After a 5-minute delay, in which participants completed 100 trials of an arrow flanker task as a non-verbal filler, participants completed the implicit memory test. Participants were told that they would perform the same object categorization task, except now for all trials they were to decide if both objects could fit together inside a desk drawer. Again, participants were asked to respond as quickly as possible without sacrificing accuracy. Unbeknown to the participants, the stimuli consisted of intact and rearranged pairs from the some- and full-binding blocks, randomly intermixed with old picture-new word pairs from the no-binding block.

Following the computer tasks, participants completed a graded awareness questionnaire that probed participants' knowledge of the repeated stimuli. They were first asked, "Did you notice a connection between any of the tasks you did?". If the participants answered no, then no further questions were asked. If they responded "yes", then they were asked, "What did you notice?", "When did you notice it", and "How did you notice?", and critically, "Did you consciously try to use or avoid using the words you saw in the first task as responses to the last task?" (i.e., switch to an explicit retrieval strategy). Participants were considered aware if they reported intentionally trying to retrieve the pairs at test. The use of an explicit retrieval strategy has been shown to impact implicit memory, as opposed to awareness of repeated stimuli per se (McKone & Slee, 1997). Lastly, participants completed the MoCA, Shipley Vocabulary Test, and a demographic questionnaire.

Results and Discussion

Anticipatory responses faster than 200 ms and slow responses longer than 4000 ms were first removed, then RTs for each participant were trimmed (>±2.5 SD) separately within each condition. This process removed 5.93% of encoding trials (young: 3.97%, old: 7.97%) and 4.02% of test trials (young: 3.72%, old: 4.32%). Only accurate responses to the object categorization question were included in the RT analyses.

Encoding phase RTs and accuracy data are reported in Table 2 and 3. For the encoding phase, mean accuracy on the classification task was submitted to a 2 (Age: young, old) x 3 (Block Type: no-binding [NB], some-binding [SB], full-binding [FB]) mixed ANOVA. Overall, accuracy was high and did not differ between older and younger adults, F (1, 53) = .05, p = .830, r = .03. Block type had no effect on accuracy, F (2, 106) = 1.17, p = .313, r = .10, nor was there a block type x age interaction, F (1.83, 96.75) = 2.74, p = .074, r = .17[2]. RT data for the encoding phase was entered into the same ANOVA as the accuracy data. Older adults responded more slowly, on average, than younger adults, F (1, 53) = 20.57, p < .001, r = .53. There was a significant main effect of block type, F (2, 106) = 56.25, p < .001, r = .59, which was superseded by a block type x age group interaction, F (2, 106) = 3.18, p = .046, r = .17. Follow-up tests show that older adults responded more slowly than young adults in the NB block, MD = 320.21, SE = 84.03, p < .001, 95% CI [151.69, 488.74], the SB block, MD = 243.46, SE = 79.97, p = .005, 95% CI [73.85, 394.64], and FB block, MD = 404.39, SE = 77.40, p < .001, 95% CI [249.559.63]. Thus, this interaction appears to be driven by the size of the age difference varying across blocks, with older adults being particularly slowed in the full binding block.

For the test phase, trials from the no-binding condition were dummy coded, such that trials were randomly assigned to the intact and rearranged conditions. This allowed us to submit data from the no-binding block to the same ANOVAs as data from the some- and full-binding blocks. Accuracy and RT data were submitted to separate 2 (Age: young, old) x 3 (Block Type: NB, SB, FB) x 2 (Pair Type: intact, rearranged) mixed ANOVAs. Accuracy was again high and did not differ between older and younger adults, F (1, 53) = .65, p = .424, r = .11. There was no main effect of block type, F (2, 106) = 1.87, p = .159, r = .13, or pair type, F (1, 53) = .08, p = .776, r = .04, but there was a significant block type x pair type interaction, F (2, 106) = 4.73, p = .011, r = .21. This was due to participants being more accurate for the intact (M = 92.41%, SE = .96, 95% CI [90.50, 94.35]) than rearranged pairs (M = 89.42%, SE = 1.21, 95% CI [86.99, 91.85]) from the some-binding block (p = .012) but not the full-binding block (p = .850). There was no significant difference between intact and rearranged pairs from the no-binding block (p =

[2] Both main effect of block and block by age interaction are Huynh-Feldt adjusted (ε > .75)

.064). Finally, the three-way interaction between age, block type, and pair type was not significant, F (2, 106) =.776, p = .463, r = .09.

