

# Using Attribute Amnesia to Test the Limits of Hyper-Binding and Associative Deficits in Working Memory

John M. McCormick-Huhn  
The Pennsylvania State University

Hui Chen  
Zhejiang University

Bradley P. Wyble and Nancy A. Dennis  
The Pennsylvania State University

Previous work has shown mixed evidence regarding age-related deficits for binding in working memory. The current study used the newly developed attribute amnesia effect (H. Chen & Wyble, 2015a) to test the associative-deficit hypothesis during working memory and to probe whether hyper-binding extends to include binding of de-selected information. In studies of attribute amnesia, participants use target attributes (e.g., identity, color) to demonstrate near ceiling levels of reporting of a second target attribute (e.g., location) across a series of trials (H. Chen & Wyble, 2015a, 2016). Yet, despite having just processed the target-defining attribute, they have difficulty reporting it on a surprise trial. This effect provides several predictions for associative binding in aging. The associative-deficit hypothesis predicts age-related decline on the surprise trial, whereas an extension of hyper-binding predicts age-related increase in performance in older adults. In Experiment 1, when working memory load was low, older adults demonstrated attribute amnesia equal to that found in younger adults. When load increased in Experiment 2, older adults again demonstrated attribute amnesia as well as an age deficit for reporting target attributes. In lieu of spontaneous binding, results suggest that expectancy plays a critical role in older adults' propensity to encode and bind target attributes in working memory. Results further suggest that expectancy alone is not enough for older adults to form bound representations when task demands are high. Taken together results revealed a boundary condition of hyper-binding and further provided conditional support for the associative-deficit hypothesis in working memory.

**Keywords:** attribute amnesia, aging, associative-deficit hypothesis, hyper-binding, working memory

How people perceive the world, and how people later come to remember it, is the direct result of binding together many pieces of information to form complex memories of past events. Despite the importance of binding, several lines of research have shown that one's ability to bind discrete pieces of information in episodic memory declines with age (for review see, Old & Naveh-Benjamin, 2008; Spencer & Raz, 1995). Although similar findings have emerged in

short-term and working memory (e.g., T. Chen & Naveh-Benjamin, 2012; Cowan, Naveh-Benjamin, Kilb, & Sauls, 2006; Mitchell, Johnson, Raye, & D'Esposito, 2000; Mitchell, Johnson, Raye, Mather, & D'Esposito, 2000; Peterson & Naveh-Benjamin, 2016) other reports have failed to find evidence for age-related binding deficits in working memory tasks (e.g., Bopp & Verhaeghen, 2009; Brockmole, Parra, Della Sala, & Logie, 2008; Parra, Abrahams, Logie, & Della Sala, 2009; Read, Rogers, & Wilson, 2016). In the current investigation, we used a recently developed paradigm, the attribute amnesia task, (see H. Chen & Wyble, 2015a), as a novel methodology for investigating an age-related associative, or binding, deficit during a working memory task.

Age-related deficits in binding, including memory for item-item and item-source information, has been characterized by the associative-deficit hypothesis (Naveh-Benjamin, 2000), which states that older adults show a deficit for associative memory over and above the deficit (if any) that is found for item memory. For example, in a seminal finding, Chalfonte and Johnson (1996) reported that memory for individual attributes of an object (e.g., item identity or color) was comparable between young and older individuals, whereas the memory for conjunctions of attributes (e.g., color and identity) was significantly impaired in older compared with younger adults. Like the foregoing example, considerable evidence has supported this associative-deficit hypothesis including age-deficits in memory for face-name pairs (e.g., Naveh-

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John M. McCormick-Huhn, Department of Psychology, The Pennsylvania State University; Hui Chen, Department of Psychology and Behavioral Science, Zhejiang University; Bradley P. Wyble and Nancy A. Dennis, Department of Psychology, The Pennsylvania State University.

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Correspondence concerning this article should be addressed to Nancy A. Dennis, Department of Psychology, The Pennsylvania State University, University Park, PA 16801, or to Hui Chen, Department of Psychology and Behavioral Science, Zhejiang University, Xixi Campus, Hangzhou, People's Republic of China, 310007. E-mail: [nad12@psu.edu](mailto:nad12@psu.edu) or [psychenhui@gmail.com](mailto:psychenhui@gmail.com)

Benjamin, Guez, Kilb, & Reedy, 2004; Rendell, Castel, & Craik, 2005), word pairings (e.g., Castel & Craik, 2003) and face-location pairings (e.g., Bastin & Van der Linden, 2005).

Despite the wealth of research characterizing the associative deficit in episodic memory, studies evaluating associative binding in short term and/or working memory have been far from consistent (for a review of age-related effects in visual feature binding and working memory, see Allen, Brown, & Niven, 2013). Although some studies have shown support for an age-related binding deficit in working memory (e.g., T. Chen & Naveh-Benjamin, 2012; Cowan et al., 2006; Mitchell, Johnson, Raye, & D'Esposito, 2000; Mitchell, Johnson, Raye, Mather, et al., 2000; Peterson & Naveh-Benjamin, 2016), others have found no specific age-related decline in feature binding, but report an overall age decline for both single attributes and their bound representation (e.g., Bopp & Verhaeghen, 2009; Brockmole et al., 2008; Parra et al., 2009; Read et al., 2016; Rhodes, Parra, Cowan, & Logie, 2017).

