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Further Studies on the Role of Attention and Stimulus Repetition in Item–Item Binding Processes in Visual Working Memory

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A fundamental question for human memory research relates to the role of attention during the binding of distinct components into an integrated representation. A number of important differences exist between the working memory and episodic memory literature in terms of methodological implementation and empirical outcomes. For instance, episodic memory studies indicate that, although divided attention reduces performance, the magnitude of this reduction is similar regardless of whether distinct item components or the associative binding between these components is tested (e.g., Naveh-Benjamin, Guez, & Marom, 2003). In contrast, recent examinations of working memory indicate that reductions in performance under divided attention are larger during tests of item–item binding compared with item tests (Peterson & Naveh-Benjamin, 2017). The current study used methods typical of both episodic and working memory paradigms to further examine the role of attention in item–item binding in visual working memory. Faces and scenes used to create face–scene pairs were either sampled with replacement (i.e., repeated across trials as is typical in working memory experiments) or without replacement (i.e., nonrepeated across trials as is typical in episodic memory experiments) to examine visual working memory performance under parametric variation of concurrent load. Results from Experiment 1 (no load, articulatory suppression) and Experiment 2 (articulatory suppression, backward counting by two) revealed greater reductions in item–item binding relative to single item performance under divided attention regardless of whether item components were repeated or not repeated across trials of each experiment. These results provide further evidence that visual working memory binding requires attention.

Keywords: visual working memory, binding processes, attention

The formation and temporary storage of integrated representations from distinct stimulus features are key components of the visual working memory (VWM) process. Identifying the precise mechanism(s) underlying this "binding" process remains an active frontier in cognitive science. Classic approaches suggest that attending to features sharing the same spatial location allows these features to become bound into an integrated visual representation (e.g., feature integration theory; Treisman, & Gelade, 1980). In the context of typical VWM tasks, distinct features (e.g., color, shape) belonging to a given object in a stimulus array comprised of multiple objects must be bound and maintained as a unified representation to avoid conjunction errors during binding test phases (Baddeley, 2000; Luck & Vogel, 1997).

Feature integration theory posits that the deployment of attention is a necessary precondition for the binding of visual features. As such, it is possible that attention is necessary when forming and storing bound features from objects within VWM (Wheeler & Treisman, 2002). However, recent empirical evidence suggests that the role of attention may vary depending on the type of binding required during a given VWM task. For instance, a number of experiments have examined VWM performance corresponding to tasks which require intra-item binding of features occurring within the same spatial location (e.g., color, shape). In many of these studies, dividing attention between the VWM task and a concurrent load task (e.g., articulatory suppression, backward counting, visual search, tone categorization) has little impact on intra-item binding (e.g., shape–color) performance relative to performance for maintaining only the individual features (e.g., color or shape; Allen, Baddeley, & Hitch, 2006, 2014; Allen, Hitch, Mate, & Baddeley, 2012; Brown & Brockmole, 2010;

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Gajewski & Brockmole, 2006; Johnson, Hollingworth, & Luck, 2008; Morey & Bieler, 2013; van Lamsweerde & Beck, 2012; Vergauwe, Langerock, & Barrouillet, 2014).

In contrast to these findings, other recent studies of intra-item binding in VWM indicate a divided attention-related binding deficit characterized by differentially lower VWM performance during tests of binding relative to tests for single features under divided relative to full attention. For instance, feature misbinding errors (i.e., akin to conjunction errors), in the form of choosing nontarget features at test, are more likely to occur under divided attention (e.g., a visual search task during the delay period) relative to full attention (Zokaei, Heider, & Husain, 2014). A similar divided attention-related binding deficit emerges when participants perform a multiple-object tracking task during the delay period, and, as a result exhibit disproportionately lower performance during tests of shape–color bindings compared with single features (e.g., color or shape; Fougnie & Marois, 2009).

In addition to the numerous studies which have focused on intra-item binding, the relationship between attention and VWM performance has been examined in another type of binding process, often referred to as item-context binding. In item-context binding an item (e.g., picture, letter, shape) must be bound to a more abstract feature (e.g., a background shape or color, an occupied location). In the case of VWM tasks that require item-context binding, performance during tests of binding tends to decrease under divided relative to full attention. For example, requiring participants to remember tones during a letter-location change detection task results in a marked reduction in performance relative to when the VWM task is performed with no concurrent tone task (Elsley & Parmentier, 2009). Moreover, when a probed object (e.g., colored shape) changes location between the study phase and the test phase, binding performance decreases to a greater extent than single-feature performance even under articulatory suppression relative to no concurrent load (Treisman & Zhang, 2006, but see also, Allen, Castellà, Ueno, Hitch, & Baddeley, 2015; Logie, Brockmole, & Jaswal, 2011; Woodman, Vogel, & Luck, 2012). Given these somewhat diverging patterns of results in the VWM binding literature, it may be the case that intra-item binding occurs in a more automatic fashion relative to item-context binding, with attention conceivably playing a larger role during item-context binding processes in VWM (Ecker, Maybery, & Zimmer, 2013).

Recently, a third type of binding process has been examined in VWM. Item–item (or inter-item) binding refers to the integration of two distinct items or objects occurring at different spatial locations (e.g., faces, scenes). Consistent with some of the previous studies of intra-item and item-context binding that have found divided attention-related binding deficits in VWM, a recent study has identified attention-mediated binding deficits during tasks requiring item–item binding. Face–scene pairs (two per stimulus array) were required to be maintained during a VWM change detection task performed under either no load, articulatory suppression (AS),[1] or backward counting by two-digits (BC-2, Peterson & Naveh-Benjamin, 2017). Across three experiments, VWM binding performance for face–scene pairs was disproportionately lower than single-item (i.e., faces, scenes) performance under conditions of divided attention relative to full attention.

Although the effects of divided attention on item–item binding in VWM have been demonstrated only recently, item–item binding has been examined thoroughly in studies of long-term associative memory. In associative memory paradigms distinct, nonrepeated stimulus pairs (e.g., face–scene pairs, word pairs) are typically presented during a study phase followed by a delay period (e.g., typically ≥30 s) and ultimately a test phase in which single-item components (half target, half distractor) or item–item associative pairs are presented either intact (i.e., targets) or recombined (i.e., distractors) between item components which appeared during the original study phase (see Naveh-Benjamin, 2000).

In previous experiments that have examined the impact of divided attention at encoding on subsequent associative memory relative to item memory performance in long-term memory, no divided attention-related associative memory deficit was evident (Naveh-Benjamin et al., 2003). Specifically, although overall memory performance is reduced under divided attention relative to full attention, the magnitude of this reduction in performance is similar for both item and associative memory. Other recent findings have shown similar patterns indicative of no differential effect of divided attention at encoding on item memory compared with associative memory in long-term memory, also showing that learning instructions during encoding (i.e., incidental, intentional) do not influence these patterns of results (Naveh-Benjamin, Guez, Hara, Brubaker, & Lowenschuss-Erlich, 2014). When compared with the aforementioned review of the VWM binding literature, these findings from the associative memory literature reveal important differences regarding the role of attention in binding processes examined during typical VWM and LTM paradigms. However, important methodological differences exist between these paradigms, which may potentially be the source of these discrepant findings regarding the role of attention in binding processes in VWM and LTM.

Current Experiments

Given important differences in the task paradigms typically employed in previous LTM and, more recently, VWM studies of binding processes, the precise role of attention in item–item binding in VWM remains unknown. In typical VWM paradigms involving change detection tasks a limited set of stimuli (e.g., colors, shapes) are sampled with repetition across trials throughout the blocks of the experiment. In the most recent examination of item–item binding in VWM, a limited number of faces and scenes were used to form face–scene pairs presented in the stimulus arrays, with faces and scenes repeated across trials of the experiment (Peterson & Naveh-Benjamin, 2017). In contrast, LTM paradigms examining associative (i.e., binding) and item memory typically sample item components to form stimulus pairs without replacement throughout the experiment (e.g., Naveh-Benjamin et al., 2003, 2014).

As such, it is possible that stimulus repetition across trials of this recent set of VWM experiments may have led to increased famil-

[1] We note that although working memory experiments typically employ articulatory suppression (AS) simply to prevent verbal rehearsal of verbal material or prevent verbal recoding of visual material, in our previous (e.g., Peterson & Naveh-Benjamin, 2017) and current experiments, the AS task functions as a lower level of concurrent load, which varies parametrically between no concurrent load and higher levels of concurrent load (e.g., backward counting by two digits, BC-2). Simultaneously, the AS task likely prevents verbal recoding of visual material, to the extent that the face–scene stimuli can be verbalized under no concurrent load.

iarity with the items (e.g., faces, scenes), thus increasing the proportion of false alarms during tests of VWM binding relative to single-item tests, due to increased difficulty in detecting recombined pairs comprised of repeated item components, thus reducing overall performance during tests of binding. In this most recent study, no formal analysis of false alarm rates was conducted, leaving unclear the role of stimulus repetition as a mediating factor of the false alarm rate during tests of VWM binding. Thus, it may be the case that the use of nonrepeated stimuli, similar to approaches used in LTM paradigms, may result in no differential effect of divided attention on binding relative to single-item performance in VWM.

Additionally, recent findings suggest that item–item binding, relative to single-item, performance in VWM is reduced in a robust manner, regardless of the requirements of the concurrent load task. Specifically, a divided attention-related binding deficit was evident under both AS relative to no concurrent load (Experiment 1 & 2: Peterson & Naveh-Benjamin, 2017) and under BC-2 relative to AS (Experiment 3: Peterson & Naveh-Benjamin, 2017). As such, this recent evidence suggests that divided attention, rather than simply the prevention of a verbal rehearsal mechanism, was responsible for the pattern of a binding deficit observed across three experiments with variable levels of concurrent task load. In the context of the current study, it may be the case that the influence of stimulus repetition on divided attention-related binding deficits in VWM may vary as a function of concurrent task requirements.