Turning to the main hypothesis, RTs from the test phase showed a main effect of age, F (1, 53) = 39.05, p < .001, r = .65, such that older adults (M = 1292.25, SE = 38.80, 95% CI [1214.43, 1370.08]) responded more slowly than younger adults (M = 952.42, SE = 38.10, 95% CI [875.10, 1028.84])). There was a main effect of block type, F (2, 106) = 5.01, p = .008, r = .21, such that participants responded more slowly to pairs from the some-binding condition (M = 1153.15, SE = 30.14, 95% CI [1092.70, 1213.61]) than the full-binding condition (M = 1092.50, SE = 27.68, 95% CI [1036.98, 1148.02]), p = .005. Moreover, there was a main effect of pair type, F (1, 53) = 15.76, p < .001, r = .48, such that all participants responded faster to intact (M = 1098.91, SE = 28.24, 95% CI [1042.26, 1155.55]) than rearranged pairs (M =1145.76, SE = 27.40, 95% CI [1090.81, 1200.72]), p < .001. The block type x pair type interaction, F (2, 106) = 2.42, p = .094, r = .15, and block type x age interaction, F (2, 106) = 2.37, p = .099, r = .15, were not significant. There was a significant pair type x age interaction, F (1, 53) = 6.58, p = .013, r = .33, which was superseded by a significant block type x pair type x age interaction, F (2, 106) = 8.90, p < .001, r = .28 (see Figure 1). As expected, young adults showed no significant difference in RT between the intact (M = 979.53, SE = 44.51) and rearranged pairs (M = 953.40, SE = 45.99) from the some-binding block, t (27) = .80, MD = 26.13, SE = 32.51, p = .425, 95% CI [-39.07, 91.34]. However, in contrast to previous work (Dew & Giovanello, 2010), they also showed no difference in RT for intact (M = 899.81, SE = 41.54) and rearranged pairs (M = 932.18, SE = 41.45), from the full-binding block, t (27) = 1.10, MD = -32.27, SE = 29.49, p = .277, 95% CI [-91.51, 26.77].

In contrast, older adults responded more quickly to intact (*M* = 1249.50, *SE* = 45.33) than rearranged pairs (*M* = 1430.18, *SE* = 46.83) from the some-binding block, t (26) = 5.46, *MD* = -180.68, *SE* = 33.11, $p < .001$, 95% CI [-247.08, -114.28]. Similarly, older adults responded more quickly to intact (*M* = 1227.77, SE = 42.30) than rearranged pairs (*M* = 1310.25, *SE* = 42.21) from the full-binding block, t (26) = 2.75, *MD* = -82.48, *SE* = 30.03, $p = .008$, 95% CI [-142.70, -22.25]. In line with our predictions, older adults learned both the to-be-attended and to-be-ignored associations. This finding replicates the results of Dew and Giovanello (2010), showing intact associative memory for target information in older adults when tested implicitly, and extends this effect to target-distractor pairs. These results lend support to the hyper-binding hypothesis, showing that older adults bind too much when faced with distraction.

Surprisingly, young adults did not show associative memory for picture-word pairs that were fully attended during the encoding phase. Healthy, young adults typically show good memory for associations in explicit and implicit memory paradigms (see Old & Naveh-Benjamin, 2008b for a meta-analysis of age effects in associative memory). Older and younger adults did not differ in accuracy during the task, suggesting that both age groups performed the task correctly. One possibility is that block order had an effect on associative memory in younger adults. In Experiment 1, the full-binding block was always viewed last. It is conceivable that during the first two blocks, younger adults developed a strategy for inhibiting the letter strings/words that interfered with their binding in the final block (despite being directed to attend to both the picture and the word). Alternatively, pairs from the full-binding block, always viewed last, were likely most susceptible to proactive interference from previous blocks and this may have affected learning and/or retrieval of these pairs (Lustig & Hasher, 2001). Presenting the full-binding block last also meant that there was less time between study and test for the full-binding pairs, which may have differentially benefited older adults (cf. Mitchell & Perlmutter, 1986). Thus, Experiment 2 included different block orders to test whether younger adults' apparent lack of associative memory in the current paradigm is due to order effects.