A review of studies suggests that factors including the type of binding being evaluated, memoranda, and timing may all contribute to age-effects in working/short term memory binding. For example, several studies have found an age deficit in item-context binding (e.g., object and location binding; Mitchell, Johnson, Raye, & D'Esposito, 2000; Mitchell, Johnson, Raye, Mather, et al., 2000; Peterson & Naveh-Benjamin, 2016),<sup>1</sup> yet there is little evidence for an age-deficit in intra-item binding (e.g., objects and color found in Brockmole et al., 2008; Parra et al., 2009; Read et al., 2016). Differences between these two types of binding are also typically confounded by different stimuli used to investigate the binding deficits. For example, many of the stimuli used for item-context probes involve complex stimuli, such as line drawings of everyday objects (e.g., Mitchell, Johnson, Raye, & D'Esposito, 2000; Mitchell, Johnson, Raye, Mather, et al., 2000) and faces and scenes (Peterson & Naveh-Benjamin, 2016). Whereas many of the studies examining intra-item binding have used basic shapes and colors (e.g., Brockmole et al., 2008; Parra et al., 2009; Read et al., 2016). Further, in the initial studies demonstrating age deficits, the retention interval was significantly longer compared with studies that have not shown evidence for the deficit (e.g., 8 s in Mitchell, Johnson, Raye, & D'Esposito, 2000, vs. 900 ms in Experiment 1, Parra et al., 2009). Finally, many of those studies not showing an age deficit have utilized concurrent tasks (Brockmole et al., 2008; Rhodes, Parra, & Logie, 2016), whereas those demonstrating deficits have not (Mitchell, Johnson, Raye, & D'Esposito, 2000; Mitchell, Johnson, Raye, Mather, et al., 2000; Peterson & Naveh-Benjamin, 2016). Taken together, evaluations of all of these factors reveal a complicated state of the literature, with inconclusive evidence for the associative-deficit hypothesis in short term and/or working memory paradigms.

An alternative account to the associative-deficit hypothesis is that of hyper-binding (e.g., Campbell, Hasher, & Thomas, 2010; Campbell, Trelle, & Hasher, 2014; Pehlivanoglu, Jain, Ariel, & Verhaeghen, 2014; Read et al., 2016; Weeks, Biss, Murphy, & Hasher, 2016). *Hyper-binding* is defined as the "obligatory formation of overly broad associations between events occurring in close temporal and spatial contiguity" (Campbell et al., 2010, p. 404). To this end, Campbell and colleagues (2010) posit that older adults often maintain too much irrelevant, or distracting, information in memory. This irrelevant information becomes bound together with task-relevant materials, with the interference caused by these ex-

traneous bindings producing impairments in memory (Campbell et al., 2014). In previous tests of hyper-binding, excessive binding of distracting information has been shown to occur during initial selection, by the means of failing to inhibit or suppress irrelevant information (e.g., Campbell et al., 2010). In such cases, only entirely *irrelevant* information has been implicated in hyper-binding. Yet, the inhibition deficit theory that hyper-binding is predicated on asserts that older adults have difficulty inhibiting both irrelevant information and de-selecting information (e.g., Lustig, Hasher, & Zacks, 2007; May, Zacks, Hasher, & Multhaup, 1999; Zacks, Radvansky, & Hasher, 1996). To that end, it stands to reason that hyper-binding could also include information that had once been activated, but was subsequently de-selected as irrelevant. Such an extension of hyper-binding would be consistent with previous reports of older adults' deficits in the ability to deactivate previously attended information (e.g., Hamm & Hasher, 1992; Scullin, Bugg, McDaniel, & Einstein, 2011) and work by Lustig et al. (2007) that state that the deletion of no longer relevant information is a critical function of inhibition. To that end, the current study also sought to test whether hyper-binding can also occur in cases where the information is initially task relevant but then is eligible to be deselected in light of a new task demand.

To do so we, used a recently developed attribute amnesia task (H. Chen & Wyble, 2015a) that allowed for a test of the associative-deficit hypothesis in working memory, as well as provided a means for testing a potential extension of hyper-binding for deselected information. Attribute amnesia (for the original reporting of this phenomenon, see H. Chen & Wyble, 2015a; for further replications and evaluation of attribute amnesia, see H. Chen & Wyble, 2016; H. Chen, Swan, & Wyble, 2016), has provided a counter argument to the misconception that nearly all attended information will be remembered and correctly reported within a time frame typical of working memory paradigms. In the original studies reported by Chen and Wyble (2015a), participants were presented with a  $2 \times 2$  stimulus array and asked to report the location of a target letter among three distracting digits, each item presented in one of four different colors. After a large number of trials, participants were presented with a "surprise trial", on which they were asked to report the identity of the target letter and the color that it was presented in, prior to being probed for target location. It is important to note that because participants had to locate the letter (i.e., the key attribute) among digits, they had to process the meaning of the target stimulus to find it and report its location. Despite highly accurate location report on presurprise trials (89% correct, four alternatives), on the surprise trial, participants had difficulty reporting the correct identity of the letter they had just located moments before (25% correct, four alternatives) as well as its color which was completely task irrelevant (30% correct, four alternatives). Despite this poor performance, on four control trials that followed the surprise trial, participants were

<sup>1</sup> Though, we should note, that recent caution has been expressed regarding the interpretation of the findings by Mitchell and colleagues (Mitchell, Johnson, Raye, & D'Esposito, 2000; Mitchell, Johnson, Raye, Mather, et al., 2000). Rhodes et al. (2017) argued that sufficient statistical evidence was not present to accurately support an age deficit specific to binding—and that such evidence requires investigation of an age group by condition interaction (see Rhodes et al., 2017, for further discussion of this concern).

again asked the same set of questions and performance markedly improved, rebounding to presurprise trial levels. Results indicate that participants had the capacity to encode and bind all stimulus attributes because they could report them in the control trials, but failed to do so when there was no expectation to report this information.

The attribute amnesia task affords us a unique means of evaluating age-related cognitive differences, in particular detecting the presence or the absence of a binding deficit in working memory. Of critical interest will be older adults' performance on the "surprise" trial, a test of whether the key attribute (e.g., the target-defining attribute) is bound with the reported attribute (e.g., location) during the presurprise trials. With respect to hyper-binding, the surprise trial tests memory for information that was initially relevant to task success, but once processed, is quickly deemed irrelevant to the remaining task. One interpretation of the young adults' failure to report the key attribute during surprise trials in past attribute amnesia experiments (e.g., H. Chen & Wyble, 2015a) could be related to this deselection process. That is, when there was no expectation to maintain the key attribute in working memory, despite being relevant only moments before, the young adults effectively deselected the information. Older adults, on the other hand, given deficits in deselection and inhibition (Hasher, Zacks, & May, 1999; Lustig et al., 2007) may hyper-bind the newly irrelevant attribute to the to-be-reported attribute. Such an occurrence would reveal itself via enhanced performance on the surprise trials.

