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The Role of Attention in Item-Item Binding in Visual Working Memory

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An important yet unresolved question regarding visual working memory (VWM) relates to whether or not binding processes within VWM require additional attentional resources compared with processing solely the individual components comprising these bindings. Previous findings indicate that binding of surface features (e.g., colored shapes) within VWM is not demanding of resources beyond what is required for single features. However, it is possible that other types of binding, such as the binding of complex, distinct items (e.g., faces and scenes), in VWM may require additional resources. In 3 experiments, we examined VWM item-item binding performance under no load, articulatory suppression, and backward counting using a modified change detection task. Binding performance declined to a greater extent than single-item performance under higher compared with lower levels of concurrent load. The findings from each of these experiments indicate that processing item-item bindings within VWM requires a greater amount of attentional resources compared with single items. These findings also highlight an important distinction between the role of attention in item-item binding within VWM and previous studies of long-term memory (LTM) where declines in single-item and binding test performance are similar under divided attention. The current findings provide novel evidence that the specific type of binding is an important determining factor regarding whether or not VWM binding processes require attention.

Keywords: visual working memory, binding processes, divided attention

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The integration of distinct visual features, or feature binding, is essential for the formation and storage of distinct object representations within visual short-term memory (VSTM) or visual working memory (VWM). Yet, the manner by which this process is carried out within the visual system remains somewhat elusive (i.e., the binding problem). *Feature Integration Theory* proposes that the deployment of visual attention to a given spatial location allows features occupying the same space to be bound into a coherent percept (Treisman & Gelade, 1980). In VWM tasks, upon brief presentation and subsequent removal of visual arrays composed of multiple "items" or "objects" in various locations, feature bindings comprising a given object (e.g., conjunction stimuli) must be maintained within VWM to differentiate which features belong to which object during the test phase (e.g., Baddeley, 2000; Luck & Vogel, 1997).

Given the proposed role of visual attention during the initial feature binding process, empirical interest has emerged focusing on the role of attention in VWM binding processes (Wheeler & Treisman, 2002). Of primary interest, does storing feature bindings in VWM require a greater proportion of capacity-limited attentional resources compared with storing only the single features comprising these bindings? It is important to distinguish between several distinct types of binding processes within VWM that may mediate the amount of attentional resources required to maintain feature bindings compared with single features. *Intra-item* binding refers to the binding of surface features from various stimulus dimensions (e.g., color, shape, orientation). In other words, the features being bound "belong" to the same item. It is important that encoding features (e.g., color, shape) belonging to the same part of an object tends to accompany higher levels of VWM performance (e.g., Delvenne & Bruyer, 2004; Xu, 2002). Moreover, features (e.g., color, shape) separated either spatially or temporally are remembered less accurately than those appearing in a unitized fashion within the same spatial location and appearing at the same point in time (Karlsen, Allen, Baddeley, & Hitch, 2010). However, even features that belong to different parts of the same object can be remembered with greater accuracy than features that must be encoded across spatially distinct objects (Xu, 2002). In contrast,

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item-context binding refers to the binding of a given item to an abstract feature (e.g., the spatial location occupied by a given item, the background color upon which an object is presented). As such, VWM binding of the intra-item, compared with the item-context, variety may comprise a more automatic form of binding (Ecker, Maybery, & Zimmer, 2013).

Previous investigations focusing on intra-item binding typically have found that VWM performance in tests of feature binding and single features are impaired to the same degree by concurrent attentional load imposed during VWM tasks (Allen, Baddeley, & Hitch, 2006, 2014; Allen, Hitch, Mate, & Baddeley, 2012; Gajewski & Brockmole, 2006; Johnson, Hollingworth, & Luck, 2008; van Lamsweerde & Beck, 2012; Vergauwe, Langerock, & Barrouillet, 2014; but see also Vul & Rich, 2010). Converging findings indicate that attention is required for VWM processes in general (Morey & Bieler, 2013). Indeed, Morey and Bieler (2013) found that VWM performance was diminished under concurrent load regardless of whether single features or feature bindings were probed at test. In the aforementioned studies, concurrent load has been manipulated using verbal (e.g., articulatory suppression [AS]), backward counting (BC), auditory (e.g., tone categorization), and visual (e.g., visual search) secondary tasks.

Other recent evidence suggests that when an attention-demanding multiple-object tracking task (three targets, nine distractors) is imposed during the delay period of a VWM task, performance during tests of feature binding (e.g., colored shapes) is reduced relative to the component features (e.g., color or shape; Fougnie & Marois, 2009). In addition, the probability of endorsing nontarget features at test (i.e., making feature misbinding errors) increases under increased attentional load (e.g., visual search task with a single letter target among five distractors during the delay period; Zokaei, Heider, & Husain, 2014). Other recent work suggests that single-features (e.g., color, shape) are encoded separately, such that incomplete encoding of the feature combinations from a fixed number of objects within a VWM array can occur. However, for the subset of objects from the array encoded into VWM (e.g., ~3), at least one feature per object (i.e., color or shape) is represented. It is important that directing attention at encoding to single-features of objects in the memory array results in higher capacity estimates compared with directing attention to both features of the objects within the array (Cowan, Blume, & Saults, 2013).

With respect to item-context (i.e., item-location, object-position) binding, increased attentional load has been shown to increase error rates in tests of binding performance. For instance, when working memory is preloaded with tones that must be retained over the course of a change detection task involving letter-location stimuli, performance decrements for these feature bindings are evident relative to the same task completed under no concurrent load (Elsley & Parmentier, 2009). In addition to the detrimental influences of divided attention on item-context binding, items within VWM memory arrays have been shown to compete for attention, with participants more likely to endorse nontarget features at test (e.g., misbinding errors) when spatially proximal, compared with more distal, items (e.g., colored squares) were originally presented (Emrich & Ferber, 2012). Finally, under AS, feature bindings (e.g., colored shapes), relative to single features, are impacted to a greater extent when the location of a single-probed item changes from study to test (Treisman & Zhang, 2006). In contrast, an emerging perspective suggests a more flexible VWM system given recent findings that shared location between features may be initially important for perceptual binding purposes, but that spatial location is not necessary for maintaining surface-feature (e.g., color, shape) bindings (Allen, Castellà, Ueno, Hitch, & Baddeley, 2015; Logie, Brockmole, & Jaswal, 2011; Saiki, 2016; Woodman, Vogel, & Luck, 2012).