In the current experiments the role of stimulus repetition during a VWM task requiring item–item binding under varying levels of divided attention was examined. Using a recently developed VWM change detection task paradigm (see Peterson & Naveh-Benjamin, 2017), face and scene stimuli used to create face–scene pairs were either repeated or not repeated across trials of separate blocks of the experiment. In Experiment 1 the VWM task was performed either under no concurrent load or under AS to examine whether the predicted divided attention-related binding deficit would vary as a function of stimulus repetition. In Experiment 2 the VWM task, including blocks of repeated and nonrepeated item components, was performed under AS and under BC-2 to examine the possibility that the binding deficit predicted in Experiment 1 may have been due solely to the prevention of a verbal rehearsal mechanism (i.e., no load vs. AS) rather than purely because of divided attention during VWM binding.

Experiment 1

Based on the recent findings described above, we predicted that the results of Experiment 1 would reveal a divided attention-related binding deficit characteristic of a greater decline in item–item binding test performance, relative to single-item tests, during blocks performed under AS compared with those performed under no concurrent load. Second, if stimulus repetition mediates the predicted divided attention-related binding deficit, such a deficit is expected during repeated, but not nonrepeated stimuli blocks of the experiment. If this were the case, a separate analysis of the false alarm rates should reveal disproportionately higher false alarm rates under divided attention (i.e., AS) during tests of binding compared with single-items during the repeated, but not the nonrepeated, blocks. In contrast, it is possible that stimulus repetition does not mediate the predicted deficit, in which case, an overall divided attention-related binding deficit is expected during both repeated and nonrepeated stimuli blocks of the experiment. In this case, the increase in false alarm rates during AS relative to no load blocks between single-item and item–item binding tests should be similar.

Method

Participants. The participants included 74 undergraduate students (age range: 18–22, 33 female) from the University of Missouri and Concordia College who received course-related credit in exchange for their participation (see Table 1 for demographic information). All protocols were approved by the Institutional Review Boards at the University of Missouri and Concordia College. All participants were healthy physically and mentally, had no known memory deficits, and normal or corrected-to-normal visual acuity. Thirty-six participants were removed prior to subsequent group analyses given that they met our a priori exclusion criteria of chance-level (or below chance-level) performance (i.e., ≤ 0 proportion hits minus false alarms values) in either of the repeated or nonrepeated stimuli blocks during either of the item test conditions or the binding test condition during the no load (lower level of concurrent load) blocks of the experiment. Given that their baseline (i.e., under no load) performance was at or below chance-level, we lacked the sensitivity necessary to detect any further declines in performance under AS for these 36 participants.

Stimuli and materials. Faces of younger and older adults (both male and female), derived from the FACES database, were used as the facial stimuli (Ebner, Riediger, & Lindenberger, 2010). The scenes were natural images of forest and mountain scenes that contained no people or faces. Both the face and scene stimulus images subtended approximately $5.5° \times 6.5°$ of visual angle (see Figure 1). The experiment was automated using E-Prime 2.0.10 software (Schneider, Eschmann, & Zuccolotto, 2002). A Dell desktop computer was used to run E-Prime 2.0.10 software via a flat-screen LED monitor running at a resolution of $1,920 \times 1,080$ with a refresh rate of 60 Hz.

Procedure. Participants completed a single-probe working memory change detection task under no load or under AS (see Figure 1). From a viewing distance of 57 cm, participants first viewed a secondary task prompt (2,000 ms) to indicate whether a concurrent task was to be performed during the presentation of the fixation cross ($0.60° \times 0.60°$ for 500 ms), the stimulus array (encoding period: 2,000 ms), and the blank delay period (1,000 ms) of each trial. During the encoding period, two face–scene pairs appeared with one face–scene pair in each of two quadrants (four possible quadrants total) of the computer screen. On-screen quadrant locations were pseudorandomly determined from trial-to-trial

Table 1
Demographic Information for Experiments 1 and 2

Experiment	*N*	Proportion female	Age, in years	Education, in years
Experiment 1	74	.45	19.00 (1.09)	12.70 (1.02)
Experiment 2	67	.42	20.06 (2.67)	13.52 (1.42)

Note. The values for age and education depict means (standard deviations).

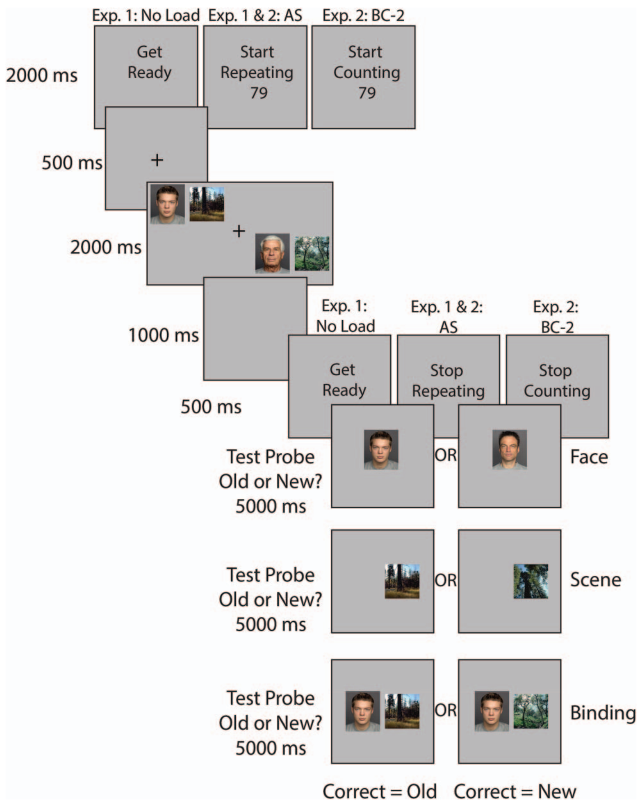

Figure 1. Task paradigm used in Experiments 1 and 2, depicting an example of a memory array during the encoding phase, and test probe configurations. In Experiment 1 participants viewed a secondary task prompt (2000 ms; either "Get Ready" under No Load, or "Start Repeating XX" under AS) and then viewed a fixation cross (500 ms). Following fixation, the sample array, including two face–scene pairs appeared (2000 ms). After a delay-period (1,000 ms), a secondary task prompt (500 ms; either "Get Ready" under No Load, or "Stop Repeating" under AS) appeared. Finally, 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 task paradigm was used with the exception that participants either repeated a number (AS) or counted backward by two-digits (BC-2; "Start Counting XX") during the fixation period, encoding phase, and maintenance phase of each trial. Either a "Stop Repeating" prompt or a "Stop Counting" prompt (500 ms) immediately followed the delay period in Experiment 2. 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.

with the constraint that one face–scene pair appear on each side of the fixation cross (e.g., one left, one right) either in the lower or upper portion of the monitor. During the two no load blocks of the experiment the secondary task prompt displayed the phrase "Get Ready" and the phrase "Start Repeating Number" (e.g., "Start Repeating 72") appeared during the two AS blocks. Following the delay period either a "Get Ready" prompt or a "Stop Repeating" prompt appeared (500 ms).

Finally, during the test probe phase, either a single face appeared (left of center), a single scene (right of center), or a face–scene pair appeared at the center of the screen. During face test probes, one of the two faces originally presented during the stimulus array was presented or a new face was selected from the set chosen for a given participant. Likewise, during scene test probes one of the two scenes from the stimulus array was chosen, or a new scene was selected. During the face–scene (i.e., binding) test probes, either an original face–scene pair from the stimulus array was presented intact or the face and scene from each of the two pairs were presented as a recombined pair. Test probe trials were randomly intermixed within a given block of trials (10 of each test probe type per block). Participants were given 5,000 ms to respond either "old" or "new" in response to each type of test probe by pressing the "o" or "n" key on the keyboard, respectively. After an intertrial interval (1,000 ms), participants initiated the start of the next trial by pressing the space bar.

Half of the trials involved a change and in the other half of the trials no change occurred. During the two "repeated" stimuli blocks of the experiment (one performed under no load, one performed under AS), participants viewed the same stimulus set of 8 faces (4 younger, 4 older) and 8 scenes (4 forests, 4 mountains) repeated across all 30 trials within a given block (60 trials total). In the remaining two "non-repeated" stimuli blocks of the experiment (one performed under no load, one performed under AS) face and scene stimuli were used only once (e.g., 30 unique face–scene pairs were used in each block, 60 trials total). Across the four blocks of the experiment, participants completed 120 trials total (40 trials per test probe condition). Concurrent task block order (e.g., no load blocks, AS blocks) was counterbalanced such that participants either completed two blocks under no load followed by two blocks of AS (or two under AS and two under no load) with stimulus repetition order (e.g., repeated, nonrepeated), within a given level of concurrent load, counterbalanced across participants.

