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The Role of Aging in Intra-Item and Item-Context Binding Processes in Visual Working Memory

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Aging is accompanied by declines in both working memory and long-term episodic memory processes. Specifically, important age-related memory deficits are characterized by performance impairments exhibited by older relative to younger adults when binding distinct components into a single integrated representation, despite relatively intact memory for the individual components. While robust patterns of age-related binding deficits are prevalent in studies of long-term episodic memory, observations of such deficits in visual working memory (VWM) may depend on the specific type of binding process being examined. For instance, a number of studies indicate that processes involved in *item-context* binding of items to occupied spatial locations within visual working memory are impaired in older relative to younger adults. Other findings suggest that *intra-item* binding of visual surface features (e.g., color, shape), compared to memory for single features, within visual working memory, remains relatively intact. Here, we examined each of these binding processes in younger and older adults under both optimal conditions (i.e., no concurrent load) and concurrent load (e.g., articulatory suppression, backward counting). Experiment 1 revealed an age-related *intra-item* binding deficit for surface features under no concurrent load but not when articulatory suppression was required. In contrast, in Experiments 2 and 3, we observed an age-related *item-context* binding deficit regardless of the level of concurrent load. These findings reveal that the influence of concurrent load on distinct binding processes within VWM, potentially those supported by rehearsal, is an important factor mediating the presence or absence of age-related binding deficits within VWM.

Keywords: aging, visual working memory, binding processes, attentional resources

Age-related declines in episodic memory processes are prevalent and well documented. At long-term memory (LTM) retention intervals, older compared to younger adults have difficulty binding distinct components together to form associations (e.g., item-color, item-location, face-scene, face-name, word-word, and picture-picture pairings), while memory for these individual components (e.g., colors, faces, scenes, names, words, and pictures) remains largely intact (Bastin & van der Linden, 2005; Castel & Craik, 2003; Chalfonte & Johnson, 1996; Naveh-Benjamin, 2000; Naveh-Benjamin, Guez, Kilb, & Reedy, 2004; Naveh-Benjamin, Hussain, Guez, & Bar-On, 2003). An associative deficit hypothesis (ADH) has been proposed as a theoretical framework to explain these findings. The ADH suggests that age-related deficits within episodic memory are driven by older adults' difficulty, relative to younger adults, in forming and retrieving associations between distinct components, while memory for the individual components remains largely intact (Naveh-Benjamin, 2000). A number of experiments examining the role of aging on episodic memory processes have provided evidence in favor of the ADH as a prominent theoretical perspective (for a meta-analytic review see Old & Naveh-Benjamin, 2008). With respect to visual short-term or working memory processes, however, observations of age-related deficits are inconsistent and the factors mediating these binding deficits have yet to be established.

Visual working memory (VWM) refers to our ability to temporarily maintain a limited amount of visual information despite brief interruptions (e.g., blinks, saccades) to visual input (Baddeley, 2010; Hollingworth, 2006; Simons & Levin, 1997; Simons & Rensink, 2005). Recent studies have examined a variety of factors underlying capacity limitations associated with VWM processes in younger adults (Bays & Husain, 2008; Cowan, 2001; Vogel & Machizawa, 2004; Zhang & Luck, 2008; for a recent review see Luck & Vogel, 2013). However, despite evidence of general decline in working memory processes with aging (for reviews see Carpenter, Miyake, & Just, 1994; Craik & Jennings, 1992; Salthouse, 1994; and for meta-analyses see Bopp & Verhaeghen, 2005; Verhaeghen & Salthouse, 1997), the mechanisms underlying impairments to this essential cognitive process remain poorly understood (see Reuter-Lorenz & Sylvester, 2005; Vaughan & Hartman, 2009).

One intriguing possibility is that age-related deficits observed in VWM emerge from difficulties in binding distinct item compo-

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nents (e.g., colors, shapes, and locations) into integrated representations, despite proficient processing of the individual item components or features. However, the presence, absence, or magnitude of age-related deficits may vary depending on the type of binding process being examined within VWM. *Intra-item* binding refers to the binding of surface features from various stimulus dimensions (e.g., color and shape). In other words, the features being bound "belong" to the same item. In contrast, *item-context* binding refers to the binding of a given item to a distinct or abstract feature (e.g., item–item pairings, the spatial location occupied by the item). The terms *intra-item* binding and *item-context* binding are analogous, respectively, to the terms *conjunctive* binding and *relational* binding, distinguished previously within the literature (for a review see Allen, Brown, & Niven, 2013). Indeed, several studies examining VWM processes in both younger and older adults have found evidence for an age-related binding deficit. For instance, Mitchell, Johnson, Raye, Mather, and D'Esposito, (2000a) found that older adult's VWM performance was significantly lower than that of younger adults when objects and their locations were tested after a short retention interval. However, no age-related difference in VWM performance was found when only objects or locations were tested in isolation.

Several other studies involving separate single item and binding tests have replicated and extended findings of an age-related binding deficit in VWM using a variety of stimulus materials paired with locations (e.g., picture-location binding: Borg, Leroy, Favre, Laurent, & Thomas-Antérion, 2011; color-location binding: Cowan, Naveh-Benjamin, Kilb, & Saults, 2006; letter-location binding: Fandakova, Sander, Werkle-Bergner, & Shing, 2014). Moreover, deficits in item-location binding cannot be attributed to impairments in maintaining the spatial locations occupied by the to-be-remembered items, as previous work has shown that brief retention of spatial information is largely intact in older adults (Olson, Zhang, Mitchell, Johnson, Bloise, & Higgins, 2004). Furthermore, when an association with no spatial component must be formed between two distinct items (e.g., face-scene pairs) and maintained across short retention intervals, age-related VWM binding deficits, similar in magnitude to those observed across long-term memory retention intervals, are evident (Chen & Naveh-Benjamin, 2012).

Despite these recent findings of an age-related VWM deficit when item-context forms of item-location or item-item binding are required, little evidence has been shown in favor of impairments when conjunction stimuli containing *intra-item* features (e.g., shape-color conjunctions) must be bound and processed within VWM. For instance, in a suite of previous experiments, while overall lower levels of VWM performance were observed for older relative to younger adults, for older adults, performance in the binding (e.g., shape and color) test condition was equivalent to performance in the shape only test condition (Brockmole, Parra, Della Sala, & Logie, 2008). This general pattern of results indicating no age-related *intra-item* binding deficit has been replicated in several other recent experiments using similar stimulus materials (i.e., *intra-item*, surface features), task parameters, and both single feature and feature binding tests (e.g., shape-color stimuli: Brockmole & Logie, 2013; Experiment 1, Brown & Brockmole, 2010; color-color stimuli: Parra, Abrahams, Logie, & Sala, 2009). A notable exception from the literature, in which an age-related *intra-item* binding deficit was observed, occurred in an experiment that examined shape-color binding (Experiment 2, Brown & Brockmole, 2010; but see Allen, Hitch, Mate, & Baddeley, 2012). More important, these recent findings suggest that *item-context* binding mechanisms may underlie age-related declines in VWM capacity, while *intra-item* binding processes appear to remain intact.

One potential impediment to progress in identifying the impact of aging on VWM binding processes relates to methodological differences across studies. Among these differences, the implementation of "baseline" task conditions is especially relevant. Previous experiments have revealed reductions in intra-item binding (e.g., color and shape) relative to single-feature performance (e.g., color or shape) for younger adults when a multiple object-tracking task was required during maintenance compared with when no tracking task was imposed (Fougnie & Marois, 2009). While it is often the case that interference is greater when primary working memory tasks and secondary concurrent load tasks require processing within the same modality (for a review see Logie, 1995), it is possible that subvocal rehearsal plays a role in the ability to maintain the visual features of color, shape, or shape-color bindings. Indeed, recent findings indicate important asymmetries between the influences of verbal versus visual load during visual and verbal working memory processes, respectively. Namely, while the maintenance of visual information within working memory is disrupted with increases in concurrent verbal load, visual load has been shown to have little effect on the maintenance of verbal information (Morey, Morey, van der Reijden, & Holweg, 2013). While previous findings indicate selective disruption of VWM binding processes in younger adults (e.g., Fougnie & Marois, 2009), it is possible that concurrent load may impact binding performance for older adults as well.

With respect to the aging literature, several studies that examined binding processes in VWM did not require participants to perform any articulatory suppression or attention-demanding tasks concurrent with VWM single-feature and binding tasks (Borg et al., 2011; Chen & Naveh-Benjamin, 2012; Cowan et al., 2006; Fandakova et al., 2014; Parra et al., 2009). As such, performance in these tasks may reflect binding processes under optimal conditions. However, other studies, in an effort to either control influences from verbal working memory or to directly examine the influence of increasing load on VWM binding processes, did require an articulatory suppression and/or a backward counting concurrent task during single-feature and feature binding VWM tasks (Brockmole et al., 2008; Brown & Brockmole, 2010).

In a recent study examining shape-color (i.e., *intra-item*) binding processes, an overall effect of concurrent load (e.g., articulatory suppression during encoding and maintenance) was evident, impacting both younger and older adults' performance for binding of colors adjacent to corresponding shapes to a greater extent than when the colors where intrinsic to the shapes (van Geldorp, Parra, & Kessels, 2015). More important, this study found no evidence of an age-related deficit when binding of shape and color was required. Moreover, while this study compared each subtype of shape-color binding under both no load and under articulatory suppression, VWM performance for single-features comprising these bindings was not measured. As such, it remains unclear whether observations of age-related deficits may be mediated by the presence or absence of concurrent tasks that place additional constraints on binding, relative to single-feature, processes within

VWM. In our view, direct comparison of memory performance for single-features and feature bindings under both baseline and concurrent load conditions may comprise an important mediating factor related to observations of age-related binding deficits in VWM.

In the current study, we provide a novel examination of the role of aging in both intra-item and item-context binding processes and compared performance between younger and older adults under both optimal baseline conditions and when secondary concurrent tasks were required. To our knowledge, this is the first effort to examine the role of aging in these two distinct binding processes while varying concurrent load within the same study. In three experiments, we presented multifeature stimulus arrays during VWM change detection tasks that tested younger and older adults' ability to maintain either feature bindings or the individual features comprising those bindings over brief retention intervals.

In Experiment 1 we examined the impact of aging on shape-color *intra-item* binding processes in VWM under both baseline conditions and under conditions of articulatory suppression. In Experiment 2 we examined *item-context* binding processes by testing younger and older adults' VWM for objects and locations in isolation in addition to their memory for object-location bindings. In addition to testing VWM under baseline and articulatory suppression conditions, Experiment 2 included a backward counting task condition to examine the influence of increasing load on age-related VWM binding processes. Experiment 3 examined *item-context* binding while controlling for several methodological differences present between Experiment 1 and Experiment 2. These experimental parameters allowed us to examine and directly compare age-related differences in performance for *intra-item* and *item-context* VWM binding processes under various levels of concurrent load, clarifying previous mixed evidence regarding the role of aging in VWM binding processes. Theoretically, we may expect overall age-related binding deficits in item-context but not in intra-item binding, as these bindings have been suggested to be mediated by distinct neural correlates. For instance, item-context binding activates medial temporal lobe regions (Bergmann, Rijpkema, Fernandez, & Kessels, 2012; Mitchell, Johnson, Raye, & D'Esposito, 2000b) while activation in parietal and occipital regions occurs during VWM tasks involving intra-item binding processes (Parra, Della Sala, Logie, & Morcom, 2014; Shafritz, Gore, & Marois, 2002: see General Discussion section for further information). In addition, in the intra-item binding tasks younger adults may resort to the use of strategies (e.g., rehearsal) in the no load condition, providing them with a binding advantage over the older adults, which may disappear under concurrent load conditions that prevent them from using such strategies. Alternatively, older adults' intra-item binding deficits may also increase under such load conditions.