While the role of attention in intra-item and item-context binding processes has been frequently examined in the VWM literature, empirical investigation of another important type of binding, item-item (or inter-item) binding, is lacking. Item-item binding refers to the formation of an associative link between distinct items and storage of this link within an integrated memory representation (e.g., word–word pairs, face–scene pairs, face–name pairs). Although previous studies have examined item–item binding in VWM, to our knowledge, none have examined the role of divided attention on item-item binding relative to single-item performance (e.g., face–house pairs: Piekema, Kessels, Rijpkema, & Fernández, 2009; Piekema, Rijpkema, Fernández, & Kessels, 2010). Item-item binding is often examined in the long-term episodic memory literature examining associative memory binding between distinct components (see Naveh-Benjamin, 2000; Old & Naveh-Benjamin, 2008). In a typical long-term associative memory experiment, study pairs (e.g., faces–scenes) are presented within a study phase, followed by an interpolated activity and a subsequent memory test phase. To assess item and associative memory performance separately, participants are tested on either the single items originally presented within the study pairs (e.g., old or completely new faces or scenes presented at test) or face–scene pairs presented, at test, either intact or recombined between face and scene components presented initially during the study phase.

It is interesting that storing item-item bindings (e.g., word–nonword pairs) across long-term memory (LTM) retention intervals does not require additional attentional resources compared with single-item components (Naveh-Benjamin, Guez, & Marom, 2003). For instance, when participants are required to perform item and associative memory tasks under divided attention during encoding (e.g., a continuous tone discrimination task) proportional declines in performance are evident during both item and associative memory tests compared with when the task is completed under full attention. Thus, memory for item components was reduced to the same degree as memory for item-item bindings, suggesting that no additional attentional resources, beyond that required for the item components, are required to form an associative link between item–item pairs (Naveh-Benjamin et al., 2003). However, the role of attention in item-item binding processes within VWM has yet to be examined.

Current Experiments

While the effects of divided attention on LTM for single items and item-item bindings are similar, it is possible that attention plays a different and more important role in the formation and maintenance of item-item bindings across shorter retention intervals. For instance, LTM paradigms typically involve the presentation of item–item pairs sequentially throughout the length of a study phase followed by separate item and associative test phases. In contrast, VWM paradigms require relatively brief presentation rates during which multiple, distinct item-item bindings must be encoded appropriately (i.e., Item A belongs with Item B, but not with Item C or Item D), stored briefly, and retrieved during the test phase of each trial. Thus, given the relatively quick pace at which the encoding, maintenance, and retrieval of item-item bindings must be accomplished, additional domain-general attention may be required to carry out these processes within VWM compared with LTM.

As such, the goal of the current experiments was to examine the role of domain-general attention in item-item binding processes within VWM. First, stimulus pairs typically used in the associative LTM literature (i.e., face–scene pairs) were employed to examine item-item binding in VWM. Second, a modified change detection task paradigm was used to Test VWM performance for both single-item components (i.e., faces, scenes) and item-item bindings (i.e., face–scene pairs). Third, in Experiments 1 and 2 an AS task was used to compare VWM performance for single-items and item-item bindings under both baseline (i.e., no load) and concurrent attentional load conditions. Finally, in Experiment 3, in order to further assess the role of domain-general attention, we measured single-item and item-item binding performance in this modified VWM change detection task under the concurrent AS task used in Experiments 1 and 2 compared with a more demanding concurrent task involving backward counting by two digits (BC-2).

Experiment 1

The predictions for Experiment 1 are straightforward. If item-item binding within VWM requires additional attentional resources beyond what is required to process the single-item components comprising these bindings, disproportional declines in item-item binding performance compared to single-item performance should be evident when an AS task, compared with when no load, is imposed during the VWM change detection task. In contrast, if item-item binding processes within VWM are not resource demanding, equivalent declines in performance under AS, compared with no load, are expected when single-items and item-item bindings are tested.

Method

Participants. Participants were 55 undergraduates (ages: 18–23, 35 women) from the University of Missouri who participated in exchange for course-related credit (Table 1).The institutional review board at the University of Missouri approved all experimental protocols. 10 participants were excluded from subsequent group-level analyses because of performance at or below chance-level (i.e., hits minus false alarms values of ≤0) in one or more of the test conditions performed under no load, leaving 45 participants total.

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

Experiment	*N*	Proportion (female)	Age (years)	Education (years)
1	55	.64	18.70 (1.19)	12.70 (1.17)
2	33	.70	19.00 (1.06)	12.55 (.91)
3	38	.79	18.46 (.93)	12.61 (.95)

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

Stimuli and materials. Images of younger and older adult faces (male and female) from the previously normed FACES database were used as face component stimuli (Ebner, Riediger, & Lindenberger, 2010). Scenes consisted of natural images of mountain and forest scenes void of people or faces. The experimental parameters were controlled electronically using E-Prime 2.0 software (Schneider, Eschmann, & Zuccolotto, 2002). E-Prime 2.0 was run via a Dell Optiplex 755 desktop computer and the stimuli were presented on a 20-in 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 single-probe working memory change detection task either under no concurrent load or while under AS. During each trial, participants first saw a prompt indicating whether the concurrent task was to be performed during the encoding phase and delay period of the trial. During each trial in half 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 the other half of the blocks, participants viewed a "Start Repeating Number" prompt (e.g., "Start Repeating 79") prior to the onset of the presentation of the fixation cross and encoding phase. Participants were instructed to start repeating the two-digit number (with a new number randomly selected from the range of 33–99 for each trial) aloud that was presented at the center of the screen until they were presented with a "Stop Repeating" prompt immediately after the delay period indicating that they should stop repeating the word (Figure 1).

Following the concurrent task prompt a fixation cross (0.60° × 0.60°), presented at the center of the screen (500 ms), preceded the encoding phase. Participants were instructed to maintain fixation and try to remember the faces, the scenes, and the binding between the faces and scenes and were told they would be tested on this information after a brief delay. For a given participant, eight (four younger adult, four older adult) faces and eight scenes (four mountain, four forest) were sampled (with replacement between experimental trials) from a larger set of 68 faces and 68 scenes from each subcategory (e.g., younger male faces, mountains). On a given trial, the two faces presented during the encoding phase belonged to the same age and gender category (e.g., both younger males) to avoid the ability to reject recombined pairs based solely on categorical familiarity with the facial feature of age or gender. During the encoding phase, two face–scene pairs (faces: 5.5° × 6.5°; scenes: 5.5° × 6.5°) were presented (2,000 ms) simultaneously in one of four quadrants of the computer screen (pseudorandomly determined from trial-to-trial with the constraint that one face–scene pair appear left of central fixation and the other right of central fixation in either the upper or lower portion of the screen; Figure 1). A blank delay period (1,000 ms) immediately followed the encoding phase. After the delay period, depending on the concurrent task block, either the "Get Ready" or "Stop Repeating" prompt was presented (500 ms).