Experiment 2

The goal of the current study was to replicate the results from Experiment 1 and to determine if block order was affecting younger adults' performance. As such, the procedure remained the same except for the addition of two alternative block orders. It was hypothesized that older adults would respond faster to intact pairs than rearranged pairs from both the some-binding and full-binding blocks. Younger adults were again expected to respond faster to intact pairs than rearranged pairs from the full-binding block, but not the some-binding block, though this difference may interact with block order.

Methods

The methods in Experiment 2 were the same as Experiment 1 except two additional block orders were added and the three orders were counterbalanced across participants: 1) no-binding, some-binding, full-binding (same as Exp 1); 2) some-binding, full-binding, no-binding; and 3) full-binding, no-binding, some-binding. Additionally, four new words were chosen to serve as distractors for the practice trials that came before the some- and full-binding conditions, as previously the distractors during the practice were always letter strings.

Participants.

Participants were 45 older and 45 younger adults who were recruited and compensated the same way as Experiment 1. Fifteen additional participants were tested per group to allow for greater power to test the effect of the new block order. Eleven older and 15 younger adults were replaced for various reasons, such as, reporting use of an explicit strategy during the implicit memory test (old N = 3; young N = 9), misunderstanding task instructions (old N = 1), and experimenter error (young N = 1). Further, seven older adults scored below the MoCA cut-off (< 23) and four younger adults did not meet the age criteria (ages 18-28) for the study. One older adult was excluded from the sample because their average RTs in test phase were 3 SD above the group average, resulting in a final sample of 44 older adults, aged 61-82 (34 female; M_{age} = 70.44; *SD* = 5.87; one older adult did not report their age), and 45 younger adults, aged 17-28, (36 female; M_{age} = 19.53; *SD* = 5.87). There were 15 older and 15 younger adults per block order, with the exception of the older adult group that viewed the no-binding block first, which had 14 participants.

On average, older adults scored higher on the Shipley Vocabulary Test, t (82.52) = 9.58, $p < .001$, $d = 1.02$, and had more years of educations, t (58.13) = 4.33, $p < .001$, $d = .46$[3], compared to younger adults.

Results.

Encoding RTs and accuracy are reported in Table 2 and 3. RTs were pre-processed in the same way as Experiment 1. This process removed 4.99% of encoding trials (young: 3.55%, old: 6.47%) and 3.56% of test trials (young: 3.27%, old: 3.82%). Accuracy data from the encoding phase were submitted to a 2 (Age: young, old) x 3 (Block Type: NB, SB, FB) mixed ANOVA. Overall, accuracy was again high and did not differ between young and older adults F (1, 87) = .33, $p = .569$, $r = .06$. Accuracy was also not affected by block type, F (2, 174) = .81, $p = .448$, $r = .07$, and there was no block by age interaction, F (2, 174) = .57, $p = .564$, $r = .06$. RT data was entered into the same ANOVA as above. Older adults responded more slowly on average than young adults, F (1,87) = 58.49, $p < .001$, $r = .63$. There was a main effect of block type, F

[3] T-tests for education and vocabulary were adjusted for heterogeneity of variance. Levene's Tests were significant (*ps* < .02).

(2,174) = 84.24, $p < .001$, $r = .57$. This main effect is due to participants responding slower with increasing task demands (NB < SB < FB; *ps* < .034). There was no interaction between block and age, F (2,174) = 2.29, $p = .104$, $r = .11$.

For the test phase, pairs from the no-binding block were randomly assigned to the intact or rearranged conditions. Accuracy scores were submitted to a 2 (Age: young, old) x 3 (Block Type: NB, SB, FB) x 2 (Pair Type: intact, rearranged) mixed ANOVA. Again, accuracy did not differ between young (M = 88.03%, SE = .88, 95% CI [86.28, 89.77]) and older adults (M = 88.38%, SE = .89, 95% CI [86.62, 90.15]), nor was it affected by block type or pair type (*p's* >.198).