Experiment 1: The Role of Aging in Intra-Item Binding Processes in VWM

In Experiment 1 we examined *intra-item* binding processes within VWM by examining younger and older adult performance for either single features or intra-item (i.e., surface) feature bindings for shape-color conjunction stimuli. We implemented a VWM change detection task, which was performed under either no concurrent load or while performing an articulatory suppression task. If *intra-item* binding processes within VWM are differentially affected by normal aging, we predicted an overall age-related VWM binding deficit wherein the decline in performance from single features to feature binding tests should be larger for older relative to younger adults. However, if this type of VWM binding is unaffected by normal aging, as suggested in the recent literature, there should be little difference between age groups in any decrease in performance from VWM tests of single features (e.g., shape or color) compared to those that require feature binding (e.g., shape and color). Additionally, we predicted that overall accuracy, regardless of age, would be highest during the no load blocks compared to the concurrent articulatory suppression blocks of the experiment under which VWM processes would be taxed to a greater extent than under no load. We expected younger adult VWM performance for shape-color bindings to decline relative to single-feature performance under concurrent load, given previous findings (e.g., Fougnie & Marois, 2009). Finally, if the aging process makes VWM change detection tasks especially difficult under articulatory suppression compared to no concurrent load, we predicted additional decreases in performance, especially in the feature binding test condition, for older compared to younger adults when a concurrent suppression task was required.

Method

Participants. The participants included 36 undergraduate students (age range: 18–22) from the University of Missouri who participated in exchange for course-related credit and 36 older adults (age range: 65–85) from central Missouri who were compensated $15 for their time (see Table 1 for demographic information). All participants were healthy physically and mentally, had no known memory deficits, normal color vision, and normal or corrected-to-normal visual acuity. The proportion of males and females was similar in each age group, however, the older adults had significantly more formal education than younger adults, $t(70) = 5.64$, $p < .001$.

Stimuli and materials. The stimuli were colored (RGB values in parentheses) shapes, noncanonically shaped color "blobs," and white (255, 255, 255) shapes outlined in black (0, 0, 0); see Figure 1. The eight colors and color blob stimuli included black (0, 0, 0); red (254, 0, 0); green (0, 255, 1); blue (0, 0, 254); yellow (255, 255, 1); purple (201, 0, 200); cyan (1, 255, 255); and brown (99, 50, 22). The eight shapes used included an arch, a circle, a

Table 1
Demographic Information for Experiments 1, 2, and 3

Experiment	*N*	Proportion (female)	Age (years)	Education (years)
Experiment 1				
Younger	36	.47	18.7 (.92)	12.5 (.84)
Older	36	.50	73.0 (6.32)	14.4 (1.82)
Experiment 2				
Younger	45	.51	20.0 (1.68)	13.6 (1.50)
Older	48	.56	72.3 (5.10)	14.5 (1.79)
Experiment 3				
Younger	21	.75	18.5 (.93)	12.3 (.91)
Older	20	.85	72.4 (6.12)	15.2 (2.01)

Note. The values for age and education depict means (*SD*s).

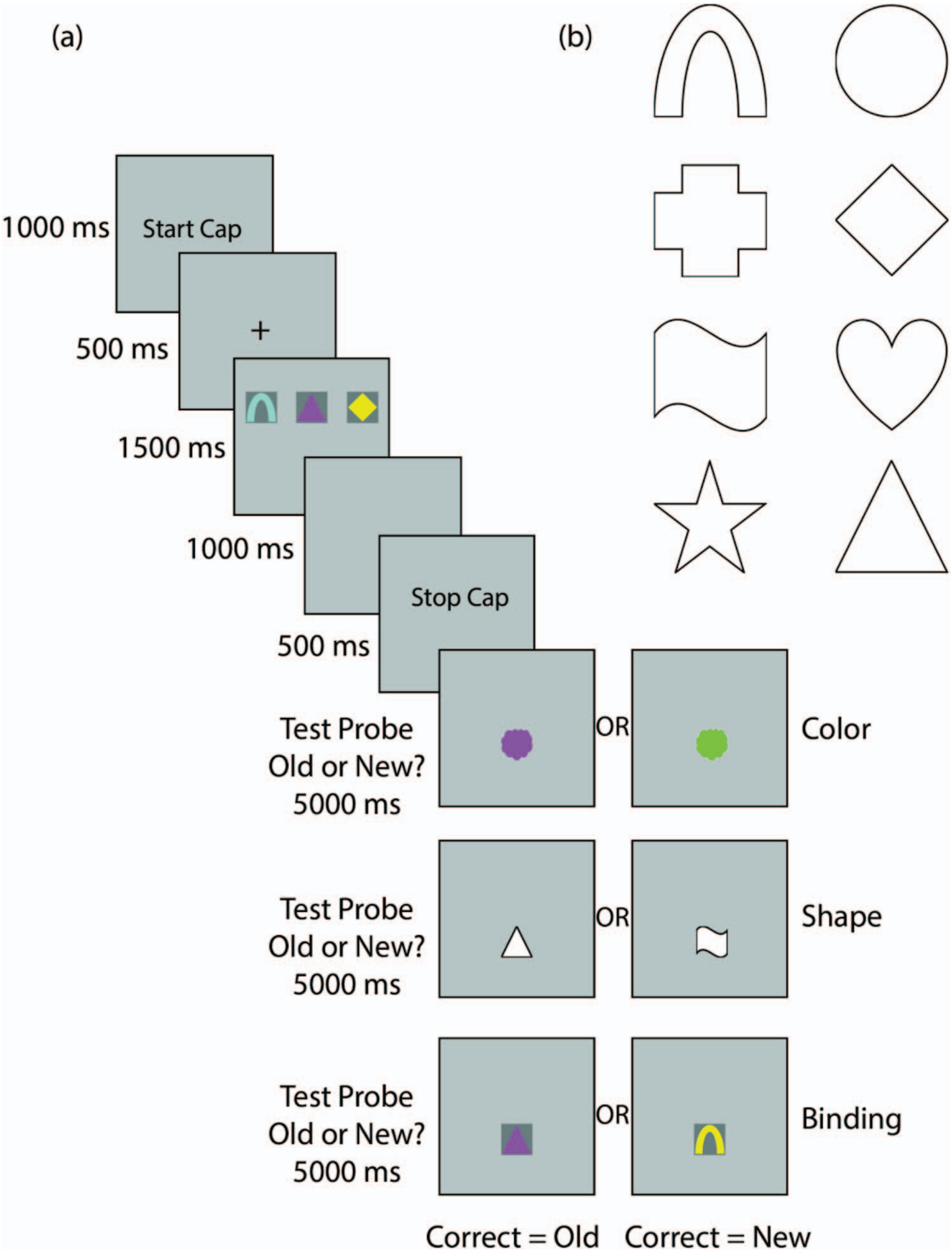

Figure 1. Task paradigm for Experiment 1 and shape stimuli used in the current study. *Note:* (a) Experiment 1 task paradigm, trial sequence, sample array, and test probe configurations. Participants viewed a secondary task prompt (1,000 ms) and then viewed a fixation cross (500 ms). After fixation, the sample array, including three shape-color conjunctions appeared (1,500 ms). After a delay-period (1,000 ms), a single probed item appeared that was either the same color, shape, or shape-color conjunction ("old" trials) that was originally presented or was a different color, shape, or binding between one shape and one color previously presented during the sample array ("new" trials). Participants were given 5 s to respond. (b) The eight shape stimuli used in Experiment 1 and Experiment 2 are depicted. Note that, in both panels of the figure, stimuli are depicted for illustrative purposes only and do not reflect the exact dimensions of the stimuli displayed during the actual experiment. See the online article for the color version of this figure.

cross, a diamond, a flag, a heart, a star and a triangle. For intrinsic stimuli, each shape was filled in with one of the eight possible colors and was presented in front of a gray (128, 128, 128) square. For extrinsic stimuli, each shape was filled with the same gray color and the background square was filled with one of the eight possible colors. Each stimulus was presented within a background square, which subtended 3.5° × 3.5° of visual angle. For the color blob only and shape only test probe stimuli, the color of the background square matched the larger silver-gray (192, 192, 192) background color of the entire screen. The experimental parameters were controlled electronically using E-Prime 2.0 software (Psychology Software Tools, Pittsburg, PA). E-Prime 2.0 was run via a Dell Optiplex 755 desktop computer and the stimuli were presented on a 20-inch ASUS flat-screen LED monitor with a resolution of 1,920 × 1,080 (refresh rate: 60 Hz).

Procedure. Participants, seated at a viewing distance of approximately 57 cm, were required to complete a visual working memory change detection task either under no concurrent load or while under articulatory suppression. During each trial, participants first saw a prompt indicating the concurrent task to be completed throughout the trial. During each trial in half of the experimental blocks (no load), a "Get Ready" prompt was presented (1,000 ms) at the center of the screen in black, bolded, and Courier New 18-point font. During each trial in the other half of the blocks, participants viewed a "Start Word" prompt (e.g., "Start Cap," "Start Toy") before the onset of the presentation of the fixation cross and stimulus display. Participants were instructed to start repeating the single syllable word (with a new word selected for each block) aloud that was presented at the center of the screen until they were presented with a "Stop Word" prompt immediately after the delay period indicating that they should stop repeating the word; see Figure 1a.

Following the concurrent task prompt a fixation cross (0.60° × 0.60°), presented at the center of the screen (500 ms), preceded presentation of the memory array. Participants were instructed to maintain fixation and try to remember the colors, the shapes, and the binding between the colors and shapes and were told they would be tested on this information after a brief delay. During the presentation of the memory array three shape-color conjunction items, randomly sampled without replacement from the eight colors and eight shapes, were presented (1,500 ms) simultaneously approximately 3° above the center of the fixation cross to the center of the stimulus in the middle position directly above the fixation cross. The other two stimuli were presented in positions to the left and right of the middle stimulus position. The edge-to-edge distance between each stimulus position subtended 4° of visual angle. A blank delay period (1,000 ms) immediately followed the presentation of the memory array. After the delay period, depending on the concurrent task block, either the "Get Ready" or "Stop Word" prompt was presented (500 ms).