Finally, depending on the type of test trial: face only, scene only, or face–scene pair (i.e., binding), a single face (left of screen center), a single scene (right of screen center), or a face–scene pair was presented as the test probe stimulus. In the face test trials, one of the two faces originally presented during the encoding phase or a new face sampled from the remaining faces from the set chosen for a given participant was presented. During the test phase of each

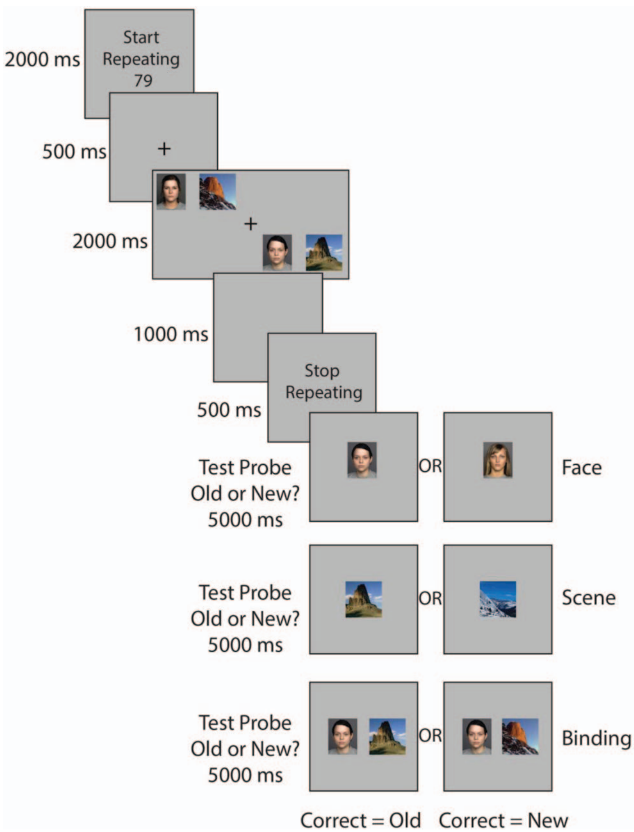

Figure 1. Experiment 1 paradigm, trial sequence, memory array during the encoding phase, and test probe configurations. Participants viewed a secondary task prompt (2,000 ms) and then viewed a fixation cross (500 ms). Following fixation, the sample array, including two face-scene pairs appeared (2,000 ms). After a delay period (1,000 ms), a test probe appeared that was either the same as one of the faces, scenes, or face-scene pairs ("old" trials) that was originally presented or was a different face, scene, or face-scene pair recombined between one face and one scene previously presented during the sample array ("new" trials). Participants were given 5 s to respond. In Experiment 2, the same paradigm was used except that one face–scene pair appeared directly above, while the other face–scene pair appeared directly below, central fixation during the sample array for 3,000 ms instead of 2,000 ms. In Experiment 3, participants performed the same task used in Experiment 2, with the exception that they either repeated a number (AS) or counted backward by two digits (BC-2) during the fixation period, encoding phase, and maintenance phase of each trial. Note that stimuli are depicted for illustrative purposes only and do not reflect the exact dimensions of the stimuli displayed during the actual experiments. See the online article for the color version of this figure.

face probe trial, participants had to indicate whether or not a face change had occurred. In the scene trials, a single scene was presented that either matched one of the two scenes presented previously during the encoding phase or was a new scene sampled from the remaining set of scenes not presented during the encoding phase. Finally, in the binding test trials, the test probe was either an intact face–scene pair (i.e., old) or was a recombination (i.e., new) of face and scene from the two face–scene pairs presented previously during the encoding phase. Test probe trial types were randomly intermixed within a block of trials.

During all test phases in all blocks of the experiment, participants were required to press the "o" key (labeled "old") if no change had occurred or the "n" key (labeled "new") within 5 seconds after the onset of the probe stimulus, if a change had occurred. If the response time elapsed, the trial was considered incorrect and the program advanced to the next trial (minimum intertrial interval: 1,000 ms). 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 two blocks with 30 trials per block (60 total). Half of the participants viewed male younger and older adult faces while the other half viewed younger and older adult female faces. All faces from each gender and age category were used at least once with a given participant viewing memory arrays created by sampling (with replacement across trials) from a set of eight faces (four younger, four older) and eight scenes (four mountain, four forest). In one of the blocks participants performed no concurrent task while in the other block, they were required to perform the concurrent AS task described above. Concurrent task block order (i.e., first, second) was counterbalanced across participants. Prior to beginning the actual experiment, participants completed 12 practice trials to familiarize them with the task and each type of test.

Results

We measured response accuracy by computing the proportion of hits and the proportion of false alarms and then subtracted the proportion of false alarms from the proportion of hits (i.e., proportion hits minus false alarms) in each experimental condition for each participant. In addition, 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 (using the formulas provided by Stanislaw & Todorov, 1999). As indicated in Table 2, the patterns of the results provided by the different accuracy measures converged (see Table 2 for group means and standard deviations).

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 employed (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., 2006, 2012), and to follow previous methodological recommendations advocating the use of the A' measure (Donaldson, 1993), we report statistical analyses related to the A' values (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' measures (see Table 2 for means and *SD*s).

The A' values were submitted to a 2 × 3 repeated-measures analysis of variance (ANOVA) including the within-subjects factors of load (no load, AS) and test (face, scene, face-scene binding). There was a main effect of concurrent load, $F(1,44) = 11.61$, $p = .001$, $\eta_p^2 = .21$, indicating that performance was significantly higher ($M = .88$, $SD = .04$) during the no load block compared with the AS block of the experiment ($M = .84$, $SD = .07$). There was a significant main effect of test type, $F(2,88) = 16.78$, $p < .001$, $\eta_p^2 = .28$. Pairwise comparisons indicated that performance

Table 2
Experiments 1, 2 (No Load, Articulatory Suppression [AS]), and 3 (AS, Backward Counting by Two Digits [BC-2]) Measures of Mean (SD) Response Accuracy