If block order in the encoding phase of Experiment 1 affected younger adults' learning of associative pairs from the full-binding block, then we would expect block order to affect test RTs in Experiment 2. To test this possibility, RT data were submitted to a 2 (Age: young, old) x 3 (Block Type: NB, SB, FB) x 2 (Pair Type: intact, rearranged) x 3 (Block Order: NB 1st, SB 1st, FB 1st) mixed ANOVA. None of the interactions with block order approached significance (*p's* > .523). We looked at the effect of block order in young adults alone by submitting their RT data to a 3 (Block Type: NB, SB, FB) x 2 (Pair Type: intact, rearranged) x 3 (Block Order: NB 1st, SB 1st, FB 1st) mixed ANOVA. There was no main effect of block order, F (1, 42) = .52, p = .599, $r = .11$, block type, F (2, 84) = 1.05, $p = .354$, $r = .11$, or pair type, F (1, 42) = .003, p = .955, $r = .01$, and the interaction between block, pair type, and block order was not significant, F (4, 84) = 1.35, $p = .258$, $r = .13$. Therefore, it seems that block order was not responsible for the lack of associative memory for pairs from the full-binding block in younger adults. All subsequent analyses were collapsed across block order.

Test phase RTs were entered into a 2 (Age: young, old) x 3 (Block Type: NB, SB, FB) x 2 (Pair Type: intact, rearranged) mixed ANOVA. RTs were not affected by block type, F (2, 174) = 1.63, p = .199, r = .09, but on average, older adults (M = 1236.24, SE = 31.81, 95% CI [1173.02, 1299.46]) responded more slowly than young adults (M = 903.11, SE = 31.45, 95% CI [840.60, 965.63]), F (1,87) = 55.46, p < .001, r = .62. Further, there was no effect of pair type, F (1, 87) = 2.93, p = .090, r = .18 and no interactions between block type x age, F (2, 174) = .53, p = .590, r = .06, or pair type x age, F (1, 87) = 2.71, p = .103, r = .17, but there was a significant interaction between block type and pair type, F (1.94, 168.33) = 3.95, p = .021, r = 15. Importantly, there was a significant three-way interaction between age, block type, and pair type, F (1.94, 168.33) = 3.32, p = .040, r = 14[4] (see the right panel of Figure 1). In line with the results from Experiment 1, younger adults did not differ in RTs to the intact (M = 902.68, SE =36.03) and rearranged pairs (M = 904.90, SE = 36.20) from the some-binding block, t (44) = .08, MD = 2.22, SE = 28.32, p = .938, 95% CI [-58.51, 54.07], nor the full-binding block (intact M = 886.40, SE = 38.22; rearranged M = 889.71, SE = 37.50), t (44) = .11, MD = 3.31, SE = 29.54, p = .911, 95% CI [-62.02, 55.40]. Although we replicated our findings from Experiment 1, the results do not fully support our original hypothesis that younger adults would respond faster to intact than rearranged pairs from the full-binding block, but not those from the some-binding block.

As for older adults, they responded faster to intact (M = 1188.28, SE = 36.43) than rearranged pairs (M = 1250.90, SE = 36.60) from the some-binding block, t (43) = 2.19, MD = -62.62, SE = 28.64, p = .031, 95% CI [-119.55, -5.69], and faster to intact (M = 1178.29, SE = 38.76) than rearranged pairs (M = 1291.84, SE = 37.93) from the full-binding block, t (43) =

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[4] Block type x Pair type and block type x pair type x age interactions are Huynh-Feldt adjusted (ε > .75)

3.80, *MD* = -113.54, *SE* = 29.87, $p < .001$, 95% CI [-172.92, -54.17][5]. These findings replicate the results from Experiment 1 and support our hypothesis that older adults would incidentally encode both target-target and target-distractor pairs.

General Discussion.