Specifically, in Experiment 1, we probe individuals' memory for letter identity and location under a working memory task that required them to locate a target letter's location among an array of distracting digits. In Experiment 2, we similarly probed memory for ink color and word identity in a modified Stroop paradigm that also tests attribute amnesia. Experiment 2 also required participants to manipulate and compare information in working memory (congruency judgments), which allows us to see how the necessity to draw upon additional executive function resources interacts with spontaneous binding of target attributes. We posit that, if an associative-deficit holds in working memory, then older adults will be just as susceptible, if not more susceptible (showing lower rates of percent correct on surprise task), to attribute amnesia on the surprise trial. Alternatively, if older adults fail to de-select no longer relevant information (i.e., the key attribute) and bind it with the reported attribute, then they will be less susceptible to attribute amnesia than young adults, showing better memory performance on the surprise trial. Should this evidence emerge, it would provide an initial demonstration of an extension of hyper-binding from its current interpretation.

### Experiment 1

In Experiment 1, we evaluated age-related differences in associative binding during visual working memory using the attribute amnesia task. Specifically, individuals were asked to identify the location of a letter among three distractor numbers during presurprise trials (in a  $2 \times 2$  grid). Then, in a surprise trial and all following control trials, indicate the identity of the letter in addition to its location. In the surprise trial, we will probe if older adults are able to encode and bind these two features implicitly, when there is no expectation of having to maintain both pieces of

information in working memory. Superior performance in older adults on the surprise trial would be evidence for the extension of hyper-binding to previously relevant information. Alternatively, a lack of hyper-binding for deselected and no longer relevant information should result in attribute amnesia. It is important to note that we will probe older adults' performance on subsequent control trials. Persistent poor performance by older adults on these control trials compared with young adults would suggest the presence of an associative deficit.

### Method

**Participants.** Twenty young and 20 older adults participated in the current study. The young adults were recruited from the Psychology Department subject pool (average age: 19.20 years,  $SD = 1.34$ ; range = 18–23) and the older adults were recruited from the State College community (average age: 72.90 years,  $SD = 5.09$ ; range = 65–84). Young adults were compensated with course credits, and older adults paid for their participation. Prior to participating in the experimental task, older adult participants completed a battery of cognitive assessments (see Table 1 for additional details). These tests were administered to screen for dementia and depression in the older adult sample. None of the older adults were excluded, as they all demonstrated performance within normal ranges for their age, thus verifying that they were cognitively healthy. Both young and older adults reported normal or corrected-to-normal visual acuity. All experimental procedures were approved by The Pennsylvania State University's Institutional Review Board for the ethical treatment of human participants.

**Apparatus.** Stimuli were presented on a 17 in. computer monitor at a resolution of  $1280 \times 1024$  pixels and refresh rate at 60 Hz using Matlab (MathWorks, Inc., Natick, MA) with the Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997). Participants sat at an approximate viewing distance of 50 cm from the monitor. All responses for the experimental task were made on a standard QWERTY computer keyboard.

**Stimuli.** The fixation display included four black placeholder circles ( $0.58^\circ \times 0.58^\circ$  of visual angle) and a black fixation cross ( $0.58^\circ \times 0.58^\circ$ ) presented in the center of the screen. The four black placeholder circles were presented at the four corners of an invisible square ( $6.69^\circ \times 6.69^\circ$ ). The stimulus array consisted of one target letter (i.e., A, B, D, or E;  $0.87^\circ \times 0.58^\circ$ ) and three-digit distractors (values ranging 1 to 8;  $0.87^\circ \times 0.58^\circ$ ) arranged at the four corners of an invisible square ( $6.69^\circ \times 6.69^\circ$ ). All stimuli were presented in black (RGB: 0/0/0) ink color, uppercase Arial font, and size 30. Stimuli were presented on a gray background (RGB: 150/150/150). All participants reported being able to clearly read the screen.

**Procedure and design.** Figure 1 shows the procedure order for Experiment 1. Prior to the start of each trial, participants saw a fixation cross on the center of the screen for 800 to 1,800 ms. On each trial, participants saw an array of 4 items, one appearing in each of the 4 quadrants of an invisible  $2 \times 2$  array. Stimuli on each trial always contained 1 letter (target) and 3 numbers (distractors, ranging between 1 and 8). The array remained on the screen for 267 ms. A blank screen then appeared for 533 ms, followed by the probe question. In presurprise trials (the first 11 trials), the probe question asked partic-

Table 1  
Participant Demographic and Cognitive Assessment Information

	Experiment 1		Experiment 2	
	Young adults	Older adults	Young adults	Older adults
Demographic information				
<i>N</i>	20	20	40	40
Age	19.20 (1.34)	72.90 (5.09)	18.80 (1.34)	73.03 (5.12)
Proportion female	.95	.90	.88	.53
Education (years)	12.75 (0.99)	16.61 (2.77)	12.60 (1.08)	16.79 (2.18)
Cognitive assessments				
MMSE		29.75 (0.54)		29.45 (0.85)
GDS		1.03 (2.25)		0.55 (0.60)
WCST				
Trials correct	48.30 (8.41)	48.50 (7.95)	47.25 (7.79)	48.68 (7.22)
Categories completed	3.70 (1.30)	3.50 (1.28)	3.65 (1.12)	3.53 (1.30)
WAIS-III				
Digit Symbol		13.20 (2.77)		12.73 (3.41)
Symbol copy		107.40 (22.07)		106.70 (22.20)
L-N sequencing		11.95 (1.93)		11.85 (2.07)

Note. All values (excluding *N* and bender) are means (standard deviations). MMSE = Mini-Mental State Exam; GDS = Geriatric Depression Scale (short form); WCST = Wisconsin Card Sorting Test; WAIS-III = Wechsler Adult Intelligence Scale—Third Edition; L-N = Letter-Number.

ipants to “Press a number to indicate the location of the letter” with digits appearing on the screen as placeholders for the prior presentation of the target and distractors: 1 (top left), 2 (bottom left), 3 (top right), and 4 (bottom right). Participants made their response using the number row on the keyboard. On the 12th trial (i.e., the surprise trial), participants saw the following prompt in place of the foregoing probe question: “This is a surprise test! Press a corresponding number to indicate the IDENTITY of the letter.” Below the prompt they saw a vertical list of numbers (i.e., 5, 6, 7, and 8) corresponding to the potential letters that the target may have been (i.e., A, B, D, and E; see Figure 1). Following this surprise identity task, participants saw the same probe question as they did for the first 11 trials, asking them to respond with a keypress corresponding to the location of the letter. Following the surprise trial, participants then experienced four more control trials, each including the target identity question followed by the location probe question.