	Experiment: 1 and 2: No Load 3: AS			Experiment: 1 and 2: AS 3: BC-2		
Variable	Face	Scene	Binding	Face	Scene	Binding
Hits						
Experiment 1	.87 (.07)	.81 (.13)	.84 (.10)	.84 (.14)	.81 (.10)	.81 (.11)
Experiment 2	.92 (.03)	.90 (.07)	.86 (.13)	.92 (.05)	.85 (.13)	.81 (.13)
Experiment 3	.90 (.07)	.85 (.11)	.83 (.12)	.84 (.14)	.65 (.17)	.72 (.18)
False alarms						
Experiment 1	.20 (.13)	.21 (.13)	.28 (.18)	.23 (.17)	.20 (.13)	.43 (.23)
Experiment 2	.13 (.10)	.11 (.09)	.27 (.16)	.16 (.12)	.14 (.11)	.41 (.23)
Experiment 3	.23 (.17)	.14 (.13)	.36 (.22)	.30 (.23)	.21 (.19)	.56 (.22)
Hits minus false alarms						
Experiment 1	.67 (.15)	.60 (.17)	.56 (.19)	.62 (.21)	.62 (.19)	.38 (.27)
Experiment 2	.79 (.11)	.79 (.11)	.59 (.22)	.76 (.14)	.71 (.15)	.40 (.26)
Experiment 3	.67 (.18)	.71 (.16)	.47 (.21)	.54 (.21)	.44 (.23)	.16 (.23)
A′						
Experiment 1	.90 (.06)	.87 (.07)	.86 (.08)	.88 (.09)	.88 (.06)	.76 (.17)
Experiment 2	.94 (.03)	.94 (.03)	.88 (.08)	.94 (.03)	.92 (.06)	.78 (.15)
Experiment 3	.90 (.06)	.91 (.07)	.83 (.09)	.85 (.08)	.80 (.13)	.62 (.17)
d′						
Experiment 1	2.08 (.50)	1.81 (.57)	1.69 (.61)	1.91 (.66)	1.87 (.62)	1.16 (.83)
Experiment 2	2.67 (.46)	2.69 (.52)	1.96 (.64)	2.63 (.49)	2.35 (.61)	1.29 (.83)
Experiment 3	2.20 (.66)	2.33 (.60)	1.48 (.64)	1.78 (.70)	1.41 (.79)	.51 (.73)

was significantly higher when the face component (M = .89, SD = .07; $p < .001$) or the scene component (M = .87, SD = .05; $p < .001$) in isolation was tested compared with the face-scene binding condition (M = .81, SD = .10). There was no significant difference in performance between the face and scene test conditions (p = .21). It is important that the interaction between load and test type was significant, $F(2, 88) = 7.24$, $p = .003$, $\eta_p^2 = .14$. Given that there was no overall significant difference in performance between the face and scene test conditions, we averaged the A' values for these two conditions into a single "item" condition prior to conducting follow-up analyses pertaining to the interaction between load and test.

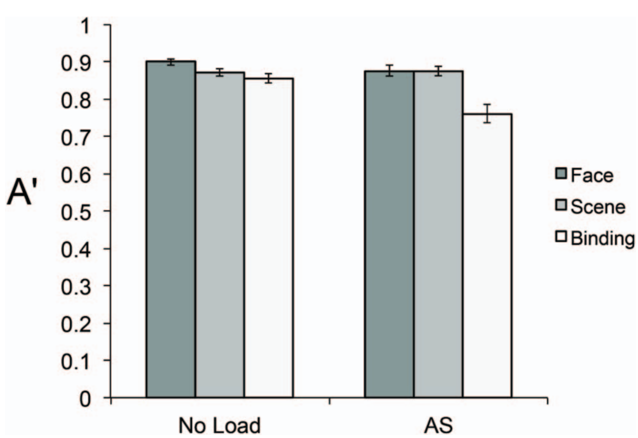

Figure 2. Behavioral results for Experiment 1 test types (face, scene, face–scene binding). The abscissa depicts performance in each test type corresponding to the no load and articulatory suppression (AS) blocks of the experiment, while the mean *A′* value corresponding to each condition is plotted along the ordinate. Error bars represent the *SEM* in each test condition. See the online article for the color version of this figure.

The follow-up paired samples t test comparing item (M = .89, SD = .05) and binding (M = .86, SD = .08) test performance under no load was significant, $t(44) = 2.35$, $p = .02$. In addition, the paired samples t test comparing item (M = .88, SD = .07) and binding (M = .76, SD = .17) test performance under AS revealed that this difference in performance between tests of item and binding was significant, $t(44) = 4.41$, $p < .001$. Difference scores (item minus binding performance) were computed in order to examine the relative difference in performance between the item test condition and binding test condition under both no load and AS conditions. Importantly, the average decline from item to binding test performance was significantly larger under AS (M = .12, SD = .18) compared with no load (M = .03, SD = .09), $t(44) = 3.03$, $p = .004$.

Finally, we computed the average number repetitions articulated during the AS block of the experiment throughout the encoding phase and maintenance period during each type of test trial. There was no significant difference in the number repetitions between the face (M = 6.22, SD = 1.54), scene (M = 6.33, SD = 1.59), and binding (M = 6.29, SD = 1.55) test conditions, $F(2, 88) = 2.61$, $p = .08$.

Discussion

The results of the current experiment indicate that dividing attention between a primary VWM change detection task and a secondary AS task leads to greater memory declines in item-item binding relative to single-item performance in comparison to performance under full attention (i.e., no load). Importantly, the difference between single-item and item-item binding performance under AS was significantly larger than when under no load, suggesting that larger amounts of attentional resources are needed when forming and storing item-item bindings compared with single-item representations within VWM. These novel findings suggest that item-item binding processes within VWM are reliant on attention, given the disproportionate decline in binding relative single-item performance when resources were diverted from the primary change detection task under AS. Given the novelty of these results, replication of these findings with a different sample of participants is an important next step.

Experiment 2

The primary goal of Experiment 2 was to replicate the findings of Experiment 1 while holding constant the spatial locations within the memory array, to rule out any influences on VWM performance due strictly to differences in the distribution of spatial attention at encoding across the different trial types (e.g., face, scene, binding), in which the face–scene pairs appeared. In addition, we doubled the number of trials in both the no load and AS blocks (i.e., 60 per block). Finally, to assess the robustness of the results of Experiment 1, the duration of the encoding phase was increased from 2 to 3 s.

Method

Participants. A different group of 33 undergraduates (ages: 18–22, 23 women) from the University of Missouri participated in Experiment 2 in exchange for course-related credit (see Table 1 for demographic information). The institutional review board at the University of Missouri approved all experimental protocols. Only one of the participants from Experiment 2 met the exclusion criteria established for Experiment 1 and, thus, data from the remaining 32 participants were included in the group-level analyses.

Stimuli and materials. The face and scene stimuli were identical to those used in Experiment 1. Again, eight face (four younger, four older) and eight scene (four mountain, four forest) stimuli were sampled with replacement across the trials of a given block. Half of the participants viewed male faces while the other half viewed female faces.

Procedure. The procedure of Experiment 2 was identical to that of Experiment 1 with the following exceptions. First, instead of the face–scene pairs appearing in two of the four quadrants of the screen during the encoding phase, the spatial locations of the face–scene pairs were held constant across all trials of the experiment. One face–scene pair appeared above central fixation (face on the left, scene on the right) while the other appeared below fixation (face on the left, scene on the right). The same left-of-center (i.e., face tests) and right-of-center (i.e., scene tests) or both (i.e., face-scene binding tests) test probe locations used in Experiment 1 were again used in Experiment 2. Second, a longer encoding phase was used (3,000 ms) to examine whether the pattern of results observed in Experiment 1 differed as a function of stimulus presentation duration. Finally, participants completed 60 trials of the VWM change detection task under no load and 60 trials under AS. There were four blocks total with 30 trials per block for a total of 120 trials. Presentation order of the concurrent load manipulation was counterbalanced across participants (i.e., half of the participants completed the no load blocks first and the other half completed the AS blocks first).