Age differences in explicit associative memory are well documented (Old & Naveh-Benjamin, 2008b), but the precise cause of these differences is still under debate. According to inhibitory deficit theory (Hasher & Zacks, 1988) and more specifically, the hyper-binding hypothesis (Campbell et al., 2010), memory binding is an automatic process that remains relatively intact with age. What declines instead is the ability to maintain focus on relevant information and inhibit distraction, leading older adults to have more distracting information in mind and, as a result, to form more non-target associations than younger adults. Across two experiments, we found that older adults were faster to make categorization judgments about object pairs that remained intact from encoding versus those that were rearranged, and they showed this implicit associative memory effect for both fully attended (target-target) pairs and partly attended (target-distractor) pairs. Young adults, on the other hand, showed no evidence of implicit associative memory in the current study.

Older adults' faster responding to intact pairs from the full-binding condition replicates the effects of Dew & Giovanello (2010) and suggests that associative memory is maintained with age when tested implicitly. These findings suggest that the binding mechanism itself is not impaired with age (Naveh-Benjamin, 2000; Chalfont & Johnson, 1996), in that even implicit

[5] It is worth noting that the pattern of results is reversed from Experiment 1, in that older adults now show a larger difference between intact and rearranged pairs from the full-binding block than the some-binding block (whereas in Experiment 1, they showed a larger difference for pairs from the some-binding block). We had no *a priori* hypotheses about which block should show the larger difference. The important point is that older adults responded more quickly to intact than rearranged pairs from both blocks.

associative memory would decline with age if older adults were less able to bind. Rather, it seems that older adults have a specific deficit in limiting attention to and intentionally binding relevant components of an episode together (Old & Naveh-Benjamin, 2008b), potentially due to a decline in the use of effective associative strategies (Naveh-Benjamin et al., 2007). In addition, older adults may have difficulty accessing associations explicitly, possibly due to impaired controlled retrieval (Cohn et al., 2008; Jennings & Jacoby, 1993, 1997; Healey, Hasher & Campbell, 2013) and/or increased interference at retrieval from non-target associations (Campbell et al., 2010; Biss et al, 2012). In the current study, older adults not only learned the attended pairs from the full-binding block, but they also learned the target-distractor pairs from the some-binding block, as predicted by the hyper-binding hypothesis.

We have argued that hyper-binding likely contributes to older adults' associative memory deficit by leading to greater interference at retrieval, in a manner similar to classic fan or cue-overload effects (i.e., the finding that associating more responses to a single cue can decrease one's ability to retrieve any one of those responses, an interference effect that is exacerbated with age; Anderson, 1974; Watkins & Watkins, 1975; Gerard, Zacks, Hasher, & Radvansky, 1991). Previous work suggests that explicit memory for associations may be more vulnerable to interference from non-target associations than implicit memory for associations (Graf & Schacter, 1987; cf. Lustig & Hasher, 2001) and thus, hyper-binding may contribute to older adults' associative deficit under explicit retrieval conditions while leaving implicit memory for associations relatively spared.

Most of our hyper-binding work has used target-distractor pairs, or examined older adults' greater binding of entirely irrelevant information (e.g., Campbell et al., 2012). But can older adults' reduced inhibitory control account for age-related deficits on standard associative memory paradigms that do not include distracting information? We addressed this issue in one study (Campbell, Trelle, & Hasher, 2014) that looked at binding across successive pairs on a standard paired associate learning task. Memory for the pairs was tested using an associative recognition task that included intact pairs and two types of rearranged pairs: those from close together in the study list (i.e., one trial apart) and those from far apart (i.e., nine trials apart in Exp 1, seven trials apart in Exp 2). While hit rate did not differ between the groups, older adults made more false alarms to near than far rearranged pairs, suggesting that they had formed associations across successive pairs at study due to their lessened ability to inhibit the recent past. Thus, hyper-binding may contribute to older adults' typically higher false alarm rate on standard tests of associative memory that do not include experimenter-manipulated distraction, but this is certainly a question that deserves further attention.