Results

**Presurprise performance.** To account for practice effects, we evaluated performance across the last 4 presurprise trials in both age groups. Overall, performance was high for both age groups (young adults: 99%, older adults: 94%), indicating that both age groups were able to correctly identify the target among the distractors and correctly report target location (see Table 2 for summary of Experiment 1 findings).

**Surprise trial performance.** Analysis for each age group on the surprise trial (i.e., identity report) indicated that only 11 out of 20 (55%) young adults and only 8 out of 20 (40%) older adults were able to correctly report the identity of the letter (with chance at 25% given the four-alternative forced choice design). Though the young adult accuracy for the target identity report during the surprise trial was numerically higher than that of the older group, the difference did not reach significance; young adults: 55% vs. older adults: 40%,  $\chi^2(1, N = 40) = .902, p = .342, \phi = .15$ .

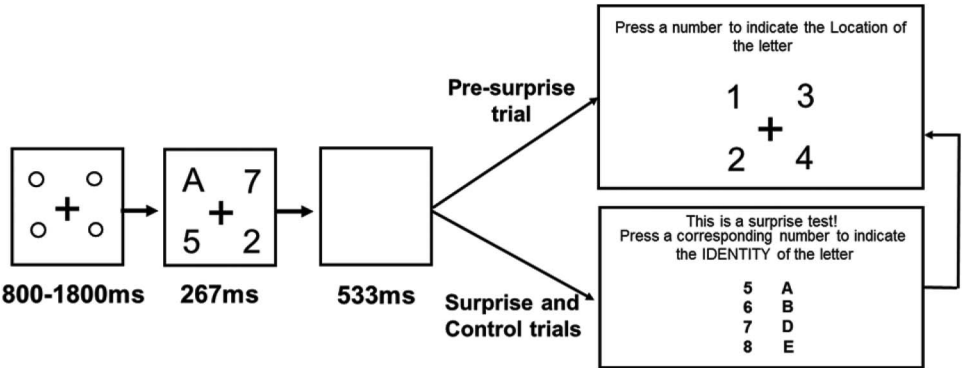


Figure 1. Sample trial sequences in Experiment 1. Stimuli not drawn to scale.

Table 2  
*The Accuracy Results of Young and Older Adults for Experiment 1 (N = 20 for Each Group)*

	Presurprise	Surprise	Control 1	Control 2	Control 3	Control 4
Identity						
Young		55%	85%	95%	100%	90%
Older		40%	80%	95%	100%	95%
Location						
Young	99%	60%	75%	90%	80%	100%
Older	94%	45%	75%	80%	90%	90%

*Note.* Percent correct for presurprise trials are for the four immediate trials prior to the surprise trial.

Similar to the identity report, the location report accuracy in the young adult group was numerically (but not significantly) higher than that of the older adults; 60% vs. 45%,  $\chi^2(1, N = 40) = .902$ ,  $p = .342$ ,  $\phi = .15$  (with chance again at 25% given the four-alternative forced choice design).

**Control trials performance.** Letter identity reporting on the first control trial (i.e., the trial immediately following the surprise trial) was significantly better than that of the surprise trial in both young and older adults; young adults: 85% vs. 55%,  $\chi^2(1, N = 40) = 4.286$ ,  $p = .038$ ,  $\phi = .33$ ; older adults: 80% vs. 40%,  $\chi^2(1, N = 40) = 6.667$ ,  $p < .01$ ,  $\phi = .41$ . No age difference was found in reporting letter identity on the first control trial,  $\chi^2(1, N = 40) = 0.173$ ,  $p = .677$ ,  $\phi = .07$ . Performance on the identity probe remained constant in both age groups for the three remaining control trials (young adults: 95%, 100%, 90%; older adults: 95%, 100%, 95%).

With respect to reporting location information on the first control trial, both young and older adults showed numerically higher performance than that of the surprise trial, but this increase did not reach significance in either group; young adults: 60% vs. 75%,  $\chi^2(1, N = 40) = 1.03$ ,  $p = .311$ ,  $\phi = .16$ ; older adults: 45% vs. 75%,  $\chi^2(1, N = 40) = 3.75$ ,  $p = .053$ ,  $\phi = .31$ . The increase did reach significance in both age groups when comparing the surprise trial to the second control trial, young adults: 60% vs. 90%,  $\chi^2(1, N = 40) = 4.80$ ,  $p = .028$ ,  $\phi = .35$ ; older adults: 45% vs. 80%,  $\chi^2(1, N = 40) = 5.23$ ,  $p = .022$ ,  $\phi = .36$ . Performance on the location probe remained constant in both age groups for the three remaining control trials (young adults: 75%, 90%, 80%, 100%; older adults: 75%, 80%, 90%, 90%).

## Discussion

Consistent with previous findings in young adults (H. Chen et al., 2016; H. Chen & Wyble, 2015a, 2015b, 2016), the results revealed both young and older adults were able to successfully find the target and report its location across presurprise trials. Furthermore, with respect to the surprise trial, results showed that both groups were equally susceptible to attribute amnesia and often failed to bind the letter identity with its location during the foregoing visual working memory task. This finding did not provide evidence for the extension of hyper-binding to the deselection of material in working memory, which would have predicted that older adults should show higher accuracy on the surprise trial as hyper-binding would predict binding in the absence of expectancy due to holding excessive information in working memory and not deselecting previously attended information.

Despite the presence of attribute amnesia on the surprise trial, both age groups demonstrated an increase in performance for identity reporting during the first control trial, once expectancy about which attributes needed to be bound had shifted. Accuracy of reporting location information also increased in the first control trial, but it was not until the second control trial that it rose significantly above that of the surprise trial (and equal to performance on presurprise trials). This suggests that both age groups were able to encode and bind both key attributes of the target in working memory, and the failure to report this information on the surprise trial cannot be attributed to presentation duration, capacity deficits or binding deficits in either age group. To this end, results of Experiment 1 also failed to provide specific evidence for the associative-deficit hypothesis because older adults were not worse than younger adults on any of the measures. Rather, the results suggest that this failure of associative binding is related to expectancy of reporting information encountered in the attribute amnesia task.