On a given trial, both of the faces within the stimulus array were sampled from the same gender category to avoid memory judgments corresponding to the face test probes which could have otherwise been made on the sole basis of categorical changes to the gender of the face. As such, half of the participants viewed female younger and older adult faces and the other half viewed younger and older adult male faces throughout all trials of the experiment. The overall stimulus set included 68 faces from each age and gender category (i.e., 68 younger females, 68 older females, 68 younger males, 68 older males) and 68 scenes from each category (i.e., 68 forest scenes, 68 mountain scenes). In the two "stimuli repeated" blocks of the experiment, 8 faces (4 younger, 4 older) and 8 scenes (4 mountain, 4 forest) were sampled from the larger stimulus set and used throughout all trials within these two blocks. In the two "stimuli non-repeated" blocks of the experiment, all the remaining 64 faces and 64 scenes from each stimulus subcategory were sampled with each image used only in a single trial throughout the two blocks of the experiment. As such, the "stimuli repeated" stimulus set of 8 faces and 8 scenes chosen from the larger set was changed, across participants, to create different counterbalanced versions of the experiment (36 total versions: half of the versions used male faces, the other half used female faces), and equate the appearance of a given face and scene across participants in the repeated and nonrepeated conditions. Prior to beginning the actual experiment, participants completed 12 practice trials (4 trials per test probe type, half performed under no load and half performed under AS) to familiarize them with the concurrent load task and each type of test probe.

Results

To measure VWM performance we first computed the proportion of hits and the proportion of false alarms along with the proportion hits minus proportion false alarms (i.e., correct recognition) for each experimental condition for each participant. Using the proportion hits and proportion false alarms values, for each participant signal detection theory measures of A' and d' were computed in accordance with the extreme value adjustment procedures and computational formulas provided by Stanislaw and Todorov (1999). Given previous recommendations (e.g., Allen et al., 2012; Donaldson, 1993), and consistent with recent examinations of item–item binding in VWM (e.g., Peterson & Naveh-Benjamin, 2017), the statistical analyses described below were applied to the A' values from the 38 participants meeting inclusion criteria described in the methods section above (see Table 2 for group means and standard deviations).

Memory accuracy analyses—A'. A 2 (load: no load, AS) × 2 (repetition: repeated, nonrepeated) × 3 (test: face, scene, binding) repeated-measures analysis of variance (ANOVA) was applied to the A' values (in all instances, p values appearing below were Greenhouse-Geisser corrected). The main effect of load, $F(1, 37) = 54.16$, $p < .001$, $\eta_p^2 = .59$), was significant, with higher levels of performance in the no load ($M = .87$, $SD = .04$) relative to the AS ($M = .79$, $SD = .08$) blocks. A main effect of test was present, $F(2, 74) = 38.15$, $p < .001$, $\eta_p^2 = .51$, with higher performance during the face tests ($M = .88$, $SD = .06$) relative to the scene tests ($M = .85$, $SD = .06$), and finally the binding tests ($M = .76$, $SD = .10$). Each pairwise comparison was borderline significant or significant (face vs. scene: $p = .052$; face vs. binding, $p < .001$; scene vs. binding: $p < .001$, Bonferroni corrected). No main effect of repetition[2] (repeated: $M = .83$, $SD = .07$; nonrepeated: $M = .83$, $SD = .06$) was evident, $F(1, 37) = .13$, $p = .73$. It is important to note that the load by test interaction was significant, $F(2, 74) = 10.82$, $p < .001$, $\eta_p^2 = .23$, see Figure 2. Additionally, the repetition by test, $F(2, 74) = 5.19$, $p = .014$, $\eta_p^2 = .12$, interaction was significant. The remaining interactions of repetition by load, $F(1, 37) = 3.71$, $p = .062$, and it is important to note, the triple interaction between repetition × load × test, $F(2, 74) = .48$, $p = .62$, was not significant.[3]

To examine the origin of the load by test interaction, 2 × 2 repeated-measures ANOVAs were conducted. The load by test interaction in the comparison of the face and scene tests as a function of concurrent load was nonsignificant, $F(1, 37) = .17$, $p = .68$. In contrast, and, supporting our hypothesis, in all remaining 2 × 2 comparisons, the load by test interaction was significant (face vs. binding: $F(1, 37) = 17.63$, $p < .001$, $\eta_p^2 = .32$; scene vs. binding: $F(1, 37) = 9.95$, $p = .003$, $\eta_p^2 = .21$; item (i.e., the average of face test and scene test performance) versus binding: $F(1, 37) = 14.44$, $p = .001$, $\eta_p^2 = .28$).[4]

Finally, paired-samples t tests revealed that the reduction in performance between the no load blocks and the AS blocks was significant in each test condition—for example, $\text{face}_{\text{no load:}}$ $M = .90$, $SD = .05$ vs. $\text{face}_{\text{AS:}}$ $M = .86$, $SD = .07$, $t(37) = 4.89$, $p < .001$; $\text{scene}_{\text{no load:}}$ $M = .88$, $SD = .05$ vs. $\text{scene}_{\text{AS:}}$ $M = .83$, $SD = .10$, $t(37) = 3.27$, $p = .002$; $\text{item}_{\text{no load:}}$ $M = .89$, $SD = .04$ versus $\text{item}_{\text{AS:}}$ $M = .84$, $SD = .07$, $t(37) = 5.46$, $p < .001$; $\text{binding}_{\text{no load:}}$ $M = .83$, $SD = .07$ versus $\text{binding}_{\text{AS:}}$ $M = .69$, $SD = .16$, $t(37) = 5.61$, $p < .001$. Difference scores (average no load minus average AS) were computed for each participant for the item tests and binding tests and compared using a paired-samples t test, which revealed that divided attention had a significantly greater impact, $t(37) = -3.80$, $p = .001$, on binding memory performance ($M_\Delta = .14$, $SD = .16$) compared with item memory performance ($M_\Delta = .04$, $SD = .05$).

Next, separate 2 × 2 repeated-measures ANOVAs were used to examine the repetition by test interaction. The 2 × 2 examining the face and scene test comparison across both repeated and nonrepeated stimuli blocks revealed a nonsignificant repetition by test interaction, $F(1, 37) = 3.60$, $p = .066$. Additionally, the interaction between the scene and binding tests across both levels of repetition was nonsignificant, $F(1, 37) = 2.81$, $p = .10$. In contrast, the interaction between the face and binding test comparison across both levels of repetition was significant, $F(1, 37) = 8.36$, $p = .006$, $\eta_p^2 = .18$. Follow-up paired-samples t tests revealed that the overall repetition by test interaction was driven by significantly greater face test performance during nonrepeated ($M = .89$, $SD = .04$) compared with repeated ($M = .86$, $SD = .09$) blocks, $t(37) = -2.19$, $p = .035$. No significant differences were observed between scene test performance during repeated ($M = .85$, $SD = .08$) and nonrepeated ($M = .85$, $SD = .08$), blocks, $t(37) = -.04$, $p = .97$, or between binding test performance during repeated ($M = .78$, $SD = .12$) and nonrepeated ($M = .74$, $SD = .11$), blocks, $t(37) = 1.93$, $p = .061$.

Memory accuracy analyses—Hits. Separate 2 × 2 × 3 ANOVAs were applied to both the proportion hits data and the proportion false alarms data (see Table 2). The proportion hits analysis revealed a main effect of load, $F(1, 37) = 15.24$, $p < .001$, $\eta_p^2 = .29$, with greater hit rates under no load ($M = .83$, $SD = .05$) compared with AS ($M = .78$, $SD = .08$), and a main effect of test, $F(2, 74) = 8.72$, $p = .001$, $\eta_p^2 = .19$. Hit rates were significantly higher during the face tests ($M = .84$, $SD = .06$) compared with the scene tests ($M = .78$, $SD = .10$, $p < .001$, Bonferroni corrected). There was a nonsignificant difference between face and binding performance ($M = .81$, $SD = .07$, $p = .09$, Bonferroni

[2] Note that the factor of "repetition" refers to the manipulation of sampling with replacement (i.e., during repeated stimuli blocks) or sampling without replacement (i.e., during non-repeated stimuli blocks) from the larger stimulus set across the trials within a particular block of the experiment. Within the stimulus array of a single trial, a given stimulus (i.e., face, scene) was presented only once.

[3] Applied to the A' values, a 2 × 2 × 3 repeated-measures ANOVA with the addition of a between-subjects factor of sample location (i.e., University of Missouri, Concordia College) was used to assess whether any notable differences were observed as a function of sample location. No main effect of sample location, $F(1, 36) = .48$, $p = .49$, nor any other interactions between sample location and any other experimental factors were evident, indicating that both subsamples contributed similar results to the overall group level analyses.

[4] The same 2 × 2 × 3 repeated-measures ANOVA, follow-up 2 × 2 ANOVAs, and paired-samples t-tests were applied to the d' and proportion hits minus false alarms values, which yielded the same overall patterns of significant main effects, a significant load by test interaction and a significant repetition by test interaction. No other interaction effects were significant, with the exception that the repetition by load interaction was borderline significant in the separate analyses of the d' values ($p = .046$) and proportion hits minus proportion false alarms ($p = .055$).

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

	No load			Articulatory suppression		
Response measures	Face	Scene	Binding	Face	Scene	Binding
Hits						
Repeated	.87 (.06)	.81 (.15)	.83 (.09)	.86 (.09)	.77 (.14)	.79 (.14)
Nonrepeated	.86 (.09)	.80 (.13)	.82 (.12)	.78 (.19)	.72 (.20)	.78 (.12)
False alarms						
Repeated	.27 (.23)	.21 (.14)	.31 (.21)	.31 (.24)	.24 (.20)	.47 (.26)
Nonrepeated	.13 (.05)	.18 (.11)	.35 (.23)	.22 (.14)	.21 (.14)	.56 (.24)
Hits minus false alarms						
Repeated	.61 (.23)	.60 (.18)	.52 (.21)	.55 (.22)	.52 (.24)	.33 (.30)
Nonrepeated	.72 (.09)	.62 (.16)	.47 (.20)	.56 (.19)	.51 (.22)	.22 (.27)
A′						
Repeated	.87 (.09)	.87 (.07)	.84 (.09)	.85 (.10)	.83 (.12)	.72 (.20)
Nonrepeated	.92 (.04)	.88 (.06)	.82 (.08)	.86 (.08)	.83 (.12)	.66 (.18)
d′						
Repeated	1.90 (.70)	1.84 (.57)	1.58 (.62)	1.72 (.68)	1.59 (.75)	.99 (.90)
Nonrepeated	2.25 (.33)	1.88 (.54)	1.44 (.59)	1.71 (.59)	1.53 (.70)	.67 (.81)

corrected), and no difference between scene and binding performance ($p = .23$, Bonferroni corrected). There was also a main effect of repetition, $F(1, 37) = 4.57$, $p = .039$, $\eta_p^2 = .11$, with higher hit rates during repeated ($M = .82$, $SD = .06$) compared with nonrepeated ($M = .79$, $SD = .08$) blocks. No interactions pertaining to the hit rate data were significant (all *p's* > .07).