In contrast to previous work (Dew & Giovanello, 2010), young adults in this study did not respond faster to intact than rearranged pairs, even when these pairs were fully attended. Experiment 2 aimed to test whether this lack of priming was due to the order of conditions in Experiment 1, which always presented the full-binding block last after two blocks of ignoring letter stimuli. However, block order had no effect on RTs in Experiment 2, and indeed, even when younger adults received the full-binding block first, they showed no difference in RTs to intact (M = 927.64, SD = 259.63) and rearranged pairs (M = 930.97, SD = 194.81) from the full-binding condition, t (14) = .08, p = .935, d = .02, suggesting that block order was not responsible for the lack of effect in the younger group. The lack of priming observed in the younger adults is unforeseen, however, there were a number of changes made to Dew & Giovanello's paradigm that were necessary to extend hyper-binding to this task, including the creation of new block types (i.e., no- and some-binding) that were critical to testing the hyper-binding hypothesis.

Other differences include: 1) we used overlapping picture-word pairs, while they used non-overlapping picture-picture pairs; 2) our test list consisted of 48 old (24 intact, 24 rearranged) and 24 half-new pairs (no fillers), while their test list consisted of 24 old, 24 new, and 20 filler pairs; and 3) we included two additional encoding blocks that required a slightly different judgment (i.e., would the picture *alone* fit inside a drawer). The decision to use similar stimuli to the original hyper-binding paradigm (i.e., picture-word pairs) is an important difference that could be contributing to the current findings. Further, in both experiments, older adults scored significantly higher on the vocabulary test than young adults (see Table 1), in line with previous work (Verhaeghen, 2003). It is plausible that the use of word stimuli could have improved older adults' implicit memory for the pairs. However, if superior language ability in older adults was driving the current results, we would expect a correlation between vocabulary and binding in the some- and/or full-binding blocks, which we do not see in younger (some-binding: r (71) = .13, p = .283; full-binding: r (71) = -.08, p = .492) or older adults (some-binding: r (69) = .047, p = .695; full-binding: r (69) = -.07, p = .547). This nonsignificant relationship suggests that the decision to use picture-word pairs did not differentially affect older and younger adults' performance in our experiments. Future research should investigate whether systematically varying stimulus types influences the strength of implicit memory in older and younger adults.

Another possible reason for young adults' lack of implicit associative memory in the full-binding block could be due to the self-paced nature of the task. In both experiments, stimuli offset once participants responded and young adults' encoding phase RTs were significantly faster than those of older adults (see Table 2). Thus, young adults may not have had enough time to bind each pair (c.f., Voss & Gonsalves, 2010, who showed that longer study actually decreased priming in younger adults). If longer encoding time was related to binding, we would expect to see a correlation between encoding RT and binding in the some- and/or full-binding blocks, but there was no correlation in younger (some-binding: r (71) = -.07, p = .56; full-binding: r (71) = -.005, p = .969) or older adults (some-binding: r (69) = .04, p = .759; full-binding: r (69) = .02, p = .891, even when collapsing across experiments to maximize power. Further, across both experiments, when encoding RT is accounted for in the main analysis the pattern of results does not change, providing further evidence that encoding RT does not seem to account for the results. Future research investigating implicit associative memory should use consistent encoding durations to determine if encoding RT plays a significant role.

A final potential explanation for why young adults did not show significantly faster RTs for intact than rearranged pairs in the full-binding block is that the young adults in our study responded faster overall than the young adults in Dew and Giovanello (2010). In their Experiment 1 (which included the same desk drawer judgment as the current study), young adults' mean RTs at test were as follows: Intact M = 969 (SD = 183), Rearranged M = 1039 (SD = 179). In this study, for the full-binding condition (which is most equivalent to Dew & Giovanello), our young adults responded numerically faster to intact than rearranged pairs, but were notably faster in both conditions compared to those from Dew & Giovanello: Exp 1 Intact M = 899.81 (SD = 212.78), Rearranged M = 932.18 (SD = 210.37); Exp 2 Intact M = 886.40 (SD = 227.74), Rearranged M = 889.71 (SD = 196.35). Thus, floor effects may have contributed to the apparent lack of associative memory in our younger adults. Young adults' fast responding may have been caused by a realization that if one object does not fit in the desk drawer, then both objects will not fit together (avoiding the need to attend to both objects). We are currently developing a new paradigm that forces participants to attend to both objects in the full-binding condition.