## Experiment 2

Previous research has suggested that the identity location binding in Experiment 1 may be encoded automatically (H. Chen & Wyble, 2015b). Therefore, the emergence of an associative binding deficit or evidence of hyper-binding in older adults may not have arisen due to the relative ease and automaticity of the task. Therefore, we were motivated to administer an adapted attribute amnesia task that required information to be manipulated in working memory prior to generating a response (H. Chen, Carlson, & Wyble, in press). Specifically, participants were presented with color words (e.g., the word "BLUE") printed in an ink color that either matched or mismatched the word's identity. During the presurprise trials, participants made congruency judgments between the word and its presented ink color. On the surprise trial, the probe question asked the identity of the presented ink color, followed by the congruency judgment probe. Thus, on the presurprise trials, in addition to identifying and binding the word and the ink color, participants were required to generate a congruency judgment based on target attributes. This requires a subsequent step of processing relative to the potentially automatic encoding of location in Experiment 1. It is important to note that the task in Experiment 2 requires participants to explicitly identify and compare 2 target attributes, yet it did not require them to remember the bound representation to successfully answer the presurprise congruency question. As such, the current task allowed us to evaluate binding of the ink color and word under conditions where individuals were more

actively engaging executive function via the comparison task. Additionally, we introduced a visual mask to make the task more difficult, because the mask reduced the duration of the visual representation of the colored word. The mask thus places greater demands on the ability to rapidly form bindings. Additionally, Experiment 2 provided another means for testing whether hyper-binding extends to the binding of deselected information in working memory. Such an extension of hyper-binding would predict superior performance for the older adults on the surprise trial.

## Method

**Participants.** The current study collected data from 40 young adults and 40 older adults.<sup>2</sup> The young adults were recruited from the Psychology Department subject pool (average age: 18.80 years,  $SD = 1.34$ ; range = 18–25) and the older adults were recruited from the State College community (average age: 73.03 years,  $SD = 5.12$ ; range = 63–83). Young adults were compensated with course credits, and older adults paid for their participation. Just as in Experiment 1, the older adults in the current study completed the previously described battery of cognitive assessments (see Table 1 for additional details). All of the older adults performed within normal ranges for their age, thus verifying that they were cognitively healthy. Both young and older adults reported normal or corrected-to-normal visual acuity. All experimental procedures were approved by The Pennsylvania State University's Institutional Review Board for the ethical treatment of human participants.

**Apparatus.** This was identical to Experiment 1.

**Stimuli.** The fixation display included a black fixation cross ( $0.58^\circ \times 0.58^\circ$ ) presented in the center of the screen. The stimuli consisted of four different words (*RED*, *BLUE*, *YELLOW*, and *PURPLE*; visual angle of words were  $0.87^\circ \times 1.89^\circ$ ,  $0.87^\circ \times 2.33^\circ$ ,  $0.87^\circ \times 3.93^\circ$ ,  $0.87^\circ \times 3.64^\circ$ , respectively) that were displayed individually in the center of the computer monitor. Words were shown in one of four ink colors (RGB values: red = 200/0/0; blue = 0/0/200; yellow = 200/200/0; purple = 190/45/200). Words were presented either as congruent, meaning that the word identity matched its presented color ink (e.g., the word *RED* was presented in red ink color), or as incongruent, meaning that the words identity did not match its presented color ink (e.g., the word *RED* was presented in blue color ink). Each word was presented in uppercase Arial font, size 30, on a gray background (RGB: 150/150/150). The mask consisted of four colored horizontal lines and four colored titled lines, with each horizontal line and titled line being assigned one of four aforementioned colors ( $2.04^\circ \times 4.22^\circ$ ; see Figure 2).

**Procedure and design.** Just as in Experiment 1, participants were exposed to a series of presurprise, surprise, and control trials across two blocks. There were 43 presurprise trials followed by a surprise trial, followed by 4 control trials. There was also a short break after the first 40 trials. During the presurprise trials, participants were instructed that they would be presented with one of the four words and that they had to indicate if the word was congruent or incongruent with the ink color in which it was presented. Each trial first began with a fixation (ranging between 800 and 1,000 ms), after which the word appeared on the screen for 267 ms. Immediately following the duration of the word presentation, a color mask appeared on the screen for 517 ms. In presurprise trials (i.e., the first 43 trials), the congruency

probe then appeared, asking participants to discriminate the “congruency” between the word and its ink color. Half of the participants responded with a button press of the 1 number key to indicate a *congruent* response and the 2 number key to indicate an *incongruent* response (the keys were swapped in the counterbalance group). On the 44th trial (the surprise trial), participants saw the following prompt in place of the foregoing congruency prompt: “This is a surprise test! Here we test the ‘ink color’ of the word. Press a corresponding number to indicate the ink color of the word.” Below the prompt they saw a vertical list of numbers (i.e., 5, 6, 7, and 8) which indicated number keys corresponding to the potential ink colors that the just-seen word may have been presented in (i.e., blue, red, yellow, and purple; see Figure 2). Participants then made their selection by pressing the appropriate number key. Following this surprise ink color reporting, participants saw the same congruency question as they did the first 43 trials, asking them to respond with a keypress regarding the congruency of the word and its presented ink color. Following the surprise trial, participants then experienced four control trials, each including the ink color report question followed by the congruency question.

## Results

**Presurprise performance.** To account for practice effects, performance was evaluated across the last 3 presurprise trials in both age groups. Overall, performance was high for both age groups (young adults: 98%, older adults: 93% accuracy), indicating that both age groups were able to correctly identify the target among the distractors at near ceiling performance (see Table 3 for summary of Experiment 2 findings).