Results

As in Experiment 1, we computed the proportion of hits and proportion of false alarms, as well as A' and d' values corresponding to VWM performance during each condition for each participant (Table 2), and report statistical analyses based on the A' values (Figure 3). The A' values were submitted to a 2 × 3 repeated-measures ANOVA including the within-subjects factors of load (no load, AS) and test (face, scene, face-scene binding). 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' measures (see Table 2 for means and *SD*s).

There was a main effect of concurrent load, $F(1,31) = 15.20$, $p < .001$, $\eta_p^2 = .33$, indicating that performance was significantly higher ($M = .92$, $SD = .03$) during the no load block compared with the AS block of the experiment ($M = .88$, $SD = .06$). There was a significant main effect of test type, $F(2,62) = 49.80$, $p < .001$, $\eta_p^2 = .62$. Pairwise comparisons indicated that performance was significantly higher when the face component ($M = .94$, $SD = .02$; $p < .001$) or the scene component ($M = .93$, $SD = .03$; $p < .001$) in isolation was tested compared with the face-scene binding condition ($M = .83$, $SD = .08$). There was no significant difference in performance between the face and scene test conditions ($p = .10$). It is important that the interaction between load and test type was significant, $F(2, 62) = 6.56$, $p = .008$, $\eta_p^2 = .18$. Given that there was no overall significant difference in performance between the face and scene test conditions, we averaged the A' values for these two conditions into a single "item" condition prior to conducting follow-up analyses pertaining to the interaction between the factors of load and test.

The follow-up paired samples *t* test comparing item ($M = .94$, $SD = .02$) and binding ($M = .88$, $SD = .08$) test performance under no load was significant, $t(31) = 4.52$, $p < .001$. In addition, the paired samples *t* test comparing item ($M = .93$, $SD = .03$) and binding ($M = .78$, $SD = .15$) test performance under AS revealed a significant difference, $t(31) = 5.69$, $p < .001$. Difference scores

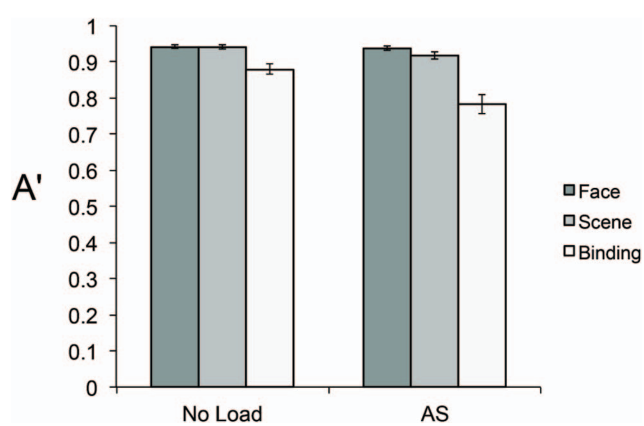

Figure 3. Behavioral results for Experiment 2 test types (face, scene, face–scene binding). The abscissa depicts performance in each test type corresponding to the no load and articulatory suppression (AS) blocks of the experiment while the mean A' value corresponding to each condition is plotted along the ordinate. Error bars represent the *SEM* in each test condition. See the online article for the color version of this figure.

(item minus binding performance) were computed in order to examine the relative difference in performance between the item test condition and binding test condition under both no load and AS conditions. Importantly, the average decline from item to binding test performance was significantly larger under AS (M = .14, SD = .14) compared with no load (M = .06, SD = .08), $t(31) = 2.71$, $p = .01$.

Finally, we computed the average amount of number repetitions articulated during the AS block of the experiment throughout the encoding phase and maintenance period during each type of test trial. There was no significant difference in the number of correct articulations made during the face (M = 6.23, SD = 1.25), scene (M = 6.26, SD = 1.27), and binding (M = 6.27, SD = 1.25) test conditions, $F(2,62) = 0.77$, $p = .45$.

Discussion

The results of the current experiment provide a constructive replication of the findings observed in Experiment 1 indicating that a larger amount of attentional resources are required for the processing of item-item bindings compared with single-items within VWM. Following the pattern of results observed in Experiment 1, in the current experiment the difference in performance between tests of item memory and binding memory was significantly larger under AS compared with no load. Overall, the findings from Experiment 1 and the current experiment suggest that item-item binding processes within VWM are reliant on attention to a greater extent than those processes involved in the encoding and maintenance of single items.

Despite the consistent pattern of results observed in both Experiment 1 and the current experiment, an important issue regarding the mechanism mediating this selective reduction in item-item binding performance under concurrent load remains potentially unresolved. For instance, it is possible that AS concurrent to the VWM change detection task simply prevents verbal recoding of the stimulus array, rather than exhausting domain-general attention. Given that a concurrent AS task is often used in the VWM binding literature as a low load control condition in comparison to higher load conditions (e.g., backward counting), a direct comparison of the influence of low and high levels of concurrent load on single-item and item-item binding performance is necessary.

Experiment 3

Experiment 3 directly compared single-item and item-item binding performance under conditions of AS and backward counting by two digits (BC-2) concurrent to the VWM change detection task used in Experiment 2. Backward counting tasks have been used previously in the literature to examine the role of attention in VWM binding processes (e.g., Allen et al., 2006, 2012). Two distinct predictions follow based on the results of Experiments 1 and 2 and previous findings from the literature. If performance under BC-2 compared with under AS is reduced in the item-item binding condition to a greater extent than the single-item conditions, domain-general attention seems a plausible mechanism underlying binding related performance decrements. As such, an interaction between test condition (e.g., item, binding) and concurrent load (e.g., AS, BC-2) is expected, driven by a greater difference between item and binding performance under BC-2 compared with AS. As an alternative, it may be the case that the pattern of results observed in both Experiment 1 and 2 was attributable solely to the prevention of verbal recoding under AS. In this case, an overall reduction in both single-item and item-item binding performance under BC-2 relative to AS would be expected. Overall, a main effect of higher (e.g., BC-2) compared with lower (e.g., AS) levels of concurrent load on VWM performance, along with an accompanying lack of an interaction between test type and concurrent load, would support the notion that AS simply reduced binding performance to a greater degree than item performance in Experiments 1 and 2 by preventing verbal recoding rather than exhausting domain-general attention, per se.