Finally, depending on the task block: color only, shape only, or both (i.e., binding), one of three test probes was presented approximately 3° below the screen center to the center of the test probe stimulus. In the color blocks, a single noncanonically shaped color blob composed of either one of the three colors originally presented during the memory array or a completely new color sampled from the remaining color values. During the test phase of each trial in the color blocks, participants had to indicate whether or not a color change had occurred. In the shape blocks, a single white shape outlined in black was presented that either matched one of the three shapes presented previously during the memory or was a new shape sampled from the remaining available shapes. Finally, in the binding blocks, the test probe was either an intact shape-color conjunction (i.e., old) or was a recombination (i.e., new) of shape and color from two of the conjunction stimuli presented previously during the memory array. Each of the three stimulus positions presented in the memory array was probed at test with equal probability during "old" trials in each block type.

During all test phases in all blocks, participants were required to press the "o" key (labeled "old") if no change had occurred or the "n" key (labeled "new") within 5 s after the onset of the probe stimulus. If the response time elapsed, the trial was considered incorrect and the program advanced to the next trial. Throughout the experiment, participants pressed the space bar to initiate the next trial. On half of the trials in each block a change occurred and in the other half no change occurred. Participants completed a total of six blocks with 48 trials per block (288 total). In three of the six blocks participants performed no concurrent task while in the remaining three blocks, they were required to perform the concurrent articulatory suppression task described above. Concurrent task block order (i.e., first half, second half) was counterbalanced across participants within each age group. During both the first and second half of the experiment, participants performed separate blocks containing either color only, shape only, and binding change detection test trials. Before beginning the actual experiment, participants completed 18 practice trials to familiarize them with the task and each type of test. To ensure compliance with the concurrent task, during the three blocks of the experiment requiring articulatory suppression, an experimenter recorded the number of verbal repetitions of the target word (e.g., "Cap," "Toy") audibly produced by participants during trials 15–30 within the color, shape, and binding blocks.

Results

We measured response accuracy by computing separately the proportion of hits and the proportion of false alarms and then subtracted the proportion of false alarms from the proportion of hits (henceforth, proportion hits minus false alarms) in each experimental condition for each participant in each age group. Participants that exhibited chance or near chance-level performance (criterion: 2 *SD* below the group mean) were excluded (4 younger, 4 older) before group-level analyses resulting in the inclusion of 32 participants in each age group. In addition to computing response accuracy as a function of proportion hits minus false alarms, we computed signal detection theory measures of A' and d' using the proportion of hits and proportion of false alarms values for each condition for each participant; see Table 2 for group means and *SD*s. As the table indicates, the patterns of the results provided by the different accuracy measures converged. However, recent work suggests that while converging statistical estimates of main effects are often derived from each of these accuracy measures of recognition performance, observations of significant interactions can vary with the measure used (e.g., Allen et al., 2012). To better compare the current results to those from previous studies in the literature (e.g., Allen et al., 2012; Brown & Brockmole, 2010), which advocate the use of A' measures, we report statistical analyses related to the A' values (see Figure 2). We note that the same pattern of significant main effects and interactions reported below was observed during separate analyses applied to the proportion hits minus false alarms and d' values. Given that there was no main effect of stimulus type (i.e., intrinsic or extrinsic; for a description see Procedure section above), $F(1, 62) = .005$, $p = .94$, we collapsed across the two levels of this factor before conducting subsequent analyses. We then submitted the A' values

Table 2
Memory Response Accuracy and Signal Detection Sensitivity Measures (Means and SDs) for the Results of Experiment 1

	No load			Suppression		
Measures	Color	Shape	Binding	Color	Shape	Binding
Hits						
Younger	.94 (.04)	.91 (.06)	.83 (.11)	.85 (.09)	.82 (.13)	.75 (.12)
Older	.91 (.06)	.85 (.11)	.78 (.10)	.71 (.17)	.77 (.15)	.75 (.12)
False alarms						
Younger	.06 (.05)	.10 (.11)	.20 (.11)	.06 (.06)	.13 (.12)	.33 (.12)
Older	.06 (.03)	.09 (.05)	.35 (.19)	.08 (.05)	.17 (.09)	.41 (.11)
Hits-False alarms						
Younger	.88 (.07)	.81 (.14)	.63 (.19)	.79 (.11)	.69 (.17)	.42 (.20)
Older	.85 (.06)	.76 (.13)	.43 (.20)	.63 (.18)	.60 (.16)	.34 (.17)
A′						
Younger	.97 (.02)	.94 (.05)	.88 (.08)	.94 (.03)	.91 (.06)	.78 (.11)
Older	.96 (.02)	.93 (.04)	.79 (.11)	.89 (.06)	.87 (.06)	.74 (.09)
d′						
Younger	3.19 (.35)	2.90 (.65)	2.04 (.72)	2.65 (.43)	2.29 (.65)	1.27 (.68)
Older	3.06 (.37)	2.59 (.54)	1.33 (.65)	2.11 (.57)	1.94 (.58)	1.05 (.54)

to a 2 × 2 × 3 repeated-measures analysis of variance (ANOVA) including the between-subjects factor of age (younger, older adults) and the within-subjects factors of concurrent task (no load, articulatory suppression) and test (color, shape, or binding).

There was a main effect of age, $F(1, 62) = 14.15$, $p = .001$, $\eta_p^2 = .19$), confirming that younger adults ($M = .90$, $SD = .04$) performed with greater accuracy than older adults ($M = .87$, $SD = .04$). There was a significant main effect of concurrent task, $F(1, 62) = 99.39$, $p < .001$, $\eta_p^2 = .62$), indicating that performance was higher when no concurrent load ($M = .91$, $SD = .03$) was required compared with when the articulatory suppression task was required ($M = .86$, $SD = .03$). Additionally, there was a main effect of test, $F(2, 124) = 157.28$, $p < .001$, $\eta_p^2 = .72$), indicating a difference between the three test conditions. Bonferroni-corrected pairwise comparisons indicated that performance was significantly higher when color ($M = .94$, $SD = .02$) compared to shape ($M = .91$, $SD = .03$) was the tested feature ($p < .001$). In addition, performance when color was the tested feature was higher than when shape-color feature bindings ($M = .80$, $SD = .06$) were tested ($p < .001$). Finally, performance when shape was the tested feature was significantly higher than during tests of shape-color binding ($p < .001$).

The 2 × 2 × 3 ANOVA indicated a nonsignificant age by test interaction, $F(2, 124) = 3.15$, $p = .07$, but did reveal a significant three-way interaction between age, task, and test, $F(2, 124) = 6.86$, $p = .005$, $\eta_p^2 = .10$). Follow-up 2 × 3 ANOVAs including the factors of age and test were conducted to examine performance separately for the blocks of the experiment involving no concurrent load and during blocks in which participants completed the articulatory suppression task. A 2 × 3 ANOVA used to analyze the A' values from the no load blocks revealed a significant age by test interaction, $F(2, 124) = 10.14$, $p = .001$, $\eta_p^2 = .14$. Independent-

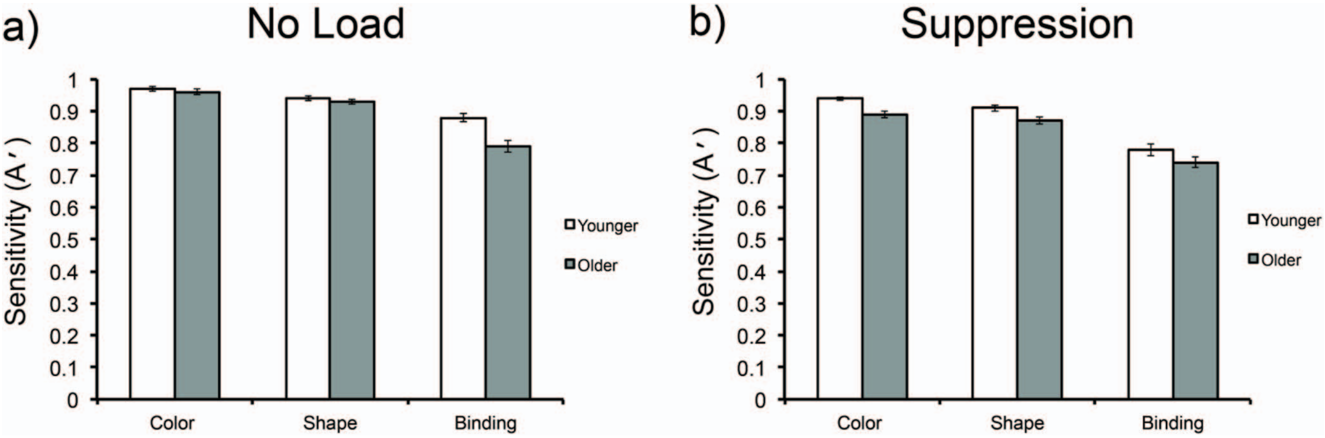

Figure 2. Experiment 1: Younger and older adult recognition performance under no load and articulatory suppression. *Note:* Behavioral results for Experiment 1 under (A) no concurrent load and (B) articulatory suppression. In both panels, the abscissa depicts the test conditions being compared while sensitivity (A') of recognition memory performance for both younger (white bars) and older (gray bars) adults is plotted along the ordinate. Error bars represent the *SEM* in each test condition. See the online article for the color version of this figure.

samples *t* tests comparing younger and older adults' performance in each test condition revealed that the age by test interaction in the no load blocks was driven by a significant difference in the binding condition, $t(62) = 3.72$, $p < .001$), wherein the younger adults ($M = .88$, $SD = .08$) performed with greater accuracy than the older adults ($M = .79$, $SD = .11$). The difference between age groups in the shape condition was not significant, $t(62) = 1.27$, $p = .21$), with younger adults ($M = .94$, $SD = .05$) performing similar to older adults ($M = .93$, $SD = .04$). Finally, there was no significant difference in the color condition between younger ($M = .97$, $SD = .02$) and older ($M = .96$, $SD = .02$) adults, $t(62) = 1.35$, $p = .18$). More important, in the follow-up analysis for the A' values corresponding to the blocks in which participants were required to perform the articulatory suppression task, however, the age by test interaction was not significant, $F(2, 124) = .32$, $p = .66$), indicating no age-related deficit when participants were under concurrent load.