**Surprise trial performance.** With regard to performance on the surprise trial (i.e., ink color report), only 26 out of 40 (65%) young adults and 11 out of 40 (27.5%) older adults correctly reported the ink color. Critically, the results revealed an effect of age, such that young adult performance on the surprise trial was better than that of the older adults (65% vs. 27.5%),  $\chi^2(1, N = 80) = 11.31, p < .001, \phi = .38$ . Further, we evaluated if the individuals who did not correctly respond with the correct ink color, responded with the color word's identity instead of its ink color. Of the 14 incorrect younger adults, 7 (7/14 = 50%) chose the ink color that actually referred to the word identity on that same trial. This occurred in 10 out of the 29 incorrect older adults (10/29 = 34%).

An analysis of performance on congruency report during the surprise trial showed that 33 out of 40 (82.5%) young adults correctly identified congruency, whereas 21 out of 40 older adults (52.5%) were able to correctly do so. This difference was significant (82.5% vs. 52.5%),  $\chi^2(1, N = 80) = 8.21, p = .004, \phi = .32$ . Note that chance performance is 50% in this response.

**Control trials performance.** We next evaluated if the ink color reporting accuracy improved on the first control trial (i.e., the trial immediately following the surprise trial). The results showed that the accuracy for the ink color reporting on the first control trial

<sup>2</sup> We collect 40 subjects for each age group in this condition because we discovered, after collecting the first 20 subjects, that there was a response bias in the congruency report that had to be counterbalanced given that the surprise trial was designed to be always incongruent, as will be explained below.

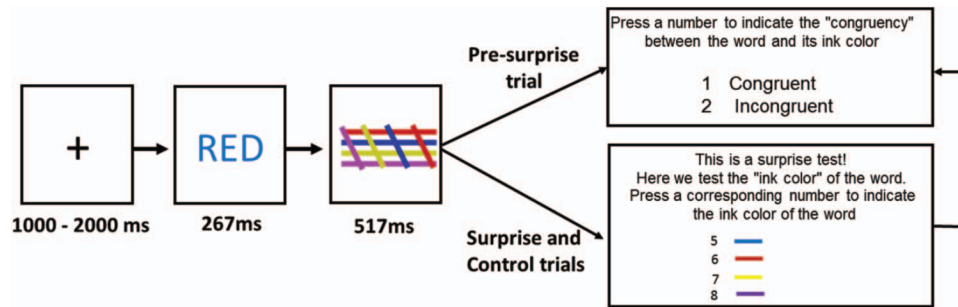


Figure 2. Sample trial sequences in Experiment 2. Stimuli not drawn to scale. Please see the online article for the color version of this figure.

was significantly better than the ink color reporting accuracy during the surprise trial for both age groups; young adults: 95% vs. 65%,  $\chi^2(1, N = 80) = 11.25, p < .001, \phi = .38$ ; older adults: 70% vs. 27.5%,  $\chi^2(1, N = 80) = 14.46, p < .001, \phi = .43$ . There was no significant difference between the first and second control trials in either age groups with respect to reporting of ink color; young adults: 95% vs. 97.5%,  $\chi^2(1, N = 80) = .35, p = .556, \phi = .07$ ; older adults: 70% vs. 82.5%,  $\chi^2(1, N = 80) = 1.73, p = .19, \phi = .15$ .

Results did reveal a significant age difference between the young and older adults on the ink report on both the first and second control trials; first control trial: 95% vs. 70%,  $\chi^2(1, N = 80) = 8.66, p = .003, \phi = .33$ ; second control trial: 97.5% vs. 82.5%,  $\chi^2(1, N = 80) = 5.00, p = .025, \phi = .25$ . Performance on the remaining control trials (i.e., control Trials 3 and 4) was also comparable (young: 97.5%, 97.5%; old: 90%, 87.5%) both within and across age groups.

We also evaluated if the congruency report accuracy improved between the first control trial and the surprise trial. Young adults showed a significant improvement; 97.5% vs. 82.5%,  $\chi^2(1, N = 80) = 5.00, p = .025, \phi = .25$ . The improvement was not significant in older adults (60% vs. 52.5%),  $\chi^2(1, N = 80) = .46, p = .50, \phi = .08$ . Improvement in older adult's performance on the congruent task became significant when comparing the second control trial to the surprise trial (85% vs. 52.5%),  $\chi^2(1, N = 80) = 9.83, p = .002, \phi = .35$ . This improvement on the second control trial was also significantly better than performance on the first control trial (85% vs. 60%),  $\chi^2(1, N = 80) = 6.27, p = .012, \phi = .28$ .

Similar to age differences on the ink reporting in control trials reported above, age differences emerged between young and older

adults for the congruency reporting task on the first, second, and third control trials; first control trial: 97.5% vs. 60%,  $\chi^2(1, N = 80) = 16.81, p < .001, \phi = .46$ ; second control trial: 100% vs. 85%,  $\chi^2(1, N = 80) = 6.49, p = .011, \phi = .28$ ; third control trial: 100% vs. 90%,  $\chi^2(1, N = 80) = 4.21, p = .04, \phi = .23$ . By the fourth control trial, age differences did not emerge; young: 100% vs. old: 95%,  $\chi^2(1, N = 80) = 2.05, p = .152, \phi = .16$ .

## Discussion

Experiment 2 found that both young and older adults were able to extract multiple target attributes during a working memory task and compare said attributes to correctly make congruency judgments. Yet, like Experiment 1, both age groups were susceptible to attribute amnesia when prompted to report one of those two attributes. Specifically results suggest that both groups do not automatically bind word identity and ink color in working memory, even when both attributes needed to be explicitly identified to perform task goals (i.e., congruency judgment). Unlike Experiment 1, Experiment 2 revealed an age deficit with respect to reporting ink color and congruency information on the surprise trial. This evidence argues against an extension of hyper-binding in working memory, as older adults failed to engage in associative binding even when the target attributes were explicitly identified during the trial to make a correct congruency judgment on the presurprise trials.