Memory accuracy analyses—False alarms. In contrast to the patterns related to the hit rates, the proportion of false alarms analysis revealed a pattern similar to the *A′* results (see Table 2). The main effect of load, $F(1, 37) = 25.30$, $p < .001$, $\eta_p^2 = .41$), was significant, with higher false alarm rates in the AS ($M = .33$, $SD = .13$) relative to the no load ($M = .24$, $SD = .09$) blocks. A main effect of test was present, $F(2, 74) = 45.08$, $p < .001$, $\eta_p^2 = .55$, with higher false alarm rates during the binding tests ($M = .42$, $SD = .16$) relative to the face tests ($M = .23$, $SD = .13$) and scene tests ($M = .21$, $SD = .09$). The comparison between face and binding false alarm rates ($p < .001$, Bonferroni corrected) and scene and binding false alarm rates ($p < .001$, Bonferroni corrected) were both significant, and the difference between face and scene false alarm rates was not significant ($p = .36$). No main effect of repetition (repeated: $M = .30$, $SD = .14$; nonrepeated: $M = .28$, $SD = .08$) was evident in the false alarm rates, $F(1, 37) = 1.66$, $p = .21$.

It is important to note that, as was the case in the *A′* analysis, the load by test interaction pertaining to the false alarm rates analysis was significant, $F(2, 74) = 10.12$, $p < .001$, $\eta_p^2 = .22$, as was the repetition by test, $F(2, 74) = 10.00$, $p < .001$, $\eta_p^2 = .21$, interaction. The remaining interactions of repetition by load, $F(1, 37) = 1.15$, $p = .29$, and the triple interaction between repetition × load × test, $F(2, 74) = .48$, $p = .61$, did not reach statistical significance.

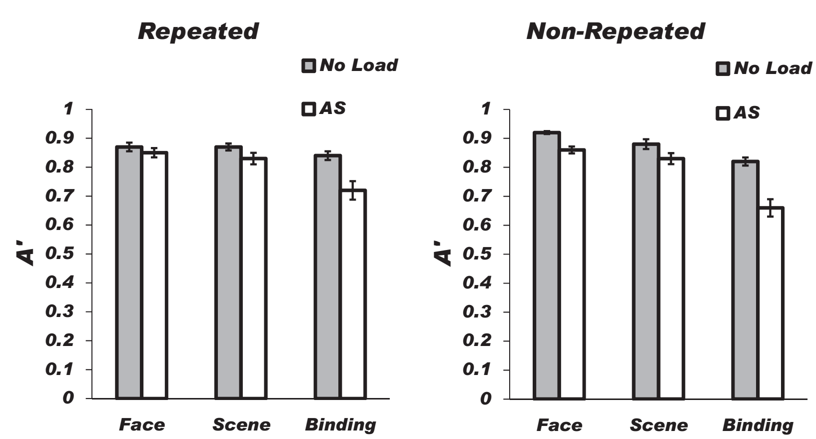

Figure 2. Experiment 1: Recognition performance under no load and articulatory suppression as a function of stimulus repetition. Behavioral results for Experiment 1 test types (face, scene, face–scene binding) as a function of stimulus repetition (repeated, nonrepeated). The abscissa depicts performance in each test type corresponding to the no load and articulatory suppression (AS) blocks of the experiment, whereas the mean A′ value corresponding to each condition is plotted along the ordinate. Error bars represent the standard error of the mean in each test condition.

Further examination of the load by test interaction was carried out using 2 × 2 repeated-measures ANOVAs. The load by test interaction comparing face and scene performance as a function of concurrent load was nonsignificant, $F(1, 37) = 1.42$, $p = .24$. In contrast, in all remaining 2 × 2 comparisons, the load by test interaction was significant (face vs. binding: $F(1, 37) = 9.49$, $p = .004$, $\eta_p^2 = .20$; scene vs. binding: $F(1, 37) = 15.65$, $p < .001$, $\eta_p^2 = .30$; item (i.e., the average of face test and scene test performance) versus binding: $F(1, 37) = 14.44$, $p = .001$, $\eta_p^2 = .28$).

Paired-samples *t* tests revealed that the difference in false alarm rates between the no load blocks and the AS blocks was significant during the binding tests—binding$_{\text{no load:}}$ $M = .33$, $SD = .17$ vs. binding$_{\text{AS:}}$ $M = .51$, $SD = .22$, $t(37) = -5.03$, $p < .001$. There was also a significant difference in false alarm rates during the face tests—for example, face$_{\text{no load:}}$ $M = .20$, $SD = .12$ vs. face$_{\text{AS:}}$ $M = .26$, $SD = .16$, $t(37) = -3.46$, $p = .001$—and the average item (averaged across the face and scene tests) item$_{\text{no load:}}$ $M = .20$, $SD = .09$ versus item $_{\text{S:}}$ $M = .24$, $SD = .12$, $t(37) = -2.84$, $p = .007$. However, there was no difference in false alarm rates during the scene tests, scene$_{\text{no load:}}$ $M = .20$, $SD = .10$ vs. scene$_{\text{AS:}}$ $M = .23$, $SD = .14$, $t(37) = -1.18$, $p = .25$. Difference scores (average no load minus average AS) were computed for each participant for the false alarm rates during item tests and binding tests and compared using a paired-samples *t* test, which revealed that divided attention had a significantly greater impact, $t(37) = 3.80$, $p = .001$, resulting in increased false alarm rates, during tests of binding ($M_\Delta = -.18$, $SD = .22$) compared with the item tests ($M_\Delta = -.04$, $SD = .10$).

Given the presence of an overall repetition by test interaction, separate 2 × 2 repeated-measures ANOVAs were used to compare false alarm rates associated with the repeated and nonrepeated stimuli blocks during the various test conditions. The comparison of false alarm rates during face and scene tests, $F(1, 37) = 6.44$, $p = .015$, $\eta_p^2 = .15$, the comparison of face and binding tests, $F(1, 37) = 16.01$, $p < .001$, $\eta_p^2 = .30$, across the repeated and nonrepeated stimuli blocks, both revealed a significant repetition by test interaction. The repetition by test interaction was also significant for the comparison of the scene and binding test false alarm rates, $F(1, 37) = 5.28$, $p = .027$, $\eta_p^2 = .13$, during repeated and nonrepeated stimuli blocks.

Similar to the pattern observed in the analysis of the A' data, paired-samples *t* tests revealed that the repetition by test interaction corresponding to the false alarm rates was driven by greater false alarm rates for the face tests occurring during the repeated ($M = .29$, $SD = .21$) relative to the nonrepeated ($M = .18$, $SD = .08$) blocks, $t(37) = 3.51$, $p = .001$. No difference in false alarm rates as a function of stimulus repetition was evident during the scene tests (scene$_{\text{repeated:}}$ $M = .23$, $SD = .14$ vs. scene$_{\text{nonrepeated:}}$ $M = .20$, $SD = .09$, $t(37) = 1.27$, $p = .21$) or the binding tests, binding$_{\text{repeated:}}$ $M = .39$, $SD = .19$ vs. binding$_{\text{nonrepeated:}}$ $M = .46$, $SD = .19$, $t(37) = -1.90$, $p = .065$.

Analysis of the number of successful verbalizations in the AS condition. Finally, the mean number of successful verbalizations during trials of the AS blocks of the experiment were computed for each participant for each experimental condition and submitted to a 2 (repetition) by 3 (test) repeated-measures ANOVA. This ANOVA revealed no main effect of test, $F(2, 74) = 1.53$, $p = .23$, no main effect of repetition, $F(1, 37) = 1.84$, $p = .18$, and no significant repetition by test interaction, $F(2, 74) = .71$, $p = .43$ (see Table 3). These results confirm that the number of successful verbalizations did not vary as a function of stimulus repetition or test condition.

Discussion

The current experiment examined the impact of divided attention (i.e., no load compared with AS) on single-item (i.e., faces, scenes) and item–item (i.e., face–scene pairs) binding performance during a VWM change detection task. Moreover, stimuli were either sampled with (i.e., repeated) or without (i.e., nonrepeated) replacement across trials throughout distinct blocks of the experiment. Results from the current experiment revealed that divided attention has a greater detrimental impact on binding relative to single-item performance measured during a VWM change detection task. Specifically, the reduction in performance under AS (relative to no load) during tests of item–item binding was significantly greater than the reduction in single-item (i.e., faces or scenes) test performance. Moreover, this divided attention-related deficit was driven by higher false alarm rates, but not hit rates, under AS relative to no load blocks during tests of item–item binding compared with single item tests (i.e., faces, scenes). It is important to note that this divided attention-related binding deficit was consistent regardless of whether stimuli were repeated throughout trials across all blocks of the experiment. These novel findings suggest that the divided attention-related deficit exhibited by participants during tests of item–item binding relative to single-items occurs regardless of whether stimuli are sampled with or without replacement across trials throughout the duration of the VWM change detection task.