To more specifically contrast memory performance on the single features (color and shape) to that on the binding of these features, we performed the same analysis after averaging across the two feature test types using a 2 × 2 × 2 repeated-measures ANOVA. This analysis revealed the same patterns of statistically significant main effects of age ($M_{younger} = .89$, $SD_{younger} = .05$; $M_{older} = .84$, $SD_{older} = .05$), $F(1, 62) = 12.94$, $p = .001$, $\eta_p^2 = .17$; test ($M_{average\_item} = .93$, $SD_{average\_item} = .02$; $M_{binding} = .80$, $SD_{binding} = .06$), $F(1, 62) = 181.00$, $p < .001$, $\eta_p^2 = .75$; and task type ($M_{no\_load} = .89$, $SD_{no\_load} = .05$; $M_{suppression} = .83$, $SD_{suppression} = .04$), $F(1, 62) = 71.34$, $p < .001$, $\eta_p^2 = .54$, when averaging across the single-feature component test conditions (e.g., color and shape). Consistent with the overall analysis including all three levels of the factor of test type, this analysis revealed a nonsignificant age by test interaction, $F(1, 62) = 3.69$, $p = .06$, but did yield a significant triple interaction between age, test, and task, $F(1, 62) = 7.97$, $p = .006$, $\eta_p^2 = .11$). Separate follow-up 2 × 2 ANOVAs for the no load and suppression task conditions including the factors of age and test revealed that the triple interaction was driven by a significant age by test interaction in the no load, $F(1, 62) = 11.48$, $p = .001$, $\eta_p^2 = .16$, but not during the suppression, $F(1, 62) = 0.03$, $p = .87$, blocks of the experiment.[1]

Finally, we used 2 × 3 repeated-measures ANOVA including the factors of age and test to analyze the number of word repetitions produced by the participants in each age group for each test block completed under articulatory suppression; see Table 3 for group means and *SD*s. The main effect of age, $F(1, 62) = 3.01$, $p = .09$, did not reach statistical significance, with younger ($M = 7.28$, $SD = 1.47$) and older ($M = 6.64$, $SD = 1.47$) adults able to produce a similar number of repetitions when articulatory suppression was required. There was no significant main effect of test, $F(2, 124) = .32$, $p = .69$). More important, there was no significant interaction between age and test, $F(2, 124) = 1.26$, $p = .29$, indicating that there was no age-related difference in the number of repetitions made during trials testing for single features compared to those testing feature binding.

Table 3
Successful Repetitions in Each Condition Verbalized During Articulatory Suppression Task in Experiment 1

Age group	Color	Shape	Binding
Younger	7.15 (1.24)	7.38 (1.30)	7.31 (1.34)
Older	6.77 (1.82)	6.65 (1.90)	6.51 (1.91)

Note. Mean number of repetitions per test block in the articulatory suppression blocks, with *SD*s in parentheses, are depicted.

Discussion

In this experiment, we observed in one condition but not in the other an age-related binding deficit for shape-color stimuli presented and tested during a VWM change detection task. Under no load, baseline VWM performance in younger and older adults was equivalent for single feature tests of color, for single feature tests of shape, and significantly different during feature binding tests of color and shape. Specifically, this age-related binding deficit was driven by significantly lower performance for the older adults compared to the younger adults. More important, while under articulatory suppression, no significant difference in performance between younger and older adults was evident during tests of feature binding of color and shape.

The results from Experiment 1 suggest that the concurrent load imposed during tests of single features compared with feature bindings may be an important factor related to the observance of age-related binding deficits in VWM. Specifically, an age-related deficit was present when no concurrent load task was required but absent under articulatory suppression. It may be the case that, when under suppression, younger adults are unable to effectively verbally recode and rehearse the visual feature information (e.g., green-circle), reducing their binding test performance to levels comparable to the older adults (see General Discussion). As such, whether or not a concurrent load is imposed during change detection tasks could account for previous findings indicating no evidence of an age-related deficit when binding of surface features (e.g., shape and color) was required. Indeed, several recent experiments that found no evidence of an age-related *intra-item* binding deficit used either an articulatory suppression, a backward counting task, or both, but did not compare younger and older adult VWM performance under these conditions to a baseline condition requiring no concurrent load (e.g., Brockmole et al., 2008; Experiment 1, Brown & Brockmole, 2010).

Intriguingly, previous experiments finding age-related deficits in *item-context* binding did not impose concurrent load during VWM tasks (Borg et al., 2011; Chen & Naveh-Benjamin, 2012; Cowan et al., 2006; Fandakova et al., 2014). As such, several factors appear to be integrally related to observations of age-related binding deficits in VWM. First, when *item-context* binding is examined, age-related binding deficits in VWM are evident. Moreover, although several previous studies have indicated that *intra-item* binding processes appear to be largely intact in older

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[1] Previous studies advocate comparing performance in the binding test condition to the single-feature test condition in which observed performance is lowest to assess whether an age-related binding deficit is truly present (e.g., Brown & Brockmole, 2010). In line with this suggestion, we conducted separate analyses applied to the A' values using a 2 (age) × 2 (test) × 2 (task) repeated-measures ANOVA including only the single-feature of shape (in which performance was lower than for the single-feature color test condition) and binding test conditions. This subsequent analysis revealed the same patterns of significant main effects and interactions as described in the Experiment 1 results section.

adults, the current results from Experiment 1 indicate that age-related deficits are evident when binding of surface features occurs under baseline (i.e., no load) conditions. However, it remains unclear whether observations of age-related deficits with respect to *item-context* binding also vary as a function of concurrent load. This possibility was examined in Experiment 2.

Experiment 2: The Role of Aging in Item-Context Binding Processes in VWM

Experiment 2 examined *item-context* binding processes under both optimal conditions (i.e., no load) and those in which concurrent tasks involving either articulatory suppression or backward counting were required. In Experiment 2 we required younger and older adults to detect whether or not a change had occurred with respect to shape-color objects (i.e., monitoring for an object level change, not a single-feature level change), the spatial locations occupied by those objects, or both (i.e., object-location binding) across a brief retention interval. Since the *item-context* binding processes required to integrate and maintain these objects and their locations within VWM are affected by normal aging, as suggested in the recent literature, we predicted an overall age-related VWM binding deficit wherein the decline in performance from single features to feature binding tests should be larger for older relative to younger adults. However, if this type of VWM binding is unaffected by normal aging, there should be little difference between age groups in any observable decrease in performance from VWM tests of individual components (e.g., object or location) compared with those that require feature binding (e.g., object and location).

In an attempt to extend the findings from Experiment 1, in Experiment 2 we had participants perform an object-location VWM change detection tasks under both no load and under articulatory suppression. We predicted that an age-related binding deficit would be observed under no concurrent load. Moreover, in addition to articulatory suppression blocks, we included additional task blocks during which participants were required to count backward by twos during each trial. Given the ubiquitous nature of *item-context* binding deficits within the VWM literature, it is possible that an age-related *item-context* binding deficit will be observed regardless of the presence or degree of concurrent load.

Method

Participants. The participants included new groups of 45 undergraduate students (age range: 18–24) from the University of Missouri who participated in exchange for course-related credit and 48 older adults (age range: 65–83) from central Missouri who were compensated $15 for their time (see Table 1 for demographic information). Again, all participants were healthy physically and mentally, had no known memory deficits, and had normal color vision and corrected-to-normal visual acuity. As in Experiment 1, the older adults had significantly more formal education than younger adults, $t(91) = 2.75$, $p = .007$.

Stimuli and materials. The same shape-color stimuli used in Experiment 1 were used in Experiment 2 with the following notable exceptions. Instead of probing single-features (e.g., color, shape) during the item or component test, as we did in Experiment 1, entire objects were probed in the "Item" test condition (see Procedure section below). As such, in Experiment 2, participants were required to monitor for a change at the level of the entire object but not changes at the level of single-features (e.g., color or shape only) as in Experiment 1. In addition, for the test probe in the occupied "Space" (i.e., location) test, a black (0, 0, 0), dashed (6 pt.) square subtending 3.5° × 3.5° of visual angle was presented. In our view, including a separate test of "occupied" space is essential, as each spatial location, occupied by an object during the sample array, comprises the remaining component that must be bound to the appropriate corresponding object to form and maintain integrated representations of object-location bindings within VWM. Finally, in the object-location binding test, participants were required to monitor whether or not a change occurred between an object and its original occupied spatial location across a brief delay period. In contrast to Experiment 1, in this experiment, no gray background appeared behind the shape-color objects. The same software, computers, and monitors used in Experiment 1 were used to conduct Experiment 2.

Procedure. Participants, seated at a viewing distance of approximately 57 cm, were required to complete a visual working memory change detection task either under no concurrent load, under articulatory suppression, or while counting backward by two's. During each trial, participants first saw a prompt indicating the concurrent task to be completed throughout the trial. During each trial in two of the experimental blocks (no load), a "Get Ready" prompt was presented (2,000 ms) at the center of the screen in black, bolded, and Courier New, 18-point font. During each trial in two of the experimental blocks, participants viewed a "Start Repeating" prompt (e.g., "Start Repeating 83"). Participants were instructed to start repeating the two-digit number (new two-digit number presented for each trial) aloud that was presented at the center of the screen (e.g., "83, 83, 83, 83") until they were presented with a "Stop Repeating" prompt indicating that they could stop repeating the word. Finally, in two of the other experimental blocks participants viewed a "Start Counting" prompt (e.g., "Start Counting 83") before the onset of the presentation of the fixation cross and stimulus display during which they were instructed to count backward by two's starting with the number appearing during the prompt (e.g., "83, 81, 79, 77") until a "Stop Counting" prompt appeared immediately after the end of the delay period; see Figure 3.

Following the concurrent task prompt a fixation cross (0.60° × 0.60°), presented at the center of the screen (500 ms), preceded presentation of the memory array. Participants were instructed to maintain fixation and try to remember the objects, the onscreen spatial locations occupied by these objects, or the binding between the objects and their locations and were told they would be tested on this information after a brief delay. During the presentation of the memory array four objects (colored shapes), randomly sampled without replacement from the set of eight colors and eight shapes, were presented (2,000 ms) simultaneously in one of three configurations. In the left-of-center configuration, the center of one object was presented 5.6° to the left of the center of each of the four onscreen quadrants. In the center configuration, the center of one object was presented at the center of each of the four onscreen quadrants. In the right-of-center configuration, the center of one object was presented 5.6° to the right of the center of each of the