Furthermore, both young and older adults demonstrated enhanced performance on the first control trial, suggesting that performance could be improved when expectancy shifted. Though, we note that an age deficit for reporting ink color was found in both the first and second control trials, whereas control Trials 3

Table 3  
The Accuracy Results of Young and Older Adults for Experiment 2 ( $N = 40$  for Each Group)

	Presurprise	Surprise	Control 1	Control 2	Control 3	Control 4
Ink color						
Young		65.0%	95.0%	97.5%	97.5%	97.5%
Older		27.5%	70.0%	82.5%	90.0%	87.5%
Congruency						
Young	98.0%	82.5%	97.5%	100.0%	100.0%	100.0%
Older	93.0%	52.5%	60.0%	85.0%	90.0%	95.0%

Note. Percent correct for presurprise trials are for the three immediate trials prior to the surprise trial.

and 4 revealed no age deficit. Therefore, it is possible, despite the improved performance in control Trial 1, that older adults required a longer period of time to shift expectancy and take advantage of this shift for associative binding. Taken together, these findings suggest that older adults demonstrated a deficit of *spontaneous* associative binding of attributes in working memory. But when there was a clear expectancy to report source information, the age-deficit in binding could be ameliorated.

Experiment 2 revealed two additional interesting findings. First, it shed light on *what* information is stored, as well as the *quality* of that stored information. Specifically, during the surprise trial, although young adult performance dropped significantly with respect to performance on presurprise trials, that of the older adults fell to chance (on both ink color and the congruency report). As such, results suggest that older adults were merely guessing on the congruency judgment during the surprise trial, despite their near ceiling performance on answering this question during presurprise trials. This suggests, not only do older adults not maintain individual attributes of the target in the absence of expectancy, but that any representation of the to-be reported information (e.g., congruency) is more fragile than those of young adults, such that their evaluation of the surprise memory question regarding ink color eliminated the information required for the congruency judgment from working memory stores. Second, Experiment 2 shed light on the time it takes for older adults to adapt (or learn) the new task. Specifically, results suggest that older adults take longer than young adults to adapt in successfully binding a different set of attributes in working memory when executive functioning resources are otherwise engaged. Although this delay results in an initial age-related deficit in associative binding during working memory, equivalent age performance by the fourth control trial suggests that this deficit can be overcome given adequate time to adjust to task expectations and reallocate limited resources.

### General Discussion

The current study conducted two experiments using the attribute amnesia task (H. Chen & Wyble, 2015a) to provide a novel test of age-related binding deficits in working memory. In doing so, the current studies sought to provide additional evidence to clarify previous discrepant findings regarding age-related associative deficits in working memory. Additionally, use of the attribute amnesia task provided a means for testing whether hyper-binding extended to include the spontaneous binding of recently de-selected information in working memory with task-relevant information. In the attribute amnesia task, the surprise trial should provide an ideal marker of testing whether hyper-binding extends to the binding of initially task-relevant, but now irrelevant information with to-be-reported information. Specifically, if older adults were binding and maintaining extraneous information (i.e., the no longer relevant attribute) in working memory, they should have successfully been able to report probed information on the surprise trial (Experiment 1: letter identity and Experiment 2: ink color). Critically, across both working memory tasks, we found no evidence of hyper-binding, yet conditional support for the associative deficit theory. Specifically, results showed that, like younger adults, older adults demonstrated attribute amnesia in both Experiment 1 and 2 as well as an age deficit in Experiment 2 on both the surprise trial and the early control trials.

One of the critical components of experiments which show attribute amnesia is that, prior to the surprise trial, participants use target attributes such as identity and color in demonstrating near ceiling levels of reporting of the location of the target item (H. Chen & Wyble, 2015a, 2016). Yet, having just processed these attributes, they fail to report them on the surprise trial. Despite this failure, attribute memory rebounds in the postsurprise controls trials. Replicated many times (H. Chen et al., 2016; H. Chen & Wyble, 2015b, 2016; Swan, Wyble, & Chen, 2017), results strongly suggest that expectation to report a piece of information plays a key role in how well it is remembered. Despite the fact that the attribute amnesia effect is qualitatively similar for both age groups in the present experiments, there are several novel findings with respect to aging that advance our understanding of associative working memory.

First, it is important to note that like younger adults, older adults demonstrated attribute amnesia in both Experiments 1 and 2, showing an age deficit in Experiment 2 on both the surprise trial and the immediate control trials. What makes this pattern notable, is that, similar to the past studies in young adults (e.g., H. Chen & Wyble, 2015a, 2016), the current study's older adults showed near ceiling performance on reporting the correct target attribute just prior to the surprise task. Although poor performance on the surprise trial suggests that older adults do not spontaneously bind target attributes, it is not reflective of an inability to bind, as performance increases in control trials. Thus, the results suggest that performance in both groups was driven by expectancy. Further, results across both experiments argue against an account of hyper-binding of recently de-selected information in aging, which would predict better performance on the surprise question. Rather, the age deficit in performance on the first surprise question in Experiment 2 (as well as the subsequent control trials), provides conditional support for the associative-deficit (Naveh-Benjamin, 2000) as older adults do not show the same level of knowledge regarding target attributes as do young (for more on this point, see below). We use the term *conditional*, as older adults are able to perform as well as young adults by the fourth control trial.

Unlike young who, in Experiment 2, showed immediate recovery of bound representations on the first control trial, older adults did not show improved performance until the third control trial. The fact that older adults took longer to recover performance across the control trials in Experiment 2 suggests that under certain conditions, such as under high working memory loads, associative binding in aging is not driven by expectancy alone, but is further mediated by the availability and efficiency of attention and/or executive function resources within the constraints of the task. That is, although performance improved across the early control trials in Experiment 2 (even when there was an expectation to maintain bound representations), older adults required additional time, compared with young adults, to reach presurprise performance levels. As such, results suggest that older participants needed additional experience with the task to learn how to perform the task and to eventually exhibit similar levels of binding as younger adults.