Moreover, the current experiment revealed that VWM performance during tests of individual faces was greater under nonrepeated relative to repeated stimulus conditions. This effect was also driven by false alarm rates, rather than hit rates, given that false alarm rates were higher when faces were repeated across trials throughout the blocks of the experiment. This effect of stimulus repetition on VWM performance was not evident during test probes involving individual scenes or face–scene binding.

The current findings suggest that, regardless of the stimulus repetition methods imposed (i.e., repeated, nonrepeated), item–item binding requires attention, over and above that which is required to process single-items (i.e., faces, scenes) in VWM. It is possible, however, that this binding deficit, observed under AS relative to no concurrent load, manifests because of the prevention of verbal recoding or rehearsal of the face–scene pairs presented during the encoding phase. As such, comparing item and binding

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

Articulatory suppression	Face	Scene	Binding
Repeated	6.11 (1.41)	6.12 (1.46)	6.16 (1.55)
Nonrepeated	6.18 (1.37)	6.18 (1.32)	6.42 (2.02)

Note. Mean number of repetitions per test block in the articulatory suppression blocks, with standard deviations in parentheses, are depicted.

performance as a function of stimulus repetition under AS and under a more demanding concurrent load task is an important next step toward further evidence indicative of a binding deficit due to a reduction in domain-general attentional resources.

Experiment 2

To determine whether the patterns observed in Experiment 1 were due exclusively to prevention of verbal recoding or rehearsal of the face–scene pairs, in Experiment 2, item and item–item binding performance was examined under conditions of AS and backward counting by two digits (BC-2). If the binding deficit observed in Experiment 1 was due exclusively to the prevention of verbal recoding of the face–scene stimuli, no interaction between test condition (i.e., item, binding) and concurrent load (i.e., AS, BC-2) is expected. In contrast, if the predicted reduction in VWM performance is greater for tests of item–item binding relative to single-item tests under BC-2, which conceivably both prevents verbal recoding and requires domain general attention, compared with AS, an interaction between test condition and concurrent load should be evident, replicating and extending the results observed in Experiment 1. Finally, stimulus repetition (repeated, nonrepeated) was again manipulated in Experiment 2.

Given the results of Experiment 1, the predicted divided attention-related binding deficit is not expected to vary as a function of stimulus repetition in Experiment 2. Likewise, a similar pattern regarding false alarm rates, as shown in Experiment 1, is expected in Experiment 2. However, it is possible that a distinction between the impact of the two stimulus repetition conditions (i.e., repeated, nonrepeated) on VWM performance may become apparent, given that the change detection task must be performed under an overall higher level of concurrent load in Experiment 2. In this case, false alarm rates should be differentially higher for the binding tests relative to item tests under BC-2 during repeated, but not nonrepeated, blocks of the experiment.

Method

Participants. A different sample of 67 participants from the University of Missouri completed Experiment 2 (see Table 1 for demographic information). All participants were healthy physically and mentally, had no known memory deficits, and normal or corrected-to-normal visual acuity. Thirty-nine participants were removed prior to subsequent group analyses given that they met exclusion criteria of chance-level (or below chance-level) performance (i.e., ≤ 0 proportion hits minus false alarms values) in either of the repeated or nonrepeated stimuli blocks during item test (average face and scene performance) or the binding test conditions during the AS (lower level of concurrent load) blocks of the experiment. Given that their baseline (i.e., under AS) performance was at or below chance-level, we lacked the sensitivity necessary to detect any further declines in performance under BC-2 for these 39 participants. Although the number of subjects meeting exclusion criteria was similar to the number excluded in Experiment 1, we note that the lower-level concurrent load task in Experiment 2, the AS condition, is more difficult than the no load condition used in Experiment 1, likely contributing to this even larger exclusion rate in Experiment 2.

Stimuli and materials. The same stimulus materials, computers, and software as used in Experiment 1 were used in Experiment 2.

Procedure. All procedures inherent to the task paradigm used in Experiment 1 were used in Experiment 2 with the following exception. In Experiment 2 the concurrent load tasks included AS and backward counting by two digits (BC-2). As such, in two of the experimental blocks, participants performed the VWM change detection task during each block of trials (one with and one without stimulus repetition) under AS and in the remaining two blocks (one with and one without stimulus repetition) participants performed the task under BC-2 (e.g., "79, 77, 75"; see Figure 1). As was the case in Experiment 1, participants completed 120 trials total (40 trials per test probe condition) across the four blocks of the experiment.

Results

The same analysis strategy used in Experiment 1 was applied to the Experiment 2 data. Statistical analyses described below were applied to the A' values from the 28 participants meeting inclusion criteria described in the methods section above (see Table 4 for group means and standard deviations for various performance measures).

Memory accuracy analyses—A'. A 2 (load: AS, BC-2) $\times$ 2 (repetition: repeated, nonrepeated) $\times$ 3 (test: face, scene, binding) repeated-measures analysis of variance (ANOVA) was applied to the A' values (in all instances, p values appearing below were Greenhouse-Geisser corrected). The main effect of load, $F(1, 27) = 77.55$, $p < .001$, $\eta_p^2 = .74$), was significant, with higher levels of performance in the AS ($M = .84$, $SD = .05$) relative to the BC-2 ($M = .73$, $SD = .07$) blocks. A main effect of test was present, $F(2, 54) = 28.93$, $p < .001$, $\eta_p^2 = .52$, with higher performance during the face tests ($M = .85$, $SD = .07$) relative to the scene tests ($M = .81$, $SD = .07$), and finally the binding tests ($M = .70$, $SD = .10$). No significant difference was evident between face and scene performance (face vs. scene: $p = .09$, Bonferroni corrected), however, performance during each of the single-item tests was significantly greater than during binding tests (face vs. binding, $p < .001$; scene vs. binding: $p < .001$, Bonferroni corrected). No main effect of repetition (repeated: $M = .79$, $SD = .06$; nonrepeated: $M = .78$, $SD = .06$) was evident, $F(1, 27) = .13$, $p = .72$. Following the pattern observed in Experiment 1, in Experiment 2 the load by test interaction was significant, $F(2, 54) = 16.88$, $p < .001$, $\eta_p^2 = .39$ (see Figure 3). The interactions including repetition by load, $F(1, 27) = .001$, $p = .98$, and the triple interaction between repetition $\times$ load $\times$ test, $F(2, 54) = 1.96$, $p = .16$, did not reach statistical significance.

To examine the origin of the load by test interaction, 2 $\times$ 2 repeated-measures ANOVAs were conducted. The load by test interaction in the comparison of the face and scene tests as a function of concurrent load was nonsignificant, $F(1, 27) = .10$, $p = .75$. In contrast, in all remaining 2 $\times$ 2 comparisons, the load by test interaction was significant (face vs. binding: $F(1, 27) = 24.05$, $p < .001$, $\eta_p^2 = .47$; scene vs. binding: $F(1, 27) = 22.10$, $p < .001$, $\eta_p^2 = .45$; item (i.e., the average of face test and scene test performance) versus binding: $F(1, 27) = 28.31$, $p < .001$, $\eta_p^2 = .51$).

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

	Articulatory suppression			Backward counting		
Response measures	Face	Scene	Binding	Face	Scene	Binding
Hits						
Repeated	.87 (.07)	.82 (.12)	.85 (.08)	.80 (.14)	.77 (.17)	.77 (.17)
Nonrepeated	.85 (.07)	.80 (.14)	.86 (.07)	.81 (.18)	.67 (.19)	.69 (.22)
False alarms						
Repeated	.30 (.22)	.26 (.19)	.39 (.16)	.37 (.22)	.34 (.24)	.60 (.27)
Nonrepeated	.21 (.16)	.29 (.16)	.45 (.23)	.21 (.13)	.28 (.18)	.60 (.25)
Hits minus false alarms						
Repeated	.58 (.21)	.56 (.23)	.46 (.18)	.43 (.26)	.43 (.28)	.18 (.26)
Nonrepeated	.64 (.16)	.51 (.22)	.42 (.21)	.60 (.21)	.39 (.24)	.09 (.32)
A′						
Repeated	.86 (.08)	.85 (.11)	.82 (.08)	.78 (.16)	.79 (.15)	.63 (.19)
Nonrepeated	.89 (.06)	.83 (.11)	.80 (.09)	.86 (.12)	.77 (.13)	.55 (.23)
d′						
Repeated	1.79 (0.63)	1.71 (0.72)	1.39 (0.55)	1.29 (0.82)	1.32 (0.86)	0.53 (0.80)
Nonrepeated	1.97 (0.53)	1.54 (0.69)	1.29 (0.59)	1.83 (0.68)	1.15 (0.72)	0.24 (0.93)

Finally, paired-samples *t* tests revealed that the reduction in performance between the AS blocks and the BC-2 blocks was significant in each test condition—for example, $\text{face}_{AS:}$ $M = .88$, $SD = .06$ vs. $\text{face}_{BC\text{-}2:}$ $M = .82$, $SD = .10$, $t(27) = 3.46$, $p = .002$; $\text{scene}_{AS:}$ $M = .84$, $SD = .10$ vs. $\text{scene}_{BC\text{-}2:}$ $M = .78$, $SD = .09$, $t(27) = 2.78$, $p = .01$; $\text{item}_{AS:}$ $M = .86$, $SD = .07$ versus $\text{item}_{BC\text{-}2:}$ $M = .80$, $SD = .06$, $t(27) = 4.64$, $p < .001$; $\text{binding}_{AS:}$ $M = .81$, $SD = .06$ versus $\text{binding}_{BC\text{-}2:}$ $M = .59$, $SD = .17$, $t(27) = 7.77$, $p < .001$. Difference scores (average AS minus average BC-2) were computed for each participant for the item tests and binding tests and compared using a paired-samples *t* test, which revealed that divided attention had a significantly greater impact, $t(27) = -5.32$, $p < .001$, on binding memory performance ($M_\Delta = .22$, $SD = .15$) compared with item memory performance ($M_\Delta = .06$, $SD = .07$).[5]