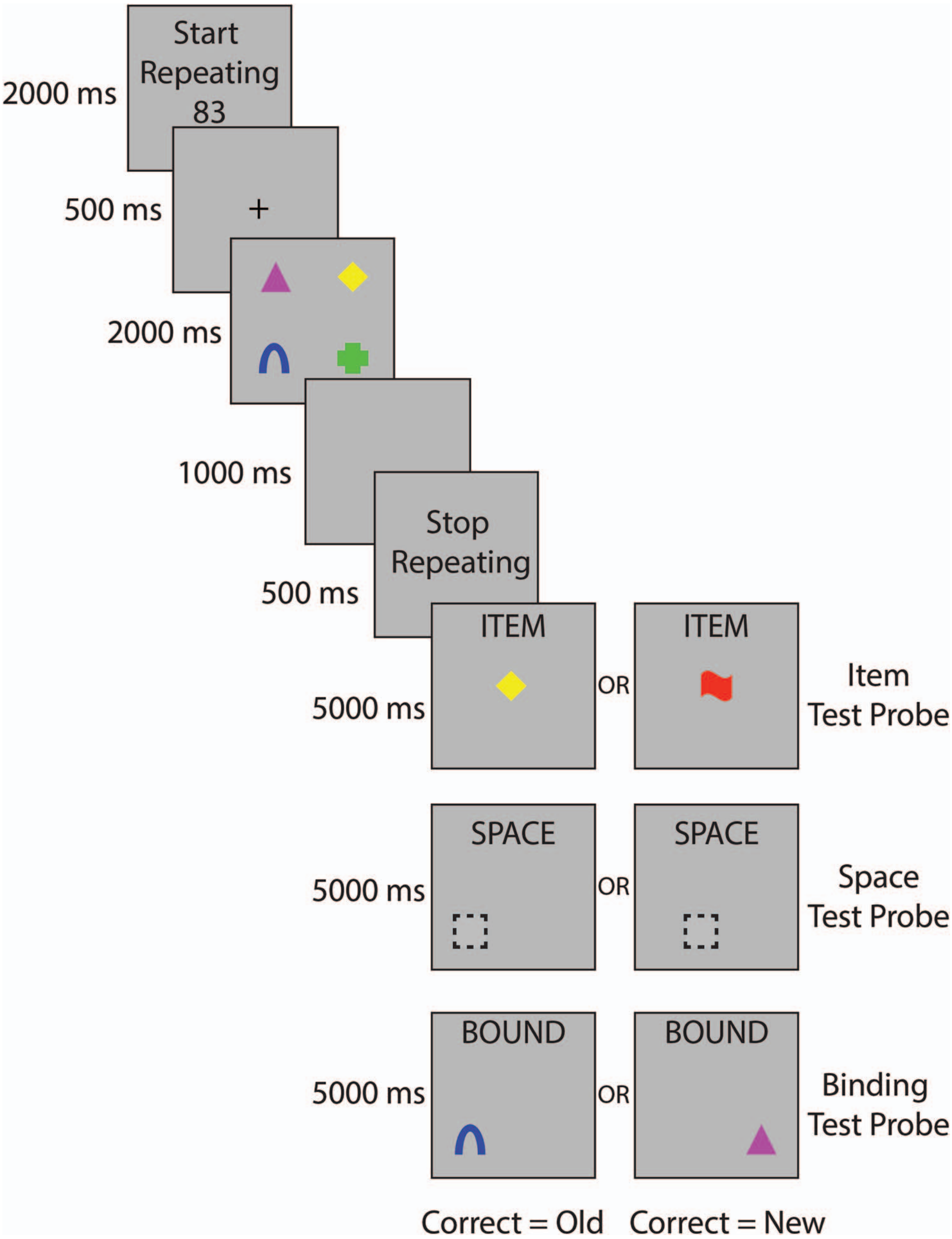

Figure 3. Basic task paradigm used in Experiments 2 and 3. *Note:* Experiments 2 and 3 trial sequence, sample array, and test probe configurations. Participants viewed a secondary task prompt (2,000 ms) and then viewed a fixation cross (500 ms). After fixation, the sample array, including four shape-color objects appeared (2,000 ms). After a delay-period (1,000 ms), during "old/no change" trials a single probe appeared that was either the same object as one of the items presented during the sample array ("ITEM" test), or was presented in the same occupied spatial location ("SPACE" test), or was the same object presented in the same previously occupied spatial location ("BOUND" test). During "new/change" trials, either a different object, completely new with respect to the colors and shapes presented during the sample array, was presented at the center of the array ("ITEM" test), or a previously unoccupied spatial location was probed ("SPACE" test), or one of the objects presented during the sample array changed to a spatial location previously occupied by a different object from sample to test ("BOUND" test). Participants were given 5 s to respond. Note that stimuli are depicted for illustrative purposes only and do not reflect the exact dimensions of the stimuli displayed during the actual experiment. See the online article for the color version of this figure.

four onscreen quadrants. The center of each onscreen quadrant was approximately 12° from central fixation. Using three distinct spatial configurations made it possible to better equate tests of the component feature of occupied space with tests of single objects and object-location bindings in which the entire stimulus set (e.g., colored shapes) could be probed at test during either change or no change trials throughout the experiment. For example, the use of only a single spatial configuration would have involved the use of persistently unoccupied spatial locations during "change" trials in which no object ever appears throughout the entire experiment. A blank delay period (1,000 ms) immediately followed the presentation of the memory array. After the delay period, depending on the concurrent task block, the "Get Ready," "Stop Repeating," or "Stop Counting" prompt was presented (500 ms).

Finally, during the test phase either an "ITEM," "SPACE," or "BOUND" prompt appeared capitalized, bolded, and in black Courier New 28-point font at the top-center of the screen to indicate the test type for each trial. During "ITEM" test phases, a single object was presented at the center of the stimulus configuration presented during the memory array. The probed object either exactly matched one of the previously presented objects (i.e., "old") or was completely new with respect to both color and shape (i.e., "new"). During "SPACE" test phases, a black dashed square was presented in one of the onscreen quadrants within one of the three potential locations within that particular quadrant (i.e., left-of-center, center, or right-of-center, 12 total possible onscreen locations). The black dashed square probe was either presented in the same position as one of the spatial locations previously occupied by one of the items in the memory array (i.e., "old") or was presented in a previously unoccupied spatial location (i.e., "new"). Finally, during "BOUND" test phases, an object appeared in one of the spatial locations previously occupied by one of the four objects in the memory array. The probed object was presented in either the same spatial location (i.e., "old") or in a different spatial location relative to the original binding of object and location presented during the sample array (i.e., "new"). Test phase types were pseudorandomly intermixed within each block with the constraint that no more than three trials per test type were presented in a row.

During all test phases in all blocks, participants were required to press the "o" key (labeled "old") if no change had occurred or the "n" key (labeled "new") within 5 s after the onset of the probe stimulus. If the response time elapsed, the trial was considered incorrect and the program advanced to the next trial. Throughout the experiment, participants pressed the space bar to initial the next trial. On half of the trials from each test condition in each block a change occurred and in the other half no change occurred. Participants completed a total of six blocks with 36 trials per block (216 total). Participants performed no concurrent task (2 blocks), a concurrent articulatory suppression task (2 blocks), and a concurrent backward counting task (2 blocks). Each of the two blocks per concurrent task type was completed back-to-back and block order between the three concurrent tasks was counterbalanced across participants within each age group. Before beginning the actual experiment, participants completed 18 practice trials (6 per test condition practiced during the 3 concurrent task block types) to familiarize them with the task. To ensure compliance with the task, during the blocks requiring articulatory suppression and backward counting, an experimenter recorded the number of verbal repetitions (e.g., "83, 83, 83") and correct subtractions (e.g., "83, 81, 79") of the target number audibly produced by each participant during trials 11–25.

Results

As in Experiment 1, we computed the proportion of hits and the proportion of false alarms and then computed response accuracy as a function of the proportion hits minus false alarms, d', and A' values (see Table 4 for means and *SD*s). Participants that exhibited chance or near chance-level performance (i.e., 2 *SD* below the group mean) were excluded (3 younger, 6 older) before group-level analyses resulting in the inclusion of 42 participants in each age group. A 2 × 3 × 3 repeated-measures ANOVA was used applied to the A' values (see Figure 4). The same overall pattern of significant main effects reported below was observed during separate analyses applied to the proportion hits minus false alarms and d' values, with some variation with respect to the interactions of interest.[2] There was a main effect of age, $F(1, 82) = 36.66$, $p < .001$, $\eta_p^2 = .31$), confirming that younger adults ($M = .88$, $SD = .06$) performed with greater accuracy than older adults ($M = .79$, $SD = .06$). There was a significant main effect of concurrent task, $F(2, 164) = 61.08$ $p < .001$, $\eta_p^2 = .43$). Bonferroni-corrected pairwise comparisons confirmed that performance was higher when no concurrent load ($M = .88$, $SD = .04$) was required compared to when the articulatory suppression task ($M = .84$, $SD = .05$) was required ($p = .001$). Performance under no load was also higher than performance during backward counting ($M = .78$, $SD = .05$, $p < .001$). Finally, performance was higher during concurrent load requiring articulatory suppression compared to backward counting ($p < .001$). Additionally, there was a main effect of test, $F(2, 164) = 46.91$, $p < .001$, $\eta_p^2 = .36$), indicating a difference between the three test conditions. Bonferroni-corrected pairwise comparisons indicated that performance was significantly higher when objects ($M = .86$, $SD = .05$) compared to object-location bindings ($M = .77$, $SD = .07$) were tested ($p < .001$). Performance when occupied space ($M = .87$, $SD = .05$) was the tested feature was higher than when object-location bindings were tested ($p < .001$). There was no significant difference in performance between the object and occupied spatial location test conditions ($p = .49$).

Given that there was no overall difference in performance between the object and occupied space (i.e., location) test conditions, we collapsed across these two component conditions, averaging A' values from the object and spatial location test conditions before examining relevant interactions. A 2 (age: younger, older) × 2 (test: average component, binding) × 3 (task: no load, suppression, counting) ANOVA revealed a significant interaction between the factors of age and test, $F(1, 82) = 12.95$, $p = .001$, $\eta_p^2 = .14$). Follow-up paired samples *t* tests revealed that perfor-

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[2] We note that the age by test interaction pertaining to the full 2 (age) × 3 (test) × 3 (load) ANOVA was not significant in the d' analysis, $F(2, 164) = 2.13$, $p = .12$. Additionally, the age by test by load triple interaction pertaining to the average item and location component Tests 2 (age) × 2 (test) × (load) ANOVA was significant in the proportion hits minus false alarms analysis, $F(2, 164) = 3.35$, $p = .04$, $\eta_p^2 = .04$, but borderline in the d' analysis, $F(2, 164) = 2.86$, $p = .06$. This approach of reporting differences in statistical outcome between these three measures of performance is in line with previous suggestions (e.g., Allen et al., 2012).

Table 4
Memory Response Accuracy and Signal Detection Sensitivity Measures (Means and SDs) for the Results of Experiment 2

	No load			Suppression			Counting		
Measures	Object	Location	Binding	Object	Location	Binding	Object	Location	Binding
Hits									
Younger	.80 (.20)	.90 (.10)	.79 (.16)	.65 (.21)	.93 (.07)	.74 (.16)	.63 (.23)	.87 (.11)	.60 (.20)
Older	.74 (.19)	.94 (.08)	.77 (.18)	.59 (.26)	.95 (.07)	.75 (.22)	.51 (.27)	.87 (.14)	.60 (.23)
False alarms									
Younger	.05 (.09)	.18 (.20)	.14 (.14)	.08 (.11)	.19 (.20)	.19 (.14)	.12 (.14)	.30 (.23)	.19 (.14)
Older	.10 (.11)	.38 (.24)	.44 (.25)	.12 (.12)	.44 (.26)	.40 (.24)	.14 (.15)	.50 (.22)	.42 (.25)
Hits-False alarms									
Younger	.75 (.21)	.72 (.21)	.65 (.21)	.57 (.22)	.74 (.21)	.55 (.23)	.51 (.20)	.57 (.27)	.41 (.23)
Older	.64 (.20)	.56 (.25)	.33 (.25)	.47 (.26)	.51 (.27)	.35 (.29)	.37 (.27)	.37 (.22)	.18 (.21)
A'									
Younger	.93 (.06)	.92 (.07)	.89 (.08)	.87 (.07)	.93 (.07)	.84 (.11)	.86 (.07)	.86 (.12)	.79 (.12)
Older	.89 (.07)	.87 (.09)	.74 (.15)	.82 (.12)	.85 (.11)	.74 (.17)	.77 (.14)	.79 (.10)	.64 (.16)
d'									
Younger	2.99 (.92)	2.80 (1.09)	2.34 (1.01)	2.13 (.87)	2.87 (1.05)	1.79 (.98)	1.89 (.71)	2.09 (1.12)	1.38 (.88)
Older	2.31 (.88)	2.28 (1.01)	1.10 (.85)	1.68 (1.01)	2.08 (.99)	1.15 (1.07)	1.37 (1.08)	1.48 (.90)	.54 (.64)

mance in the average component test (M = .89, SD = .05) was higher than performance in the object-location binding tests (M = .84, SD = .09) for the younger adults, $t(41) = 4.90$, $p < .001$, and this difference was larger in older adults, with performance in the average component test (M = .83, SD = .06) being higher than in the object-location binding tests (M = .71, SD = .12), $t(41)$ = 7.27, $p < .001$. The difference in performance between the average component and object-location binding test conditions, over twice as large for older (M_{Δ} = .12, SD_{Δ} = .11) compared with younger adults (M_{Δ} = .05, SD_{Δ} = .07), drove this age by test interaction indicating an overall age-related binding deficit. While there was a significant age by test interaction, the triple interaction between the factors of age, test, and task, $F(2, 164) = 1.49$, $p = .23$, was not significant, indicating an overall age-related binding deficit that was not contingent upon the presence or absence of concurrent load.