A final, key difference between the older and younger adults' performance is that, on the surprise trial in Experiment 2, older adults were actually unable to report either the ink color or the congruency judgment, as performance to both probe questions were at near chance levels. This finding is in contrast to that

observed in Experiment 1 (low working memory load) where both age groups performed above chance on the surprise trial, indicating that they maintained some knowledge of target attributes. This finding extends previous research that has shown that certain bound representations (such as color and shape) are relatively fragile and susceptible to disintegration from incoming information in working memory (e.g., Allen, Baddeley, & Hitch, 2006). Extending this, the current findings suggest that, under a higher executive load, older adults maintain increasingly fragile representations in working memory that are more vulnerable to disruption by concurrent processing demands. Furthermore, the near chance performance in older adults does not support the extension of hyper-binding to de-selected information in the current task. That is, within an extended view of hyper-binding, task-relevant information and previously relevant attributes should be implicitly encoded as a bound representation that are available for report. According to the hyper-binding theory, then older adults could have responded to the alternative force choice probe question on the basis of familiarity, and thus performance should have been above chance, if not better than that of younger adults. This was not the case, as the results showed that although younger adults have the ability to utilize familiarity of target attributes (i.e., not near chance levels), even when they fail to spontaneously bind them in working memory, older adults are only able to do so when task demands are low (Experiment 1).

Additionally, we consider how the current findings compare with the previous discrepant findings regarding age-related binding deficits in working memory. Consistent with other studies that also used basic shapes and colors (e.g., Brockmole et al., 2008; Parra et al., 2009; Read et al., 2016), the current finding in Experiment 2 found no age deficit with respect to intra-item binding in working memory (given that the deficit initially observed in Experiment 2 is eliminated once expectancy is accounted for). Additionally, we note that older adults remained capable of binding location, as demonstrated in Experiment 1. This provides additional support to more recent findings that have suggested location remains within older adult's ability to bind in working memory (Read et al., 2016; Rhodes et al., 2017), which runs contrary to earlier findings that have demonstrated a deficit for location binding (Cowan et al., 2006; Mitchell, Johnson, Raye, & D'Esposito, 2000). Finally, the current results are also consistent with previous work suggesting that there are no age deficits in binding when the retention interval is short (e.g., 900 ms in Experiment 1, Parra et al., 2009; 906 ms in Experiments 1 and 2, Brockmole et al., 2008). The current retention interval of 533 ms and 517 ms for Experiments 1 and 2, respectively also fell far under that used in previous studies that did find deficits (e.g., 8 seconds in Mitchell, Johnson, Raye, & D'Esposito, 2000; Mitchell, Johnson, Raye, Mather, et al., 2000).

### Limitations and Future Directions

Although the current study found no evidence for the extension of hyper-binding in working memory to previously relevant information and suggested that associative binding in aging may be limited in the absence of expectancy, there are several factors to be investigated in future studies to continue to advance our understanding of associative binding.

It is possible that the older adult deficits on the surprise trials and their slower recovery to ceiling performance across the control trials (in Experiment 2) reflected less flexibility in switching between changing task demands, as suggested by work done regarding task-switching (e.g., Kray & Lindenberger, 2000; Wasylshyn, Verhaeghen, & Sliwinski, 2011). We evaluated this possibility by evaluating the relationship between performance on the Wisconsin Card Sorting Test (WCST; Grant & Berg, 1948; as measured by the total number of correct trials and number of categories completed) and performance on the surprise trials. Collapsing across experiments, we found no evidence for a relationship between performance on the WCST and accuracy on the surprise trial in either age group (all  $ps > .1$ ). Thus, although a possible explanation, this evidence does not support the hypothesis that a task-switching deficit in the older adults was masking a hyper-binding effect.

Increased susceptibility to proactive interference on the part of older adults may have also contributed to their worse performance on the surprise trial, effectively masking an advantage induced by hyper-binding. However, we think this is an unlikely interpretation because the control trials clearly show that once participants explicitly attempt to bind the additional attributes into memory, they can do so with very high accuracy. Thus, successful binding supports accurate report, regardless of accrued proactive interference.

An additional limitation, albeit intentional in our novel approach, is that we made no direct comparison between associative memory and item memory for both age groups. Therefore, caution should be taken when trying to compare the current findings to previous findings that have compared the two types of memory. Future modifications to this paradigm can adopt a direct comparison of item and associative memory to further generalize this novel method to paradigms traditionally used to investigate associative binding deficits in short-term and long-term memory. Additionally, using more complex and realistic stimuli would further extend the current findings to real-life situations.

Finally, with respect to hyper-binding, we acknowledge that much of the current paradigm contrasts with previous approaches used to investigate hyper-binding. Therefore, caution should be exercised in making any direct comparisons between the current and past approaches. In past studies, hyper-binding has been tested by pairing irrelevant information with attended information; then, following a delay period, having participants explicitly study old and new stimuli pairs; and finally, testing memory for both types of bound representations (e.g., Campbell et al., 2010). This approach stands in contrast to the current studies' design wherein the information that was probed was relevant at one point but became eligible for deselection in light of new task demands and memory was tested immediately. Additional work will be required to understand the breadth of conditions under which hyper-binding operates (e.g., under explicit learning conditions), thus allowing for a better understanding of its generalizability in the cognitive aging literature.

### Conclusion

The current results demonstrate that older, like younger adults, do not spontaneously bind information in working memory when there is no expectation to utilize the bound representation. Specifically, we predicted that if hyper-binding extended to such conditions, older adults would encounter difficulty deselecting the irrelevant attributes, but rather bind the now irrelevant attribute to the

to-be-reported attribute. Such a process would have revealed itself on a surprise trial and would be in line with past work demonstrating older adults have difficulty in de-activating completed intentions or no longer task-related processes (e.g., Grady, Springer, Hongwanishkul, McIntosh, & Winocur, 2006; Hasher & Zacks, 1988; Lustig et al., 2007; Scullin et al., 2011). However, given that both age groups were susceptible to attribute amnesia in Experiment 1 and in Experiment 2, we did not find evidence for this. Rather, results suggest that associative binding in working memory is a controlled, directed process that is only engaged in when multiple target attributes are expected to be of subsequent use. As such, this finding suggests one limitation regarding the generalizability of hyper-binding.

Furthermore, results of Experiment 2 suggest that, when working memory resources are taxed, the bound representations of older adults are more fragile than those of younger adults, resulting in loss of the associative attributes when faced with interference associated with the introduction of the surprise memory prompt. Additionally, older adults' slow recovery on the control trials in Experiment 2 suggests that they require additional experience with the task to learn how to create successful bindings within the short temporal availability of the target presentation. Taken together, within the constraints of the current paradigm, the results offer conditional support for the associative-deficit hypothesis (Naveh-Benjamin, 2000) in working memory.

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