Method

Patricipants. A new group of 38 undergraduates (ages: 18–21, 30 women) from the University of Missouri participated in Experiment 3 in exchange for course-related credit (see Table 1 for demographic information). The institutional review board at the University of Missouri approved all experimental protocols. Seven participants from Experiment 3 met the exclusion criteria established for Experiment 1 and 2 (see Methods section of Experiment 1), thus, data from 31 participants were included in the group-level analyses.

Stimuli and materials. The face and scene stimuli were identical to those used in Experiments 1 and 2. Again, eight face (four younger, four older) and eight scene (four mountain, four forest) stimuli were sampled with replacement across the trials of a given block. Half of the participants viewed male faces while the other half viewed female faces.

Procedure. The procedure of Experiment 3 was identical to that of Experiment 2 with the exception that participants completed 60 trials of the VWM change detection task under AS (e.g., “79, 79, 79”) and 60 trials under BC-2 (e.g., “79, 77, 75”). In both the AS and BC-2 blocks of Experiment 3, at the start of a given trial a two-digit number ranging from 33–99 was randomly selected and appeared on the computer screen for 2,000 ms (with a new number randomly selected from this range for each trial) immediately preceding the fixation cross. During the AS blocks of trials, participants were required to repeat this number, aloud, during the fixation, encoding, and maintenance periods of the trial, stopping prior to the onset of the test probe stimuli. During the BC-2 blocks, participants were required to count backward by two digits, aloud, during the fixation, encoding, and maintenance periods of the trial, stopping prior to the onset of the test probe stimuli.

Results

As in Experiments 1 and 2, we computed the proportion of hits and proportion of false alarms and computed A' and d' values corresponding to VWM performance during each condition for each participant (Table 2), and report statistical analyses based on the A' values (Figure 4). The A' values were submitted to a 2×3 repeated-measures ANOVA, including the within-subjects factors of load (AS, BC-2) and test (face, scene, face-scene binding). 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' measures (see Table 2 for means and SDs).

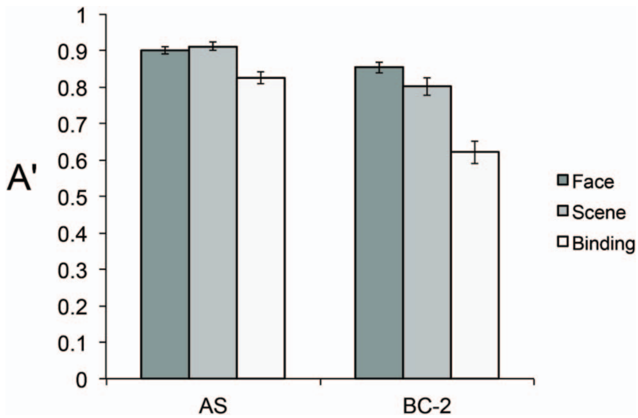

Figure 4. Behavioral results for Experiment 3 test types (face, scene, face–scene binding). The abscissa depicts performance in each test type corresponding to the articulatory suppression (AS) and backward counting by two digits (BC-2) blocks of the experiment while the mean A' value corresponding to each condition 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.

There was a main effect of concurrent load, $F(1,30) = 45.33$, $p < .001$, $\eta_p^2 = .60$, indicating that performance was significantly higher ($M = .88$, $SD = .04$) during the AS block compared with the BC-2 block of the experiment ($M = .76$, $SD = .10$). There was a significant main effect of test type, $F(2,60) = 40.63$, $p < .001$, $\eta_p^2 = .58$. Pairwise comparisons indicated that performance was significantly higher when the face component ($M = .88$, $SD = .06$; $p < .001$) or the scene component ($M = .86$, $SD = .09$; $p < .001$) in isolation was tested compared with the face-scene binding condition ($M = .72$, $SD = .10$). There was no significant difference in performance between the face and scene test conditions ($p = .23$). It is important that the interaction between load and test type was significant, $F(2, 60) = 15.93$, $p < .001$, $\eta_p^2 = .35$. Given that there was no overall significant difference in performance between the face and scene test conditions, we averaged the A' values for these two conditions into a single "item" condition prior to conducting follow-up analyses pertaining to the interaction between load and test.

The follow-up paired samples *t* test comparing item ($M = .91$, $SD = .04$) and binding ($M = .83$, $SD = .09$) test performance under AS was significant, $t(30) = 5.29$, $p < .001$. In addition, the paired samples *t* test comparing item ($M = .83$, $SD = .09$) and binding ($M = .62$, $SD = .17$) test performance under BC-2 revealed a significant difference in performance between tests of item and binding, $t(30) = 7.41$, $p < .001$. Difference scores (item minus binding performance) were computed in order to examine the relative difference in performance between the item test condition and binding test condition under both no load and AS conditions. Importantly, the average decline from item to binding test performance was significantly larger under BC-2 ($M = .21$, $SD = .15$) compared with AS ($M = .08$, $SD = .09$), $t(30) = 4.24$, $p < .001$.

Finally, we computed the average amount of successful number repetitions articulated during the AS block and successful counts made during the BC-2 block of the experiment throughout the encoding phase and maintenance period during each type of test trial. There was a main effect of load, $F(1,30) = 38.76$, $p < .001$, $\eta_p^2 = .56$, indicating that a greater amount of successful number repetitions ($M = 5.98$, $SD = 1.38$), were made during the AS blocks compared with successful backward counts ($M = 4.62$, $SD = 0.80$) during the BC-2 blocks. There was no significant main effect of test type indicating that, overall, secondary task performance (i.e., repeating, counting) did not vary across the face ($M = 5.296$, $SD = 0.95$), scene ($M = 5.298$, $SD = 0.96$), and binding ($M = 5.302$, $SD = 0.96$) test conditions, $F(2,60) = .03$, $p = .97$. It is important that there was no significant interaction between secondary task performance (i.e., AS, BC-2) and test condition, $F(2, 60) = .31$, $p = .73$, indicating that secondary task performance was consistent across all test conditions.

Discussion

In the current experiment, VWM performance for faces, scenes, and face-scene bindings was compared under both low (i.e., AS) and high (i.e., BC-2) levels of concurrent load. Significant declines in memory performance were evident when participants were required to complete a BC-2 task relative to an AS task during the encoding and maintenance phase of trials ultimately requiring the retrieval of face-scene bindings, compared with the retrieval of faces or scenes in isolation, from VWM. These results replicate and extend the patterns observed in Experiments 1 and 2. Moreover, the same overall pattern of results evident in Experiments 1 and 2 was observed in the current experiment when examining single-item and item-item binding performance under both a low-attention control (e.g., AS) and a high-attention condition (e.g., BC-2). Collectively, the findings from all 3 experiments suggest that item-item binding processes within VWM are reliant on domain-general attention to a greater extent than those processes involved in the encoding and maintenance of single items.