The current results and previous work on hyper-binding demonstrate the consequences of reduced inhibitory control for associative memory in older adults. Hasher and Zacks (1979) originally posited that automatic processes, such as the encoding of temporal order and frequency of occurrence, remain relatively stable across the lifespan. Instead what develops throughout childhood and declines in old age, they argued, are controlled processes such as the inhibition of prepotent responses and the suppression of distraction (Hasher & Zacks, 1988). Memory binding is thought to be a relatively automatic process (Moscovitch, 1992; Olsen, Moses, Riggs, & Ryan, 2012), present in species throughout the animal kingdom (e.g., Clayton & Dickinson, 1998; Crystal & Smith, 2014) and in children at a very early age (e.g., Rovee-Collier, 1999). If two or more pieces of information are co-attended (e.g., an object and its context, a pair of words), they are obligatorily bound into a joint memory trace (Logan & Etherton, 1994; Chun & Jiang, 1998; Turk-Browne, Jungé, & Scholl, 2005). Thus, attention is the gate-keeper of associative memory, and if attention is not limited to target information, as is often the case for older adults (for a recent review, see Hasher & Campbell, in press), then more non-target associations will inevitably be formed. These non-target associations likely lead to greater interference at retrieval for older adults, which again due to impaired inhibitory control, older adults are less able to resolve (Healey et al., 2013; Ikier, Yang, & Hasher, 2008).

Associative memory, when tested explicitly, shows a marked decline with age. If this decline were due to an impairment in the binding mechanism itself, then implicit associative memory would also decline with age. However, the current results and those from previous work (Dew & Giovanello, 2010; Campbell et al., 2012) suggest that implicit associative memory remains intact with age. An alternative explanation for older adults' explicit associative memory deficit is put forth by inhibitory theory, which suggests that reduced inhibitory control leads to excess (or hyper-) binding at encoding, followed by a lessened ability to inhibit these excess associations at retrieval. There may be times when these excess associations are helpful (as in face-name learning; Weeks et al., 2016), but more often than not, hyper-binding is likely detrimental to older adults' performance on explicit tests of associative memory.

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Table 1.
Demographic information for participants in Experiment 1 and Experiment 2.

	Age (years)			Education (years)			Vocabulary			MoCA		
Group	*M*	Range	*SD*	*M*	Range	*SD*	*M*	Range	*SD*	*M*	Range	*SD*
Experiment 1												
Younger	20.29	18-27	2.16	14.15	12-17	1.41	26.86	20-39	3.66	-	-	-
Older	71.44	64-82	4.78	18.73	9-29	4.25	36.37	31-40	2.51	27.07	24-30	1.75
Experiment 2												
Younger	19.53	17- 28	2.01	13.82	7-18	1.91	26.93	18-35	4.26	-	-	-
Older	70.50	61-82	5.75	16.87	4-30	4.22	34.64	22-40	3.28	26.7	23-30	1.77

Note. Education data was missing for two participants in Experiment 2.

Table 2.
Accuracy for Encoding and Test Phase within block types for Experiment 1 and Experiment 2.

	Younger		Older	
	M	*SD*	*M*	*SD*
Experiment 1				
Encoding				
No-binding	19.93	4.12	20.41	2.19
Some-binding	19.96	4.48	21.00	2.09
Full-binding	21.46	1.57	20.33	2.27
Test				
No-binding				
Intact	10.75	0.84	11.04	0.90
Rearranged	11.18	1.02	11.22	1.05
Some-binding				
Intact	11.07	0.86	11.11	0.85
Rearranged	10.57	1.07	10.89	1.09
Full-binding				
Intact	10.86	0.85	10.78	1.05
Rearranged	10.75	1.00	10.81	0.96
Experiment 2				
Encoding				
No-binding	20.67	2.33	20.73	1.78
Some-binding	20.82	1.60	20.73	1.80
Full-binding	21.24	1.96	20.77	2.24
Test				
No-binding				
Intact	10.49	1.01	10.64	0.99
Rearranged	10.38	1.53	10.66	1.18
Some-binding				
Intact	10.71	1.04	10.45	0.95
Rearranged	10.40	1.23	10.61	0.97
Full-binding				
Intact	10.53	1.10	10.55	1.37
Rearranged	10.87	1.14	10.73	1.21

Note. Maximum possible scores at encoding and test were 24 and 12, respectively.