Converging with the results observed in Experiment 1, in Experiment 2 the repetition by test interaction, $F(2, 54) = 5.10$, $p = .01$, $\eta_p^2 = .16$, was significant. Separate 2 × 2 repeated-measures ANOVAs were used to examine the repetition by test interaction. The 2 × 2 examining the face and scene test comparison across both repeated and nonrepeated stimuli blocks revealed a significant repetition by test interaction, $F(1, 27) = 7.67$, $p = .01$, $\eta_p^2 = .22$. Moreover, the interaction between the face and binding test comparison across both levels of repetition was significant, $F(1, 27) = 8.02$, $p = .009$, $\eta_p^2 = .23$. The interaction between the scene and binding tests across both levels of repetition, however, was nonsignificant, $F(1, 27) = .67$, $p = .42$. Follow-up paired-samples *t* tests revealed that the overall repetition by test interaction was driven by significantly greater face test performance during nonrepeated ($M = .88$, $SD = .07$) compared with repeated ($M = .82$, $SD = .10$) blocks, $t(27) = -2.81$, $p = .009$. No significant differences were observed between scene test performance during repeated ($M = .82$, $SD = .11$) and nonrepeated ($M = .80$, $SD = .07$), blocks, $t(27) = .92$, $p = .37$, or between binding test performance during repeated ($M = .72$, $SD = .11$) and nonrepeated ($M = .67$, $SD = .13$), blocks, $t(27) = 1.79$, $p = .084$.

Memory accuracy analyses—Hits. Separate 2 × 2 × 3 ANOVAs were applied to both the proportion hits data and the proportion false alarms data. The proportion hits analysis revealed a main effect of load, $F(1, 27) = 25.62$, $p < .001$, $\eta_p^2 = .49$, with greater hit rates under AS ($M = .84$, $SD = .05$) compared with BC-2 ($M = .75$, $SD = .08$), and a main effect of test, $F(2, 54) = 5.53$, $p = .007$, $\eta_p^2 = .17$. Hit rates were significantly higher during the face tests ($M = .83$, $SD = .07$) compared with the scene tests ($M = .76$, $SD = .08$, $p = .01$, Bonferroni corrected). There was no significant difference between face and binding performance ($M = .79$, $SD = .08$, $p = .22$, Bonferroni corrected), and no difference between scene and binding performance ($p = .44$, Bonferroni corrected). The main effect of repetition was not significant, $F(1, 27) = 3.29$, $p = .08$, with similar hit rates in both the repeated ($M = .81$, $SD = .05$) and nonrepeated ($M = .78$, $SD = .07$) conditions. No interactions pertaining to the hit rate data were significant (all *p's* > .11).

Memory accuracy analyses—False alarms. The proportion of false alarms analysis revealed a pattern similar to the *A′* results. The main effect of load, $F(1, 27) = 22.29$, $p < .001$, $\eta_p^2 = .45$), was significant, with higher false alarm rates in the BC-2 ($M = .40$, $SD = .12$) relative to the AS ($M = .32$, $SD = .10$) blocks. A main effect of test was present, $F(2, 54) = 37.16$, $p < .001$, $\eta_p^2 = .58$, with higher false alarm rates during the binding tests ($M = .51$, $SD = .16$) relative to the scene tests ($M = .29$, $SD = .11$), and finally the face tests ($M = .27$, $SD = .13$). The comparison between face and binding false alarm rates ($p < .001$, Bonferroni corrected) and scene and binding false alarm rates ($p < .001$, Bonferroni corrected) were both significant, although the difference between face and scene false alarm rates was not significant ($p = .47$). No main effect of repetition (repeated: $M = .37$, $SD = .13$; nonrepeated: $M = .34$, $SD = .09$) was evident in the false alarm rates, $F(1, 27) = 2.27$, $p = .14$. As was the case in the *A′*

[5] The same 2 × 2 × 3 repeated-measures ANOVA, follow-up 2 × 2 ANOVAs, and paired-samples t-tests were applied to the *d′* and proportion hits minus false alarms values, which yielded the same pattern of significant main effects and, it is important to note that a significant load by test interaction and a significant repetition by test interaction. No other interaction effects were significant.

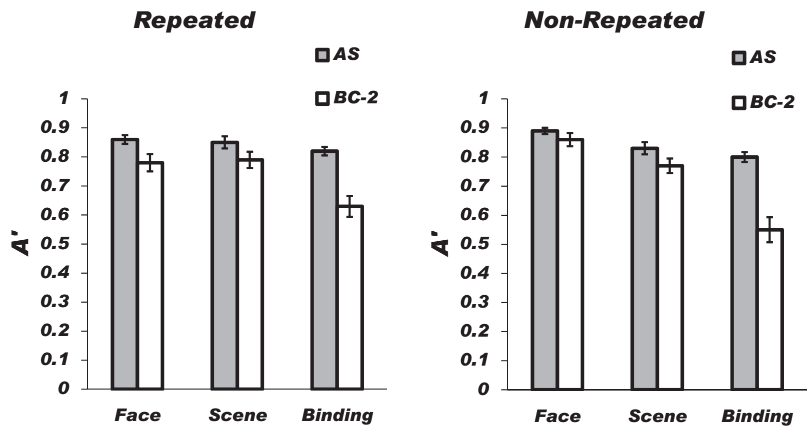

Figure 3. Experiment 2: Recognition performance under articulatory suppression and backward counting as a function of stimulus repetition. Behavioral results for Experiment 2 test types (face, scene, face–scene binding) as a function of stimulus repetition (repeated, nonrepeated). The abscissa depicts performance in each test type corresponding to the articulatory suppression (AS) and backward counting by two (BC-2) blocks of the experiment, whereas the mean A' value corresponding to each condition is plotted along the ordinate. Error bars represent the standard error of the mean in each test condition.

results, the load by test interaction pertaining to the false alarm rates analysis was significant, $F(2, 54) = 6.30$, $p = .004$, $\eta_p^2 = .19$. Additionally, the repetition by test, $F(2, 54) = 3.87$, $p = .029$, $\eta_p^2 = .13$, and the repetition by load, $F(1, 27) = 4.86$, $p = .036$, $\eta_p^2 = .15$, interactions were significant. The triple interaction between repetition × load × test, $F(2, 54) = .10$, $p = .89$, was not significant.

Further examination of the load by test interaction was carried out using 2 × 2 repeated-measures ANOVAs. The load by test interaction comparing face and scene performance as a function of concurrent load was nonsignificant, $F(1, 27) = .01$, $p = .91$. In contrast, in all remaining 2 × 2 comparisons, the load by test interaction was significant (face vs. binding: $F(1, 27) = 11.11$, $p = .003$, $\eta_p^2 = .29$; scene vs. binding: $F(1, 27) = 8.03$, $p = .009$, $\eta_p^2 = .23$; item (i.e., the average of face test and scene test performance) versus binding: $F(1, 27) = 12.13$, $p = .002$, $\eta_p^2 = .31$). Paired-samples t tests revealed that the difference in false alarm rates between the AS blocks and the BC-2 blocks was significant only during the binding tests— $\text{binding}_{\text{AS:}}$ $M = .42$, $SD = .15$ vs. $\text{binding}_{\text{BC-2:}}$ $M = .60$, $SD = .22$, $t(27) = -4.85$, $p < .001$. No other significant differences in false alarm rates were evident, for example, $\text{face}_{\text{AS:}}$ $M = .25$, $SD = .15$ vs. $\text{face}_{\text{BC-2:}}$ $M = .29$, $SD = .14$, $t(27) = -1.56$, $p = .13$; $\text{scene}_{\text{AS:}}$ $M = .28$, $SD = .14$ vs. $\text{scene}_{\text{BC-2:}}$ $M = .31$, $SD = .14$, $t(27) = -.99$, $p = .33$; $\text{item}_{\text{AS:}}$ $M = .26$, $SD = .11$ versus $\text{item}_{\text{BC-2:}}$ $M = .30$, $SD = .11$, $t(27) = -1.92$, $p = .066$.

Given the presence of an overall repetition by test interaction, separate 2 × 2 repeated-measures ANOVAs were used to compare false alarm rates associated with the repeated and nonrepeated stimuli blocks during the various test conditions. The comparison of false alarm rates during face and scene tests, $F(1, 27) = 4.50$, $p = .043$, $\eta_p^2 = .14$, the comparison of face and binding tests, $F(1, 27) = 8.03$, $p = .009$, $\eta_p^2 = .23$, across the repeated and nonrepeated stimuli blocks, both revealed a significant repetition by test interaction. The repetition by test interaction was not significant for the comparison of the scene and binding test false alarm rates, $F(1, 27) = .42$, $p = .52$, during repeated and nonrepeated stimuli blocks.

As was the case in the analysis of the A' data, paired-samples t tests revealed that the repetition by test interaction corresponding to the false alarm rates was driven by greater false alarm rates for the face tests occurring during the repeated ($M = .33$, $SD = .19$) relative to the nonrepeated ($M = .21$, $SD = .11$) blocks, $t(27) = 3.65$, $p = .001$. No difference in false alarm rates as a function of stimulus repetition was evident during the scene tests—$\text{scene}_{\text{repeated:}}$ $M = .30$, $SD = .19$ vs. $\text{scene}_{\text{nonrepeated:}}$ $M = .29$, $SD = .10$, $t(27) = .21$, $p = .83$—or the binding tests—$\text{binding}_{\text{repeated:}}$ $M = .49$, $SD = .19$ vs. $\text{binding}_{\text{nonrepeated:}}$ $M = .53$, $SD = .19$, $t(27) = -.75$, $p = .46$.