General Discussion

The focus of the current experiments was to examine the role of attention in item-item binding processes within VWM. In Experiment 1 the difference in single-item and binding performance was larger under AS compared with no load indicating a relatively greater impairment to item–item binding processes while dividing attention between a primary VWM change detection task and a secondary AS task. The findings from Experiment 2, in which the spatial locations of the stimuli were held constant, replicated the overall findings from Experiment 1 indicating that binding performance was impoverished under AS compared with no load to a greater extent than single item performance. The results from Experiment 3 replicated the patterns observed in Experiments 1 and 2 comparing both lower (i.e., AS) and higher (i.e., BC-2) levels of concurrent load. Overall, the current experiments suggest that binding and maintaining the associative link between distinct items (i.e., face–scene pairs) within VWM requires a greater amount of domain-general attentional resources relative to that required for item components (i.e., faces, scenes).

Notably, an AS task was used in the current experiments as a load manipulation concurrent to the primary VWM change detection task. Typically, AS tasks are used solely to control for potential influences of verbal WM processes during VWM experiments rather than as a load manipulation, per se. However, the current results (Experiments 1 and 2) indicate that even an AS-based manipulation of concurrent load was sufficient to observe different effects of divided attention on single-item and item-item binding performance in VWM. It is important to note that the same pattern of a selective reduction in item-item binding, relative to single-item, performance was observed when comparing both forms of VWM performance under BC-2 compared with AS. This pattern of results observed in Experiment 3 suggests that the selective reduction in item-item binding performance observed in both Experiment 1 and Experiment 2 could have been because of differential prevention of verbal recoding during tests of binding compared with single-items, to a reduction in domain-general attentional resources available to support binding under concurrent load, or to both. In either case, Experiment 3 suggests that a decline in domain-general attention appears to be a plausible mechanism underlying the robust pattern of a selective reduction in item-item binding performance under concurrent load, which was observed across all three experiments. As such, other attention demanding secondary tasks (e.g., visual search, tone discrimination) performed concurrent to VWM change detection tasks are also likely to produce selective reductions in item-item binding performance.

The current findings seem to contrast with several existing findings from the literature, which tend to indicate similar declines in performance under concurrent load regardless of whether single-features or feature bindings are probed at test. For instance, many of the previous experiments that have examined intra-item binding (e.g., colored shapes) have found no differential impact of concurrent load on binding, relative to single-feature, performance in VWM tasks (Allen et al., 2006, 2012, 2014; Brown & Brockmole, 2010; Gajewski & Brockmole, 2006; Johnson et al., 2008; Morey & Bieler, 2013; van Lamsweerde & Beck, 2012; Vergauwe et al., 2014).

It is important to note that the current experiments examined item-item and not intra-item binding. This may suggest that certain types of binding processes within VWM draw more heavily upon central executive resources, perhaps initially stored via an episodic buffer mechanism, to a greater degree than the constituent components comprising these bindings (see Baddeley, 2000). For instance, the type of intra-item binding frequently examined in the VWM literature may represent a relatively more automatic binding process, potentially carried out by the visuospatial component of working memory without the need to draw upon central executive resources (Allen et al., 2006). In contrast, the type of item-item binding examined in the current experiments may require central executive resources (e.g., domain-general attention) given the use of relatively complex, spatially distinct components (e.g., faces and scenes, which are both comprised of many features). In line with this perspective, previous evidence supports the notion that VWM binding performance is highest when features belong to the same (i.e., intrinsic) object rather than when features belong to different (i.e., extrinsic) objects (Xu, 2002). Furthermore, in a previous study by Karlsen and colleagues (2010), VWM binding performance was better for intrinsic compared extrinsic stimuli. Intriguingly, although these previous studies did not directly examine the role of attention, intrinsic binding processes seem to occur in an automatic fashion in contrast to the relatively more demanding extrinsic forms of binding (i.e., which may require attention). Future studies directly examining the role of attention in VWM binding are necessary to further elucidate whether putative "intrinsic" forms of item-item binding (e.g., a face occurring within a scene) entail higher levels of performance than the distinct, relatively "extrinsic" form of item-item binding examined in the current work.

In addition to diverging from previous findings within the VWM binding literature, the current findings contrast with previous findings regarding the role of attention in associative LTM. For instance, previous findings examining the impact of concurrent load on item-item binding within LTM indicate that single-item and item-item binding performance decline to the same degree under divided attention relative to full attention (e.g., Kilb & Naveh-Benjamin, 2007; Naveh-Benjamin et al., 2003). One potential explanation for these diverging patterns relates to differences in forgetting rates for item compared with associative memory as a function of retention interval. For example, in continuous recognition paradigms involving tests of both single items and item-item associations occurring after variable retention intervals, performance is much higher in item compared with associative tests at shorter compared with longer retention intervals (Hockley, 1992). Although somewhat surprising, steeper forgetting rates observed during tests of item relative to associative memory indicate that initially large differences between item and associative memory during shorter retention intervals are markedly reduced at longer retention intervals. Overall, it appears that potentially distinct consolidation mechanisms within item and associative memory may partially explain why dividing attention during VWM tasks (e.g., as in the current experiments), but not LTM tasks, (e.g., as in Kilb & Naveh-Benjamin, 2007; Naveh-Benjamin et al., 2003), impacts item-item binding performance to a greater extent than single-item performance.

A second potential explanation for distinctions between the role of attention in VWM and LTM binding processes relates to the presentation rate during the initial encoding (i.e., study) phase preceding item and associative memory tests. For instance, in associative LTM paradigms, shorter presentation rates (e.g., 1.5 seconds) during encoding phases lead to significantly lower associative compared with item memory performance, while longer presentation rates (e.g., 6 seconds) result in similar levels of item and associative memory performance after a 1-min retention interval (Brubaker & Naveh-Benjamin, 2014). In the current work, relatively short presentation rates during the encoding phase (e.g., Experiment 1: 2 seconds, Experiments 2 & 3: 3 seconds) were used, whereas the rate used by Naveh-Benjamin and colleagues (2003) was much longer (e.g., 7 seconds). The relatively long presentation rates in LTM paradigms potentially provide participants enough opportunities to process the binding information to a reasonable degree even under divided attention, which is presumably difficult to accomplish during the brief presentation rates used in VWM paradigms. Notably, although previous studies examining the role of attention in VWM binding processes have typically also used relatively short presentation rates and retention intervals, considerable differences exist regarding the type of binding under examination (i.e., current: item-item; previous: intra-item; Allen et al., 2006, 2012, 2014; Brown & Brockmole, 2010; Gajewski & Brockmole, 2006; Johnson et al., 2008; Morey & Bieler, 2013; van Lamsweerde & Beck, 2012; Vergauwe et al., 2014), with the binding of more complex items, as examined in the current experiments, being especially affected by the short presentation rate.