In addition to the overall analysis including three levels of the concurrent task factor, to serve as a comparison to the results obtained in Experiment 1, we performed a subsequent analysis which included only the A' values corresponding to the no load and articulatory suppression blocks. This 2 (age: younger, older) × 2 (test: average component, binding) × 2 (concurrent task: no load, suppression) repeated-measures ANOVA revealed the same pattern of statically significant main effects of age ($M_{younger}$ = .89, $SD_{younger}$ = .06; M_{older} = .80, SD_{older} = .06), $F(1, 82) = 33.90$, $p < .001$, $\eta_p^2 = .29$; test ($M_{average\_component}$ = .89, $SD_{average\_component}$ = .03; $M_{binding}$ = .80, $SD_{binding}$ = .07), $F(1, 82) = 60.87$, $p < .001$, $\eta_p^2 = .43$; and task type (M_{no_load} = .86, SD_{no_load} = .05; $M_{suppression}$ = .83, $SD_{suppression}$ = .06), $F(1, 82) = 9.00$, $p = .004$, $\eta_p^2 = .10$. Consistent with the overall analysis including all three levels of the factor of concurrent task type, this analysis revealed a significant age by test interaction, $F(1, 82) = 12.36$, $p = .001$, $\eta_p^2 = .13$ but no significant triple interaction between age, test, and task, $F(1, 82) = 2.96$, $p = .09$.

Finally, we used a 2 × 2 × 3 repeated-measures ANOVA including the factors of age (younger, older), concurrent task (suppression, counting), and test (object, location, object-location binding) to analyze the number of number repetitions and successful subtractions made by the participants in each age group for

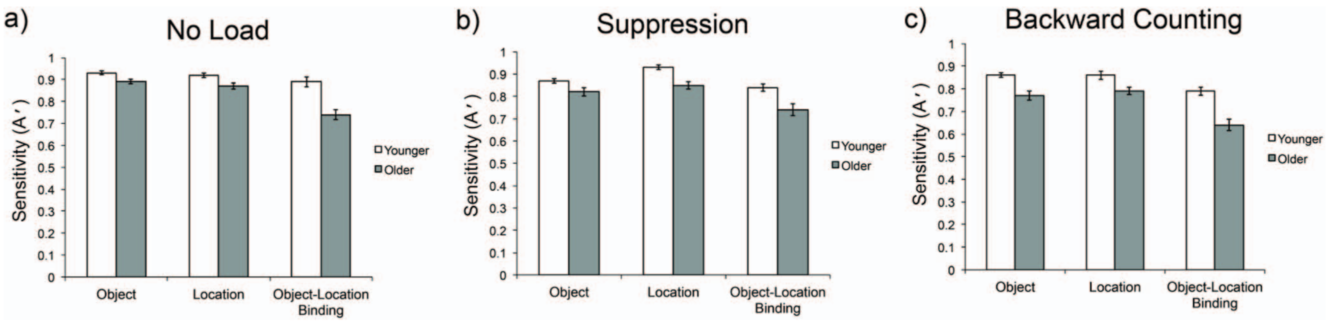

Figure 4. Experiment 2: Younger and older adult recognition performance under no load, articulatory suppression, and backward counting. *Note:* Behavioral results for Experiment 2 under (A) no concurrent load, (B) articulatory suppression, or (C) backward counting. In all panels, the abscissa depicts the test conditions being compared while sensitivity (A') of recognition memory performance for both younger (white bars) and older (gray bars) adults is plotted along the ordinate. Error bars represent the *SEM* in each test condition. See the online article for the color version of this figure.

Table 5
Successful Repetitions and Subtractions in Each Condition Verbalized During the Concurrent Articulatory Suppression or Backward Counting Tasks in Experiments 2 and 3

Experiment	Item	Location	Binding
Experiment 2			
Suppression			
Younger	6.46 (1.33)	6.51 (1.42)	6.57 (1.42)
Older	5.81 (1.33)	5.86 (1.41)	5.82 (1.34)
Counting			
Younger	4.36 (.80)	4.39 (.83)	4.42 (.86)
Older	3.87 (.92)	3.84 (.90)	3.86 (.96)
Experiment 3			
Suppression			
Younger	7.09 (1.48)	6.97 (1.37)	7.43 (1.92)
Older	7.02 (1.85)	6.99 (2.22)	7.01 (2.08)

Note. Mean responses produced in each concurrent task are depicted with *SD*s in parentheses.

each test block completed under articulatory suppression and backward counting; see Table 5 for means and *SD*s. There was a main effect of age, $F(1, 82) = 8.56$, $p = .004$, $\eta_p^2 = .10$), indicating that, overall, younger adults ($M = 5.45$, $SD = .95$) were able to produce a greater number of appropriate responses when a concurrent task was required compared to older adults ($M = 4.84$, $SD = .95$). Additionally, there was a main effect of concurrent task, $F(1, 82) = 227.66$, $p < .001$, $\eta_p^2 = .74$, indicating, as expected, that a greater number of appropriate responses were produced by participants during the articulatory suppression ($M = 6.17$, $SD = .96$) compared with backward counting ($M = 4.12$, $SD = .61$) blocks. However, there was no significant main effect of test, $F(2, 164) = 1.41$, $p = .25$), indicating that a comparable level of effort was exerted during the concurrent tasks during tests of the components and object-location bindings. More important, there were no significant interactions between age and test, $F(2, 164) = 1.32$, $p = .27$), nor between age, task, and test, $F(2, 164) = .38$, $p = .69$), indicating that there was no age-related difference in the number of repetitions or counts made during trials testing for single features compared those testing feature binding.

Discussion

The results from Experiment 2 revealed an overall age-related *item-context* binding deficit regardless of the presence or absence of a concurrent task. This pattern of results diverges from the findings from Experiment 1 wherein we observed an age-related *intra-item* binding deficit under baseline conditions, but not when articulatory suppression was required. More important, the selective impairment in *intra-item* and the general impairment shown by older adults in *item-context* binding processes cannot be attributed to the stimuli used, as the same shape-color stimuli were presented during the sample array in both Experiments 1 and 2. The overall age-related binding deficit in Experiment 2 was driven by observations of a larger difference in VWM performance during tests at the level of a single object compared with tests of object-location binding in older adults ($M_\Delta = .12$) compared with younger adults ($M_\Delta = .05$). Specifically, this interaction between age and test indicates that older adults are impaired in their ability to bind and maintain objects and the spatial locations occupied by those objects within VWM.

The current finding of an age-related *item-context* binding deficit is consistent with previous observations (e.g., Borg et al., 2011; Chen & Naveh-Benjamin, 2012; Cowan et al., 2006; Fandakova et al., 2014). However, in contrast to the findings from Experiment 1 wherein observations of an age-related *intra-item* binding deficit differed as a function of the presence or absence of a concurrent task, the results from Experiment 2 suggested that an overall age-related *item-context* binding deficit within VWM was present regardless of whether concurrent load was imposed.

Experiment 3: Examining Age-Related Differences in Item-Context Binding Using a Blocked Design Under No Load and Articulatory Suppression

Several differences in experimental design exist between Experiments 1 and 2. First, in Experiment 1 the test conditions were blocked, while in Experiment 2, the test conditions were intermixed. Second, to better equate the articulatory suppression task with the backward counting task, participants in Experiment 2 repeated numbers whereas words were repeated in Experiment 1. Finally, in Experiment 1 participants completed blocks of the VWM task under either no load or articulatory suppression whereas the participants in Experiment 2 completed the task under no load, articulatory suppression, and backward counting. As such, Experiment 3 was designed to examine *item-context* binding in a blocked design including only no load and articulatory suppression (using words instead of numbers) blocks to assess item-context binding performance under identical conditions used in Experiment 1 that examined intra-item binding.

Participants

A new group of 21 younger (18–22 years) and 20 older (65–83) adults participated in Experiment 3 (see Table 1 for demographic information). Again, all participants were healthy physically and mentally, had no known memory deficits, and had normal color vision and corrected-to-normal visual acuity. Additionally, we administered the minimental status examination (MMSE; adapted from Folstein, Folstein, & McHugh, 1975) to both younger and older adults. All participants scored within the normal range and no participants scored below 27 on the MMSE. There was no significant difference between younger and older adult's MMSE scores ($M_{younger} = 29.2$, $SD_{younger} = 0.87$; $M_{older} = 29.3$, $SD_{older} = 1.03$), $t(39) = 0.37$, $p = .72$. As in Experiments 1 and 2, the older adults had significantly more formal education than younger adults, $t(39) = 5.79$, $p < .001$.

Stimuli, Materials, and Procedure

The stimuli were the same color-shapes used in Experiment 1 and 2. The VWM change detection task parameters and procedure were equivalent to those used in Experiment 2 with the following exceptions. First, during the articulatory suppression blocks, participants repeated a three-letter word (e.g., “Cap,” “Toy”), in the same manner as in Experiment 1, instead of a two-digit number. Second, the test conditions including the three probe types (i.e., item only, spatial location only, item-context binding) were blocked and, as in Experiment 1, thus, no "probe cue" words were presented during each test phase. Finally, the backward counting load condition used in Experiment 2 was not included. Participants completed 18 practice trials followed by six blocks of the VWM change detection task including 36 trials per block (216 trials total). Concurrent load order (i.e., first half, second half), during which participants performed separate blocks containing either item only, spatial location only, and item-context binding change detection test probes, were counterbalanced across participants within each age group.

Results

As in Experiments 1 and 2, we computed the proportion of hits and the proportion of false alarms and then computed response accuracy as a function of the proportion hits minus false alarms, d', and A' values (see Table 6 for means and *SD*s). Participants that exhibited chance or near chance-level performance (e.g., 2 *SD* below the group mean) were excluded (1 younger adult) Before group-level analyses resulting in the inclusion of 20 participants in each age group.