Finally, paired-samples t tests were used to examine the repetition by load interaction corresponding to the overall analysis of the false alarm rates. No significant difference in false alarm rates under AS was found when comparing performance during the repeated ($M = .31$, $SD = .13$) and nonrepeated ($M = .32$, $SD = .10$) blocks, $t(27) = -.10$, $p = .92$. However, false alarm rates were significantly higher during repeated ($M = .43$, $SD = .15$) relative to nonrepeated ($M = .37$, $SD = .13$) blocks under BC-2, $t(27) = 2.23$, $p = .035$.

Analysis of the number of successful verbalizations and two-digit subtractions in the AS and BC-2 conditions. Finally, the mean number of successful verbalizations and the mean number of successful two-digit subtractions verbalized during trials of the AS and BC-2 blocks of the experiment, respectively, were computed for each participant for each experimental condition and submitted to a 2 (repetition) by 2 (load) by 3 (test) repeated-measures ANOVA (see Table 5). This ANOVA revealed no significant main effect of test, $F(2, 54) = .01$, $p = .98$, and no significant main effect of repetition, $F(1, 27) = .05$, $p = .82$, however, the main effect of load was significant, $F(1, 27) = 23.55$, $p < .001$, $\eta_p^2 = .47$. This main effect of load was driven by a greater overall number of successful verbalizations during the AS ($M = 6.58$, $SD = 1.54$) relative to the BC-2 ($M = 4.74$, $SD =$

Table 5
Successful Articulations and Subtractions in Each Condition Verbalized during the Concurrent Articulatory Suppression or Backward Counting Tasks in Experiment 2

Concurrent load	Face	Scene	Binding
Articulatory suppression			
Repeated	6.68 (1.61)	6.60 (1.68)	6.49 (1.50)
Nonrepeated	6.54 (1.57)	6.59 (1.54)	6.56 (1.57)
BC-2			
Repeated	4.72 (1.11)	4.74 (1.17)	4.75 (1.15)
Nonrepeated	4.68 (1.25)	4.71 (1.09)	4.83 (1.17)

Note. Mean responses produced in each concurrent task are depicted with standard deviations in parentheses. BC-2 = backward counting by two-digits.

1.13) blocks, indicating that the BC-2 task was more demanding than the AS task.

Discussion

The current experiment examined the impact of divided attention (i.e., AS compared with BC-2) on single-item (i.e., faces, scenes) and item–item (i.e., face–scene pairs) binding performance during a VWM change detection task. As was the case in Experiment 1, stimuli were either sampled with (i.e., repeated) or without (i.e., nonrepeated) replacement across trials throughout distinct blocks of the experiment. The results of the current experiment revealed a divided-attention related binding deficit that did not vary across repeated and nonrepeated stimulus presentation blocks. Namely, a greater reduction in item–item binding, relative to single-item (i.e., face or scene), performance was evident under higher (i.e., BC-2) relative to lower (i.e., AS) levels of concurrent load. Separate analyses of the hit rates and false alarm rates revealed that these results were driven primarily by the false alarm rates rather than the hit rates. Specifically, higher levels of concurrent load (i.e., BC-2 relative to AS) led to a greater increase in false alarm rates during tests of item–item binding relative to single items (e.g., faces or scenes). The current findings are in line with those observed in Experiment 1. However, the current results extend the findings of Experiment 1 and suggest that this divided attention-related binding deficit is not solely due to the prevention of verbal recoding or rehearsal, but rather, seems to emerge in a robust fashion when additional attentional resources are diverted away from the primary VWM change detection task.

Several other patterns emerged from the results of the current experiment, the first of which replicated findings observed in Experiment 1. As was the case in Experiment 1, the current experiment revealed that VWM performance during tests of individual faces was greater under nonrepeated relative to repeated stimulus conditions. Additionally, this effect was also driven by false alarm rates, rather than hit rates, given that false alarm rates were higher when faces were repeated across trials throughout the blocks of the experiment. This impact of stimulus repetition on VWM performance was not evident during tests of individual scenes or face–scene binding. Finally, novel to the current experiment, regardless of test probe condition, false alarm rates under BC-2 were higher during repeated compared with nonrepeated stimulus presentation blocks. In contrast, no difference in false alarm rate as a function of stimulus repetition was evident under AS. This suggests that under more demanding divided attention tasks, stimulus repetition hinders overall VWM performance via an increased rate of false alarms.

General Discussion

The current study replicated and extended recent novel results regarding the effects of divided attention on item–item binding in VWM tasks, by examining the role of stimulus repetition on previously identified divided attention-related item–item binding deficits in VWM. Experiment 1 revealed the presence of a divided attention-related binding deficit regardless of whether item components (i.e., faces, scenes) were repeated or not repeated during the encoding periods across the trials of the experiment. This binding deficit was defined by greater decreases in item–item binding performance relative to single-item performance under AS compared with no concurrent load. Replicating and extending the results of Experiment 1, Experiment 2 revealed the same pattern indicative of a robust divided attention-related binding deficit, which occurred during both repeated and nonrepeated block of the experiment. Notably, in Experiment 2, the AS and BC-2 verbal response data indicated that participants were able to make fewer secondary task responses under BC-2 relative to AS. As such, the BC-2 task appeared to be, overall, a more demanding secondary task than AS.

To this point, a large subset of participants from Experiment 1 ($n = 36$)[6] and from Experiment 2 ($n = 39$)[7] met exclusion criteria by exhibiting chance or below chance-level performance under either no load (Experiment 1) or under AS (Experiment 2) preventing any meaningful comparisons of item and binding performance under higher concurrent load (i.e., AS in Experiment 1, or BC-2 in Experiment 2). However, as noted in footnotes 6 and 7, the included and excluded participants in both experiments did not differ in terms of potential intellectual ability (ACT scores) or educational attainment (GPA), increasing one's confidence in the representativeness of the samples used in the analyses. Nevertheless, additional studies will be beneficial toward elucidating whether the high exclusion rate observed in the current experiments were due simply to the difficult nature of the current dual task conditions or perhaps was esoteric to the current sample

[6] Separate independent samples t-tests were used to compare both GPA and ACT between those participants included and those excluded from the group-level analyses in Experiment 1. For a subset of participants willing to provide their GPA ($n = 8$ included ($M = 3.63$, $SD = .51$) and n = 11 excluded ($M = 3.36$, $SD = .45$)) and ACT ($n = 16$ included ($M = 26.88$, $SD = 2.39$), $n = 15$ excluded ($M = 26.40$, $SD = 3.16$)) scores, we found no difference in these auxiliary measures—GPA: $t(17) = 1.23$, $p = .24$; ACT: $t(29) = .47$, $p = .64$—suggesting that, aside from memory performance in the current task, those included and excluded participants were otherwise similar.

[7] The same analyses (see Footnote 6) were used to compare both GPA and ACT between those participants included and those excluded from the group-level analyses in Experiment 2. For a subset of participants willing to provide their GPA ($n = 13$ included ($M = 3.34$, $SD = .47$) and $n = 21$ excluded ($M = 3.23$, $SD = .43$)) and ACT ($n = 13$ included ($M = 27.00$, $SD = 3.46$), $n = 22$ excluded ($M = 27.05$, $SD = 3.79$)) scores, we found no difference in these auxiliary measures—GPA: $t(32) = .69$, $p = .50$; ACT: $t(33) = -.04$, $p = .97$—suggesting that, aside from memory performance in the current task, those included and excluded participants were otherwise similar.

selected. Acknowledging these limitations, perhaps decreasing the overall difficulty of the current dual task parameters while attempting to provide a partial replication of the current findings using a novel sample would be beneficial.

Moreover, even for the higher performing participants retained in the group level analyses of both experiments, a marked reduction in VWM binding performance was evident under higher levels of concurrent load (i.e., AS in Experiment 1, BC-2 in Experiment 2) relative to the lower levels of concurrent load (i.e., No Load in Experiment 1, AS in Experiment 2). Specifically, across both experiments, this binding deficit emerged from the comparison of single-item and item–item binding performance under higher relative to lower levels of concurrent load, during which a disproportionate decrease in binding, relative to single-item, performance was evident. Together, the findings from the current experiments replicate and extend recent findings (i.e., Peterson & Naveh-Benjamin, 2017), which suggest that, relative to single-item components, a greater amount of attentional resources are required to form and maintain item–item bindings within VWM.

In the context of the extant literature that has examined the role of attention in VWM binding processes, the current findings support the position that attention is necessary during the formation and maintenance of bindings in VWM. This position stands in contrast to the majority of previous findings examining the role of attention in VWM binding. For instance, many studies have found that divided, relative to full, attention during VWM tasks results in a similar decrease in performance when either single features or binding between features are tested (Allen et al., 2006, 2014; Allen et al., 2012; Gajewski & Brockmole, 2006; Johnson et al., 2008; Morey & Bieler, 2013; van Lamsweerde & Beck, 2012; Vergauwe et al., 2014). It is likely, however, that the important difference between these previous findings and the current findings is due to the type of binding required by the VWM task.