Finally, a third set of potential explanations for the divergent pattern of results observed in the current experiments relates to both the number of items (i.e., set size) and complexity of the stimulus materials used. Regarding the number of items, in the current experiments two face–scene pairs (i.e., four items) were presented simultaneously during each encoding phase, whereas single item–item pairs (i.e., two items) are typically presented sequentially in associative LTM paradigms. From a methodological perspective, the simultaneous presentation of at least two item–item pairs is necessary in VWM change detection task paradigms in order to present both intact (i.e., no change) and recombined (i.e., change) trials during tests of item-item binding. In contrast, the use of only one pair at a time in LTM paradigms is because of the fact that the presentation of each pair occurs sequentially such that both intact and recombined test pairs can be created from single consecutive pairs. Beyond these methodological considerations, it is interesting to note that recent preliminary findings from our laboratory, using a continuous recognition task paradigm in which memory tests occur after both WM/STM and LTM intervals, indicate that the effects of divided attention, observed during WM/STM intervals, emerge even when only one pair is presented at a time. This preliminary pattern of results suggests that the consistent effect observed in the current work, and the absence of this effect noted in previous LTM studies, is likely not due solely to the number of pairs presented during the study phase.

With respect to stimulus complexity, VWM paradigms typically involve the presentation of color-shape conjunctions, relatively simpler than the distinct faces and scenes used in the current study. Notably, two contrasting perspectives have emerged within the VWM literature regarding the influence of stimulus complexity on capacity limitations. First, some evidence indicates that fewer items can be stored within VWM when the items are complex (e.g., random polygons) compared with when the items are simple (e.g., colored squares, Alvarez & Cavanagh, 2004; Eng, Chen, & Jiang, 2005). Moreover, in event-related potential (ERP) studies measuring contralateral delay activity (CDA) over posterior scalp sites during the maintenance period of a VWM change detection task, the amplitude of the CDA asymptotes at smaller set sizes when stimuli are complex (e.g., random polygons) compared with when the items are relatively simple (e.g., colored squares; Allon, Balaban, & Luria, 2014; Gao, Li, Liang, Chen, Yin, & Shen, 2009; Luria, Sessa, Gotler, Jolicoeur, & Dell'Acqua, 2010). In contrast, other findings suggest that higher levels of perceptual similarity between more complex relative to simpler items at the time of retrieval leads to an increase in comparison errors at test (Awh, Barton, & Vogel, 2007; Jackson, Linden, Roberts, Kriegeskorte, & Haenschel, 2015). These and other related findings suggest that the overall number of items to-be-remembered (i.e., set size), rather than the complexity inherent within those items, constrains capacity limits within VWM (e.g., Balaban & Luria, 2015).

In the context of the current work, attentional resources may become more important in supplementing VWM binding processes as capacity limits are approached. Moreover, although distinct face and scene stimuli may be inherently more complex than colored shapes, the perceptual similarity between the face and scene subcategories used within a given trial (e.g., two young male faces, two mountain scenes) may have increased comparison error rates at the time of retrieval when the item components were recombined during tests of item-item binding. Overall, the current findings suggest that attention does indeed play a crucial role in the facilitation of VWM binding processes when (a) presentation rates are short, (b) retention intervals are short, and (c) item-item binding of distinct components is required.

Intriguingly, the current results showing declines in VWM binding performance in younger adults under AS resemble patterns observed in recent studies examining VWM binding processes under full attention in both younger and older adults. Although several VWM and aging studies have found no evidence of an age-related binding deficit when using tasks that require memory for feature conjunctions (i.e., color and shape) compared with single features (i.e., color or shape), overall, this pattern of findings remains somewhat unclear (Brockmole, Parra, Della Sala, & Logie, 2008; Brown & Brockmole, 2010; Parra, Abrahams, Logie, & Sala, 2009; Read, Rogers, & Wilson, 2016; Rhodes, Parra, & Logie, 2016).

For example, other recent findings suggest that examining younger and older adults' VWM performance under both baseline (i.e., no load) and AS conditions is an important factor to consider when examining age-related binding deficits (Peterson & Naveh-Benjamin, 2016). In particular, under no load, younger adults outperform older adults in tests of color-shape binding, while performance in tests of single-features remains similar regardless of age. However, under AS, no differential age-related binding deficit was present, wherein both younger and older adults' performance was reduced during tests of feature binding compared with single-features (Experiment 1: Peterson & Naveh-Benjamin, 2016). It is interesting to note that the previously observed age-related binding deficits were driven, for the most part, by disproportionately high false alarm rates, rather than hit rates, in older compared with younger adults (Peterson & Naveh-Benjamin, 2016). In the current experiments, we observed the same patterns of significantly higher false alarm rates, but not hit rates, for younger adults' binding, relative to item, performance under higher (e.g., under AS in Experiments 1 and 2; under BC-2 in Experiment 3) compared with lower (e.g., under no load in Experiments 1 and 2; under AS in Experiment 3) levels of concurrent load (see online supplemental materials for statistical analyses of hit rates and false alarm rates from all three experiments).

The fact that the selective reduction in binding, relative to item, performance under divided attention observed in the current experiments appears be driven mostly by the false alarm rates rather than the hit rates is interesting. In the context of a standard VWM change detection paradigm (as was employed in the current work) a limited set of stimuli (e.g., faces, scenes) are typically presented, across different experimental trials, with replacement. Repeated presentation of the face and scene stimuli in the current experiments may have increased familiarity with these items. As such, during the test phase of trials in which a recombination between the face and scene components has occurred (i.e., a "change" trial), familiarity with these components may lead participants to incorrectly respond "no change". In turn, this pattern of erroneously endorsing recombined face–scene pairs leads to greater false alarm rates during test phases assessing the accuracy of the binding between the face and scene components, which apparently is not encoded well under divided attention. On the other hand, familiarity with the components can actually aid VWM performance during intact (i.e., "no change") trials by increasing the number of "no change" responses, which, in the current experiments, seems to have had a similar influence on hit rates under divided attention during both binding and single-item test trials. Again, the current patterns of disproportionate false alarm rates, but not hit rates, during tests of encoding and storage for bound relative to single-item representations in VWM converge with previous observations in aging populations (e.g., Peterson & Naveh-Benjamin, 2016). Taken together, the previous age-related effects and the current divided attention-related effects suggest an important role of both aging and attention in binding processes within VWM.

Conclusions

The current experiments provide novel evidence that item-item binding processes within VWM are reliant on domain-general attention. Across three experiments, VWM binding performance declined under higher compared with lower levels of concurrent load to a greater extent than single-item performance. Considering previous interpretations of findings from the VWM literature, the current findings suggest that the specific binding process required to complete a given task is an important mediating factor with respect to the role of attention in VWM binding processes.

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