A 2 × 2 × 3 repeated-measures ANOVA was applied to the A' values (see Figure 5). We note that the same pattern of significant main effects and interactions reported below was observed during separate analyses applied to the proportion hits minus false alarms and d' values. This analysis revealed a main effect of age, $F(1, 38) = 11.95$, $p = .001$, $\eta_p^2 = .24$), confirming that younger adults ($M = .93$, $SD = .04$) performed with greater accuracy than older adults ($M = .89$, $SD = .04$). There was a significant main effect of concurrent task, $F(1, 38) = 14.88$ $p < .001$, $\eta_p^2 = .28$), indicating that performance was higher when no concurrent load ($M = .93$, $SD = .03$) was required compared to when the articulatory suppression task ($M = .90$, $SD = .04$) was required. Additionally, there was a main effect of test, $F(2, 76) = 17.61$, $p < .001$, $\eta_p^2 = .32$), indicating a difference between the three test conditions. Bonferroni-corrected pairwise comparisons indicated that performance when occupied space ($M = .94$, $SD = .03$) was the tested feature was higher than when object-location bindings ($M = .88$, $SD = .04$) were tested ($p = .001$). There was also a significant difference in performance between the object ($M = .90$, $SD = .04$) and occupied spatial location test conditions ($p = .001$). There was no overall difference in performance for objects compared to object-location bindings ($p = .16$).

The ANOVA revealed a significant interaction between the factors of age and test type, $F(2, 76) = 4.70$, $p = .01$, $\eta_p^2 = .11$. More important, the triple interaction between the factors of age, test, and concurrent load was not significant, $F(2, 76) = 0.13$, $p = .86$, indicating the presence of an overall age-related binding deficit regardless of concurrent load. Follow-up paired samples *t* tests indicated that the significant age by test interaction was driven by performance differences in the older adults such that performance in the object test condition ($M_{older} = .88$, $SD_{older} = .06$) was significantly higher than in the object-location binding ($M_{older} = .85$, $SD_{older} = .06$) condition, $t(19) = 2.04$, $p = .05$. Additionally, older adults were significantly more accurate during the spatial location test blocks ($M_{older} = .93$, $SD_{older} = .06$) compared with object-location binding test blocks, $t(19) = 5.29$, $p = .001$. Finally, older adults were more accurate during spatial location test blocks compared to object test blocks, $t(19) = 4.43$, $p = .001$. In contrast, no significant differences in performance between any of the test conditions were observed for the younger adults (Object: $M_{younger} = .93$, $SD_{younger} = .05$ vs. Spatial Location: $M_{younger} = .95$, $SD_{younger} = .03$, $t(19) = 1.69$, $p = .11$; Object vs. Binding: $M_{younger} = .92$, $SD_{younger} = .06$, $t(19) = 0.20$, $p = .84$; Spatial Location vs. Binding: $t(19) = 1.84$, $p = .08$).

Consistent with our analyses for Experiment 2, we performed an additional analysis collapsing across the single-feature levels of the factor of test condition (e.g., object, spatial location) to examine average component test performance compared to binding test performance. Consistent with the pattern of results from Experiment 2 and the overall analysis from Experiment 3, a 2 (age: younger, older) × 2 (test: average component, binding) × 2 (task: no load, suppression) ANOVA revealed a no significant triple interaction between age, test, and load, $F(1, 38) = 0.05$, $p = .83$, but did reveal a significant interaction between the factors of age and test, $F(1, 38) = 6.27$, $p = .02$, $\eta_p^2 = .14$). Follow-up paired samples *t* tests revealed that performance in the average compo-

Table 6

Memory Response Accuracy and Signal Detection Sensitivity Measures (Means and SDs) for the Results of Experiment 3

	No load			Suppression		
Measures	Item	Space	Binding	Item	Space	Binding
Hits						
Younger	.83 (.14)	.88 (.11)	.91 (.08)	.78 (.12)	.86 (.10)	.81 (.13)
Older	.74 (.16)	.93 (.06)	.81 (.13)	.65 (.21)	.93 (.07)	.77 (.17)
False alarms						
Younger	.05 (.07)	.06 (.07)	.08 (.07)	.07 (.09)	.06 (.07)	.13 (.14)
Older	.11 (.09)	.14 (.14)	.21 (.13)	.08 (.08)	.19 (.15)	.28 (.18)
Hits-False alarms						
Younger	.78 (.17)	.82 (.12)	.83 (.11)	.71 (.17)	.80 (.13)	.68 (.23)
Older	.63 (.16)	.79 (.18)	.60 (.16)	.57 (.21)	.74 (.20)	.49 (.22)
A'						
Younger	.94 (.06)	.95 (.04)	.95 (.03)	.92 (.06)	.95 (.04)	.90 (.09)
Older	.89 (.05)	.94 (.06)	.88 (.06)	.87 (.08)	.92 (.07)	.82 (.10)
d'						
Younger	3.03 (.90)	3.14 (.72)	3.07 (.79)	2.53 (.85)	3.04 (.82)	2.40 (1.07)
Older	2.13 (.66)	2.95 (1.03)	1.98 (.82)	2.06 (.78)	2.75 (1.06)	1.59 (.88)

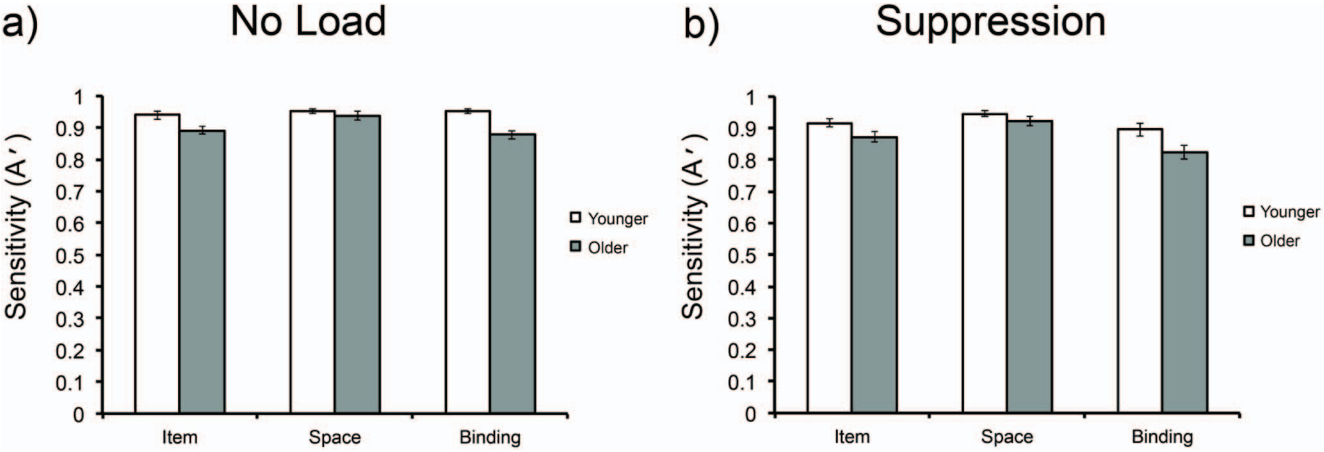

Figure 5. Experiment 3: Younger and older adult recognition performance under no load and articulatory suppression. *Note:* Behavioral results for Experiment 3 under (A) no concurrent load, (B) articulatory suppression. The abscissa depicts the test conditions while sensitivity (*A*′) of recognition memory performance for both younger and older adults is plotted along the ordinate. Error bars represent the *SEM* in each test condition. See the online article for the color version of this figure.

nent test ($M = .94$, $SD = .03$) was not significantly different from performance in the object-location binding tests ($M = .92$, $SD = .06$) for the younger adults, $t(19) = 1.66$, $p = .11$. However, there was a significant difference in performance for the older adults, in which performance in the average component test ($M = .91$, $SD = .05$) was higher than in the object-location binding tests ($M = .85$, $SD = .06$), $t(19) = 3.92$, $p = .001$.

Additionally, we used 2 × 3 repeated-measures ANOVA including the factors of age (younger, older) and test (object, location, object-location binding) to analyze the amount of successful verbal repetitions made by the participants in each age group for each test block completed under articulatory suppression; see Table 5 for means and *SD*s. There was no significant main effect of age, $F(1, 38) = .08$, $p = .78$, indicating that younger ($M = 7.17$, $SD = 1.74$) and older adults ($M = 7.01$, $SD = 1.74$) did not differ in their ability to successfully produce verbal repetitions throughout the blocks of trials that required articulatory suppression. There was no main effect of test type indicating that the number of verbal repetitions did not vary as a function of test probe condition, $F(2, 76) = 1.47$, $p = .24$. More important, there was no significant interaction between age and test, $F(2, 76) = 1.38$, $p = .26$), indicating that there was no age-related difference in the number of verbal repetitions made during trials testing for single features compared those testing feature binding.

Finally, given that, aside from the type of binding being explored, the design and procedures were comparable in Experiment 1 and Experiment 3, we conducted an exploratory cross-experimental analyses applied to each of the three measures of performance. This mixed 2 (age: younger, older) × 2 (test: average component, binding) × 2 (load: no load, articulatory suppression) × 2 (experiment: 1, 3) ANOVA included the between-subjects factors of age and experiment and the within-subject factors of test condition and concurrent load. The same pattern of main effects found in Experiments 1, 2, and 3 was observed for all three measures of performance. Moreover, significant age by test interactions were observed for the proportion hits minus false alarms, $F(1, 100) = 8.19$, $p = .005$, $\eta_p^2 = .08$, d', $F(1, 100) = 7.47$, $p = .007$, $\eta_p^2 = .07$, and A', $F(1, 100) = 8.06$, $p = .005$, $\eta_p^2 = .08$, analyses. More important, the four-way interaction between age, test, load, and experiment pertaining to the proportion hits minus false alarms was significant, $F(1, 100) = 3.71$, $p = .05$, $\eta_p^2 = .04$, but marginally significant for the d', $F(1, 100) = 3.04$, $p = .08$, and A', $F(1, 100) = 3.12$, $p = .08$, analyses, likely because of the much larger amount of statistical power required to reveal the presence of a significant four-way interaction. The follow-up triple interaction between age, test, and load, was significant for Experiment 1, (hits minus false alarms: $F(1, 62) = 13.73$, $p < .001$, $\eta_p^2 = .18$; d': $F(1, 62) = 13.59$, $p < .001$, $\eta_p^2 = .18$; and A': $F(1, 62) = 7.97$, $p = .006$, $\eta_p^2 = .11$), but not for Experiment 3 (hits minus false alarms: $F(1, 38) = .33$, $p = .57$; d': $F(1, 38) = .15$, $p = .70$; and A': $F(1, 38) = .05$, $p = .83$). This pattern supports our overall findings from Experiment 1 that the age-related deficit observed in *intra-item* binding varied as a function of concurrent load and findings from Experiment 3 indicating an age-related item-context binding deficit regardless of the level of concurrent load.

Discussion

The results from Experiment 3 replicate the findings from Experiment 2 indicating the presence of an age-related item-context binding deficit regardless of concurrent load. More important, Experiment 3 controlled for methodological differences between Experiment 1 and Experiment 2. Even when using a blocked design and comparing performance under no load versus articulatory suppression, as was the case in Experiment 1, the same interaction between age and test found in Experiment 2 was observed in Experiment 3, again indicating a ubiquitous age-related item-context binding deficit.