Table 3.
Reaction Times for Encoding and Test Phase within block types for Experiment 1 and Experiment 2

	Younger		Older	
	M	*SD*	*M*	*SD*
Experiment 1				
Encoding				
No-binding	1057.56	260.84	1377.77	356.60
Some-binding	1038.92	277.76	1273.17	314.73
Full-binding	1289.81	244.29	1694.20	325.39
Test				
No-binding				
Intact	953.04	204.88	1283.78	281.20
Rearranged	996.55	219.01	1252.02	251.19
Some-binding				
Intact	979.53	217.19	1249.50	253.15
Rearranged	953.40	192.73	1430.18	286.61
Full-binding				
Intact	899.81	212.78	1227.77	226.90
Rearranged	932.18	210.37	1310.25	228.24
Experiment 2				
Encoding				
No-binding	897.65	194.01	1254.41	341.36
Some-binding	944.37	205.40	1349.81	352.93
Full-binding	1187.96	280.00	1666.35	372.97
Test				
No-binding				
Intact	918.81	218.78	1268.34	294.15
Rearranged	916.20	232.44	1239.80	242.08
Some-binding				
Intact	902.68	235.65	1188.28	247.68
Rearranged	904.90	219.85	1250.90	264.23
Full-binding				
Intact	886.40	227.74	1178.29	283.96
Rearranged	889.71	196.35	1291.84	297.64

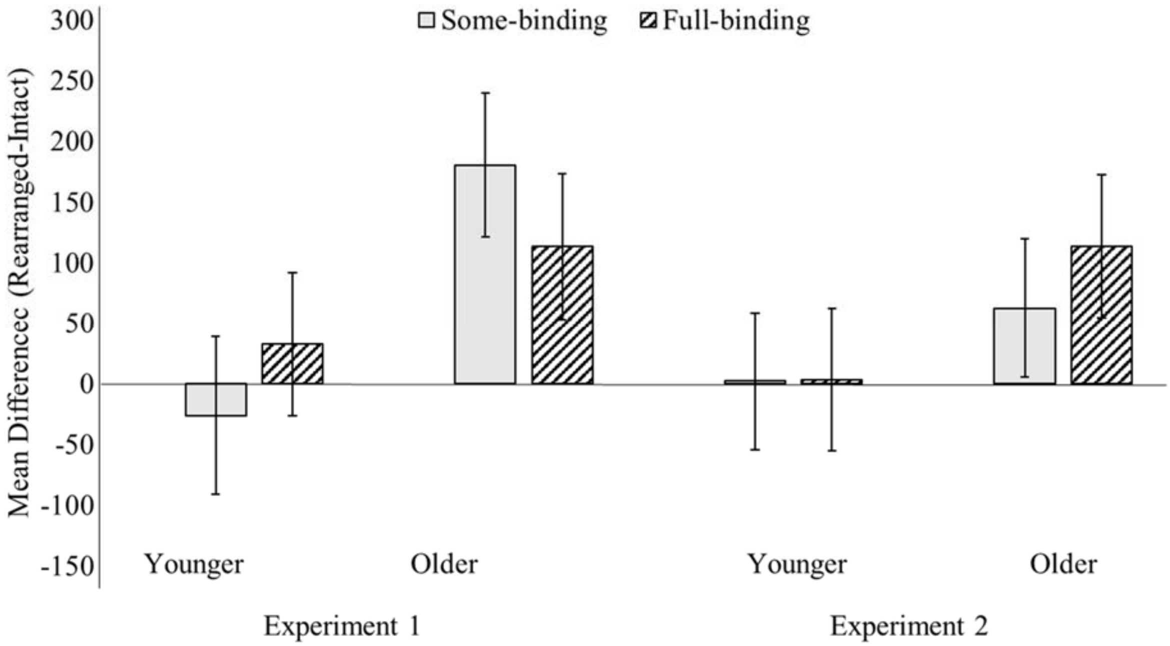

Figure 1. Results from Experiment 1 and 2. Bars represent difference scores (Rearranged – Intact) for the conditions of interest. Error Bars: 95% CI.