Indeed, these previous studies have focused on the intra-item form of binding (e.g., color–shape stimuli) in which the features are intrinsic to the to-be-remembered items within the stimulus array. In contrast, our recent and current findings, which have examined the item–item variant of VWM binding, have shown a consistent and robust pattern of a divided attention-related binding deficit (Peterson & Naveh-Benjamin, 2017). General findings from the VWM literature suggest that to-be-remembered features which belong to the same object (i.e., intrinsic) correspond to higher levels of performance than those which are spatially distinct (i.e., extrinsic) and seemingly do not appear to "belong" to the same object (Xu, 2002). Likewise, both spatial and temporal contiguity of individual features (e.g., color, shape) enhance VWM binding performance (Karlsen, Allen, Baddeley, & Hitch, 2010). By comparison, previous findings from the literature were derived from stimuli (e.g., color, shape), which required an intrinsic (i.e., intra-item) form of binding whereas the current study focused on a more extrinsic form (i.e., item–item) of binding. It may be the case that this extrinsic form of binding temporarily taxes an episodic buffer component within WM, thus requiring a greater amount of central executive resources than other, more intrinsic forms (e.g., intra-item), for which the visuospatial processing component may be sufficient (see Allen et al., 2006; Baddeley, 2000; See also a similar distinction in results of aging, e.g., Peterson & Naveh-Benjamin, 2016).

In the context of the multiple-component model (see Baddeley, 2000), it may be argued that the VWM binding deficits observed in the current experiments were merely the result of the prevention of verbal recoding or rehearsal. Indeed, in Experiment 1 binding performance during an AS task was compared with performance under no concurrent load. Given that AS tasks are typically used to prevent rehearsal, at first glance, the binding deficit observed in Experiment 1 may appear to have been due to the prevention of rehearsal, which may have been more detrimental during item–item binding relative to single-item test probes. However, the results of Experiment 2, in which VWM binding performance under AS was compared with performance under BC-2, revealed the same pattern indicative of a divided attention-related binding deficit. Given the overall lower levels of performance observed in Experiment 2 under BC-2, this more demanding concurrent task conceivably required additional resources, over and beyond those used to verbalize the next number in the two-digit subtraction sequence.

The influence of a verbal rehearsal mechanism cannot be definitively ruled out as a factor contributing to the binding deficits observed in the current experiments. However, the observance of a robust divided attention-related VWM binding deficit under varying levels of concurrent task difficulty (e.g., AS, BC-2) suggests that the recruitment of domain-general attention is necessary during item–item binding in VWM. Indeed, in Experiment 2, participants made fewer verbalizations under BC-2 relative to AS, suggesting that a greater amount of domain-general attention was required when performing the BC-2 task relative to the AS task. Moreover, the current interpretations are consistent with those from recent findings based on experiments that used nearly identical task paradigms (Peterson & Naveh-Benjamin, 2017). It is important to note that the current findings provide an essential replication of the findings from Peterson and Naveh-Benjamin (2017), which were the first to identify a divided-attention related binding deficit in a VWM paradigm requiring item–item binding. Likewise, beyond replication of these recent results, the current experiments showed a robust pattern of evidence indicating that stimulus repetition (of faces and scenes) across trials of the experiment did not mediate the magnitude of the divided attention-related binding deficit.

Another goal of the current study was to examine potential explanations as to why divided attention-related item–item binding deficits are evident in VWM studies, but not in LTM studies. For instance, divided attention tasks have a similar detrimental impact on both item and item–item binding performance during LTM tasks (Naveh-Benjamin et al., 2003; Naveh-Benjamin et al., 2014). One potentially important difference between VWM tasks and LTM tasks relates to the methodology implemented in each of these fields of memory research. An important difference between VWM and LTM tasks is that stimuli are typically sampled with replacement across trials of the experiment in the former, but sampled without replacement in the latter. In contrast to this potential influence of stimulus repetition, however, the current experiments provided no evidence that the magnitude of the observed divided attention-related binding deficit changed as a function of whether individual face and scene stimuli were repeated or not repeated across trials of the experiment.

The lack of a mediating influence of stimulus repetition on the current item–item binding deficits is important for several reasons.

First, one extraneous factor regarding recently observed divided attention-related item–item binding deficits in VWM relates to the notion that stimulus repetition of the individual components (i.e., faces, scenes) may have simply increased item familiarity across trials of the experiment (Peterson & Naveh-Benjamin, 2017). In turn, the use of repeated stimuli could have led to a disproportionately higher false alarm rate under divided attention during tests of item–item binding, relative to single-item tests, based on item familiarity with the components. As such, the influences of divided attention and stimulus repetition on item–item binding performance were confounded in this recent VWM study. However, the fact that a general divided attention binding deficit was observed in the current experiments, across both repeated and nonrepeated stimuli blocks of the experiment, suggests that stimulus repetition alone is insufficient to explain this pattern of results.

Second, false alarm rates in the current experiments were disproportionately higher during item–item binding tests compared with single-item tests under divided attention during both repeated and nonrepeated stimuli blocks of the experiments. As such, the notion that item familiarity contributed to the increased false alarm rates during recombined item–item binding tests, due to the repeated use of the same set of item components appears to be an insufficient explanation for this pattern of results. Rather, the current results suggest that when attentional resources are divided between the VWM task and a concurrent load task (i.e., AS, BC-2), false alarm rates increase to a greater extent during item–item binding tests relative to single-item tests. Finally, the lack of a stimulus repetition effect in the current experiments suggests that the role of attention in tasks that involve VWM binding is fundamentally distinct from associative LTM tasks. Although future item–item binding experiments that directly compare repeated and nonrepeated item components at both VWM and LTM retention intervals are necessary, the current study provides novel evidence that divided attention differentially impacts binding relative to single-item performance in VWM regardless of stimulus repetition.

Given that stimulus repetition (i.e., sampling) techniques, which comprise a salient methodological distinction between the VWM and LTM literatures, appear to not play a role in the magnitude of divided attention-related item–item binding (i.e., associative) deficits observed in VWM, what other factors might explain the differential role of attention in binding processes across these two memory domains? The following possibilities, aside from the stimulus repetition/replacement methodological factors examined here, may account for the differential role of attention in binding processes occurring within VWM and LTM.

First, the presentation rates at which stimuli are presented within the encoding period are generally short in VWM paradigms, but much longer in LTM paradigms. Indeed, previous findings, derived from an item and associative LTM memory paradigm, indicate that shorter presentation rates (e.g., 1.5 s) result in a large associative memory deficit, whereas longer presentation rates (e.g., 6 s) lead to similar levels of item and associative memory performance (Brubaker & Naveh-Benjamin, 2014).

Comparatively, the current and recent (Peterson & Naveh-Benjamin, 2017) VWM findings, in which a divided attention-related binding deficit was evident, used presentation rates spanning the range of 2–3 s. In contrast, previous LTM findings had used presentation rates of 7 s, finding no differential impact of divided attention on item and associative memory processes (Naveh-Benjamin et al., 2003). Conceivably, when participants have more time to form associations during encoding, as was the case in previous LTM experiments, divided attention tasks may be less detrimental to associative (i.e., binding), relative to item, memory performance. In contrast, given the relatively short presentation rates used in most VWM experiments, during which binding between distinct components would have to occur quite quickly, divided attention tasks seem to have a profound impact on associative, relative to item, memory performance.

Second, the rate at which item and associative information is forgotten varies with respect to retention interval, such that item memory performance levels are much higher than associative memory performance at shorter retention intervals (Hockley, 1992). In contrast, at longer retention intervals, the magnitude of the difference between item and associative memory performance is much smaller (Hockley, 1992). These findings suggest that, although forgetting rates are, curiously, larger for item compared with associative memory at shorter delays, these forgetting rates for item and associative memory become more similar at longer delays. Thus, given this pattern of results, we might expect divided attention to play a more diminishing role on VWM (i.e., shorter delays) binding processes relative to LTM (i.e., longer delays) binding processes. This distinction between item and associative memory performance as a function of retention interval may implicate separate initial consolidation mechanisms, potentially contributing to the apparent dissociation in the role of attention in VWM and LTM binding processes. Replicating and extending recent findings within the VWM domain, the current results suggest that divided attention-related binding deficits are notable when distinct item components (i.e., faces and scenes) must be bound into an integrated representation during a relatively short presentation rate, maintained over the duration of a short retention interval, and accurately retrieved from VWM.

Finally, the factor of set size, (i.e., the amount of items presented in the stimulus array), varies between VWM and LTM studies. For instance, in the current VWM study, to create recombination (i.e., "change") trials during tests of face–scene binding, two face–scene pairs (i.e., 4 items) needed to be presented during the stimulus array. In contrast, in comparable LTM studies typically only one face–scene pair (i.e., 2 items) is presented within each stimulus array given that face–scene pairs can be recombined at test with one the many other independent face–scene pairs that had appeared originally during the study phase. This important methodological difference, which contributes to the overall difference in set size typically used in VWM and LTM studies, may mediate the divided attention-related binding deficit. Specifically, the larger set sizes typical of VWM studies may be harder to maintain, relative to the smaller set sizes used in LTM studies, when simultaneously performing a challenging divided attention task. Notably, other preliminary results from our lab using a continuous recognition task involving single associative pairs (i.e., set size of 2 items) tested at both VWM and LTM intervals have revealed a divided attention-related binding deficit at VWM intervals. Thus, it may be the case that, even when set size is equated, divided attention-related deficits are robust within the time-course of VWM but not LTM.

Conclusions

Results from the current experiments replicate previous novel findings of a divided attention-related binding deficit in VWM for face–scene pairs (Peterson & Naveh-Benjamin, 2017). Furthermore, the divided attention binding deficit in both Experiment 1 and Experiment 2 was evident during both repeated and nonrepeated stimuli blocks of the experiment in which the item components (i.e., faces, scenes) used to create the face–scene pairs were either sampled with or without replacement. Distinct from previous findings in both the VWM and LTM literatures, which suggest that divided attention has a similar impact on both memory for single-items (or features) and binding between these items (or features), the current findings suggest that attention plays a vital role in binding processes in VWM.

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