General Discussion

Converging with previous findings, we observed and extended the conditions under which an age-related binding deficit for *item-context* binding processes is manifested (e.g., Borg et al., 2011; Chen & Naveh-Benjamin, 2012; Cowan et al., 2006; Fandakova et al., 2014; Mitchell et al., 2000a). However, in contrast to the findings from several recent studies (e.g., Brockmole et al., 2008; Brown & Brockmole, 2010; Parra et al., 2009), which indicated that older adults have no impairments with *intra-item* forms of binding, the current results revealed an age-related deficit for binding of surface features (e.g., colored shapes) with no spatial component. Moreover, age-related *intra-item* binding deficits were only observed under baseline conditions in which no concurrent load task was required (Experiment 1), whereas an overall age-related binding deficit was present when *item-context* binding was examined (Experiment 2 and Experiment 3). The current findings reveal that both the distinct type of the binding process and conditions under which the integrity of these binding processes are examined, play important roles in determining the presence or absence of age-related binding deficits in VWM. Several intriguing possibilities exist regarding the distinct role of aging in *intra-item* and *item-context* VWM binding processes.

Neural Mechanisms

One factor associated with the age-related VWM binding deficits observed in the three experiments within the current study relates to previous findings that different neural mechanisms are involved in these distinct binding processes. For instance, recent neuroimaging studies have found patterns of activation within MTL structures during *item-context* VWM binding tasks (Bergmann, Rijpkema, Fernandez, & Kessels, 2012; Mitchell, Johnson, Raye, & D'Esposito, 2000b; Olson, Page, Moore, Chatterjee, & Verfaellie, 2006). In contrast, in neuroimaging studies using tasks requiring *intra-item* binding processes, no patterns of activation within the MTL are found (Parra, Della Sala, Logie, & Morcom, 2014; Piekema, Rijpkema, Fernandez, & Kessels, 2010; Shafritz, Gore, & Marois, 2002). Intriguingly, within MTL structures like the hippocampi, decreases in neuronal volume are evident with increases in age (Du et al., 2006; Raz, Rodrigue, Head, Kennedy, & Acker, 2004; Yang, Goh, Chen, & Qiu, 2013).

In studies that have directly examined both *item-context* and *intra-item* binding processes within VWM, patients with lesions to MTL structures are often impaired when performing *item-context* but not *intra-item* binding tasks (Parra et al., 2015; van Geldorp, Bouman, Hendriks, & Kessels, 2014). Furthermore, MTL patients can maintain single items, but suffer impairments when binding between item identity and location is required (Pertzov et al., 2013). Given previous evidence that MTL structures, impacted even in healthy older adults, are involved in item-context binding processes, we might expect older, relative to younger, adults to exhibit impairments when performing *item-context* but not necessarily *intra-item* binding tasks within VWM. Indeed, extant behavioral evidence from the VWM binding literature suggests this distinction. However, the findings from Experiment 1 in the current study indicate that, under certain conditions, age-related *intra-item* binding deficits are evident even for surface feature conjunctions (e.g., colored shapes). As such, other potential mechanisms may better account for the age-related *intra-item* binding differences observed as a function of concurrent load.

Verbalization Mechanisms and Strategy Use

While distinct neural mechanisms may partially explain age-related differences in intra-item and item-context binding, why did age-related differences in VWM performance for these two types of binding processes vary as a function of concurrent load? In Experiment 1, younger adults may have taken advantage of a rehearsal strategy during the no load blocks by verbalizing only the relevant features of colors during the color-only tests, shapes during the shape-only tests, or both colors and shapes during the binding tests. As such, it is possible that when the probability of younger adults being able to verbalize and rehearse features contained within the shape-color stimuli (e.g., "green-circle, red-flag") presented in the sample array was reduced (e.g., under articulatory suppression), their ability to efficiently form or maintain the to-be-bound features as integrated representations within VWM was reduced to the level of older adults when *intra-item* binding processes were required. It seems possible that verbal rehearsal of both color and shape would take longer or tax verbal working memory rehearsal processes to a greater extent than rehearsing color or shape alone, potentially explaining the selective binding impairment for younger adults under articulatory suppression observed in Experiment 1.

To assess the above suggestion, subjective reports from our posttest questionnaires regarding the use of a rehearsal strategy (scoring: yes, no) beginning during the study phase of each experimental trial indicated that, in Experiment 1 during no load blocks, the explicit use of a rehearsal strategy in an attempt to improve performance on the VWM task varied significantly as a function of age group (contingency table analysis: 59% younger, 25% older; $p = .01$, Fisher's exact test). When under articulatory suppression, the use of a rehearsal strategy was not dependent upon age (25% younger, 6% older; $p = .08$, Fisher's exact test). In line with previous findings from the episodic memory literature, one explanation for age-related binding deficits under no load conditions relates to the notion that older adults either fail to use strategies to support memory performance, or use strategies that are inefficient compared to those used by younger adults (Naveh-Benjamin, Brav, & Levy, 2007).

With respect to the findings observed in Experiment 1, it appears that, while younger adult performance in the binding condition was significantly higher than for older adults under no load, articulatory suppression seems to "level the playing field," resulting in a selective disruption in the younger adult's binding performance. This is consistent with previous work indicating that concurrent load reduces younger adults ability to maintain bound representations in VWM (Elsley & Parmentier, 2009; Fougnie & Marois, 2009; Zokaei et al., 2014). It is also possible that for the older adults, perhaps binding of intra-item features at encoding occurs without incident, but that the quality of these bound representations degrades such that by the time they get tested on both features (e.g., binding trials) they do worse than younger adults, but may have performed in an equivalent manner had they implemented an effective strategy (e.g., verbal rehearsal under no load).

In contrast to Experiment 1, given the type of *item-context* binding required in Experiments 2 and 3, relying solely on verbal recoding of the color, shape, *and* spatial location (e.g., "green-circle-upper left, red-flag-lower right") for each item in the array, even for the younger adults, may have been more difficult or less informative given the presence of a spatial component. Indeed, posttest questionnaire responses regarding rehearsal strategy are in line with this explanation. Specifically, in Experiment 2 there was no significant difference in the number of younger and older adults reporting the use of a rehearsal strategy during the trials of the no load blocks (17% younger, 5% older; $p = .16$, Fisher's exact test) nor during the blocks performed under articulatory suppression (7% younger, 5% older; $p = 1.0$, Fisher's exact test). In Experiment 3, where participants provided rehearsal reports for each test, rehearsal strategy did not vary as a function of age or test condition under no load (item: 40% younger, 10% older, $p = .07$; spatial location: 10% younger, 5% older, $p = 1.0$; and importantly binding: 15% younger, 5% older, $p = .61$) or articulatory suppression (item: 20% younger, 20% older, $p = 1.0$; spatial location: 10% younger, 20% older, $p = .66$; and importantly binding: 20% younger, 20% older, $p = 1.0$, all *p*s reflect Fisher's exact test). Rather, perhaps other, nonverbal processing mechanisms (akin to "rehearsal") may underlie younger adults ability to outperform older adults. As such, another possibility, beyond the scope of the current work, is that a secondary task requiring visual attentional resources during the *item-context* binding task used in Experiments 2 and 3 may reduce younger adults' performance to the level of older adults (e.g., see Hartley, Little, Speer, & Jonides, 2011). Future research examining the impact of visual, rather than verbal, concurrent attentional load will further elucidate the differences found between *intra-item* (Experiment 1) and *item-context* (Experiment 2 and Experiment 3) processes regarding the impact of secondary tasks on the presence or absence of age-related binding deficits in VWM.

The results from the current experiments add clarification to the mixed evidence of age-related deficits in VWM binding. More important, these findings highlight the importance of measuring baseline performance in comparison to secondary tasks (including articulatory suppression) that impose a concurrent load on the VWM processes available to carry out a given VWM task. For instance, in several experiments in which an age-related *item-context* binding deficit was observed, no concurrent tasks were required during the VWM task (Borg et al., 2011; Chen & Naveh-Benjamin, 2012; Cowan et al., 2006; Fandakova et al., 2014). Consistent with these previous findings, performance in the VWM task used in Experiment 2 and Experiment 3 of the current study revealed an age-related binding deficit regardless of the level of concurrent load.

In contrast, studies that have examined *intra-item* binding processes in VWM, typically find no evidence of an age-related VWM binding deficit (Brockmole et al., 2008; Brown & Brockmole, 2010; Parra et al., 2009). Several of these previous experiments only examined VWM binding performance under conditions of either articulatory suppression and/or backward counting (Brockmole et al., 2008; Brown & Brockmole, 2010). Another study finding an age-related *intra-item* binding deficit did not require a secondary, concurrent task, but used stimuli that were difficult to verbalize (non-basic colors: Parra et al., 2009). These patterns from the literature, along with the results from Experiment 1 in the current study, suggest that, when the probability of verbalization or rehearsal of the stimuli is reduced, no age-related *intra-item* binding deficit is apparent.

Age-Related Binding Deficits in Episodic Memory and Working Memory

Robust patterns of age-related associative memory deficits are evident in long-term episodic memory, (see Old & Naveh-Benjamin, 2008), yet the nature of these deficits within VWM binding processes remains unclear. Borrowing from the episodic memory literature, an interesting distinction can be drawn between the putative recollection-based retrieval mechanisms recruited during intra-item and item-context binding processes within VWM. Recollection during retrieval can occur via reinstatement of target details or contextual details (Brainerd, Gomes, & Moran, 2014; Brainerd, Gomes, & Nakamura, 2015). Relevant to the current work, target reinstatement (e.g., green diamond) may be sufficient during retrieval of intra-item bindings from VWM while retrieval of item-context bindings may additionally require reinstatement of contextual details (e.g., green diamond, upper left quadrant). Given that older adults have difficulty reinstating associative links (i.e., context recollection) between previously encountered episodic components (i.e., target recollection) the ubiquitous age-related item-context binding deficit observed in Experiments 2 and 3 is in line with this theoretical distinction (Old & Naveh-Benjamin, 2008; Spencer & Raz, 1995).

Conclusions

In the current study we found evidence for a general age-related VWM binding deficit. Upon examining younger and older adult performance on VWM tasks that required either *intra-item* (Experiment 1) or *item-context* (Experiment 2 and Experiment 3) binding processes, we found that older, relative to younger, adults were impaired to a greater extent when feature bindings compared to single features required processing within VWM. These findings are consistent with robust patterns of age-related associative memory deficits observed in the episodic memory literature (Old & Naveh-Benjamin, 2008). Moreover, age-related *intra-item* binding deficits were observed under baseline conditions but not when a concurrent secondary task was required, providing an explanation for previous variability in the observations of the presence or absence of age-related binding deficits within VWM. It remains an interesting question whether the use of concurrent secondary tasks will show differential patterns of age-related binding deficits in long-term memory, as shown in VWM, with a single study so far not showing such a pattern (Kilb & Naveh-Benjamin, 2007).

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