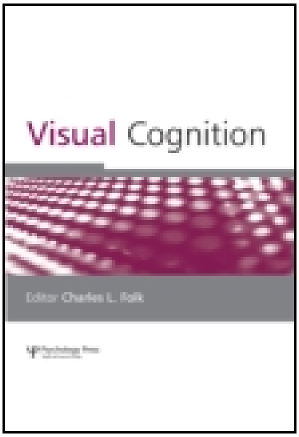

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Attention shifts or volatile representations: What causes binding deficits in visual working memory?

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Attention shifts or volatile representations: What causes binding deficits in visual working memory?

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The current study tested two hypotheses of feature binding memory: The *attention hypothesis*, which suggests that attention is needed to maintain feature bindings in visual working memory (VWM) and the *volatile representation hypothesis*, which suggests that feature bindings in memory are volatile and easily overwritten, but do not require sustained attention. Experiment 1 tested the attention hypothesis by measuring shifts of overt attention during the study array of a change detection task; serial shifts of attention did not disrupt feature bindings. Experiments 2 and 3 encouraged encoding of more volatile (Experiment 2) or durable (Experiment 3) representations during the study array. Binding change detection performance was impaired in Experiment 2, but not in Experiment 3, suggesting that binding performance is impaired when encoding supports a less durable memory representation. Together, these results suggest that although feature bindings may be volatile and easily overwritten, attention is not required to maintain feature bindings in VWM.

Keywords: Attention; Binding; Visual short-term memory; Visual working memory.

The ability to detect changes to visual objects requires that the objects are attended (Rensink, O'Regan, & Clark, 2000) and stored in visual working memory (VWM; Luck & Vogel, 1997). In a change detection task, a person views a (study) array of objects, followed by an interstimulus interval (ISI), then a second (test) array of objects and determines if any objects changed from the study array to the test array. The failure to detect such changes (change blindness) is of particular interest because it reveals how objects and their features are stored in VWM. Interestingly, it appears that it may be

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more difficult to detect changes when two objects trade features (e.g., a red square and an orange circle change to an orange square and a red circle) than to detect that an object changes to a new feature entirely (e.g., a red square changes to a blue square; Wheeler & Treisman, 2002). Detecting these binding changes requires that the viewer store each feature of a display and that they remember which features belong together; in contrast, detecting a feature change requires only that the viewer remember all of the features. In this study, we investigate why changes to feature bindings may be particularly difficult to detect.

First, it is possible that bindings are difficult to detect because feature bindings are not encoded into memory, or are encoded with a less complete representation than individual features. However, previous research has demonstrated that this is unlikely (Alvarez & Thompson, 2009; Wheeler & Treisman, 2002). Second, feature bindings may be difficult to maintain in VWM because they are vulnerable to disruption. Two possible types of disruption have been proposed: Disruptions arising from shifts of attention (*attention hypothesis*; Fougnie & Marois, 2009; Wheeler & Treisman, 2002) or from new visual stimuli (*volatile representation hypothesis*; Allen, Baddeley, & Hitch, 2006; Alvarez & Thompson, 2009). The goal of the current study was to examine whether the attention hypothesis or the volatile representation hypothesis better accounts for the failure to detect binding changes.

Wheeler and Treisman (2002) proposed that feature bindings require attention in order to be maintained in VWM (attention hypothesis), because they found that presenting a new array of several objects resulted in binding memory deficits, whereas presenting a single test object did not. According to the attention hypothesis, when the array of new objects was presented, these objects demanded attention for the creation of new perceptual feature bindings (Hyun, Woodman, & Luck, 2009; Prinzmetal, Presti, & Posner, 1986; Shafritz, Gore, & Marois, 2002; Treisman, Sykes, & Gelade, 1977; Treisman, 1999; Treisman & Gelade, 1980; Tsal & Lavie, 1988). The withdrawal of attention from the items in memory to the items on the test array caused the feature bindings in memory to be selectively lost (Wheeler & Treisman, 2002). It is important to note that the attention hypothesis rests on the assumption that the bindings were encoded into memory, because a shift in attention cannot lead to the loss of something that did not exist. Some research supports this hypothesis: Introduction of a multiple object tracking (MOT) task during the ISI of a change detection task creates a greater disruption to bindings than features (Fougnie & Marois, 2009), as does a backwards counting task throughout the entire trial (Brown & Brockmole, 2010).

However, multiple studies have shown that simple shifts of attention do not disrupt binding memory (Gajewski & Brockmole, 2006; Yeh, Yang, &

Chiu, 2005). For example, after introducing a retrocue (a cue that is presented after the offset of the study array) to orient attention to an object from the study array, participants were able to report both the colour and shape of a test item that was not cued (Gajewski & Brockmole, 2006). Rarely did participants remember one feature but not the other. However, under the assumption of the attention hypothesis, the cue should have served to orient attention away from the test item, breaking the bindings and increasing the likelihood that participants would remember only a single feature of the object. In addition, valid retrocues improve performance for both bindings and features equally (Delvenne, Cleeremans, & Laloyauz, 2010) and a visual search task introduced during the ISI also failed to produce a binding deficit (Johnson, Hollingworth, & Luck, 2008). These results suggest that shifts of attention are insufficient to disrupt binding performance. What then, can explain why a binding deficit does occur in some situations?

Other possible explanations for why binding deficits occur include (1) the bindings are not encoded as completely as features or (2) the binding representations are not as durable as representations for features. As noted earlier, research has not supported the former explanation (Alvarez & Thompson, 2009; Wheeler & Treisman, 2002). However, several authors have demonstrated evidence to support the latter explanation (Allen et al., 2006; Alvarez & Thompson, 2009; Logie, Brockmole, & Vandenbroucke, 2009). Alvarez and Thompson (2009) found that when participants were given a cued recall test for one feature of an object without presenting test items, they could report the other feature of the cued object with very high accuracy. This suggests that the binding representations were encoded. However, detecting a feature switch in which colours appeared at new locations was more difficult, suggesting that feature bindings were easily disrupted by new information. Logie et al. (2009) also reported evidence suggesting that binding representations are more easily overwritten than feature representations. Participants were better at detecting binding changes if the shape and colour bindings repeated on every trial, but not if they repeated on every third trial. The authors concluded that without repetitions on every trial, fragile memory representations of feature bindings are easily overwritten by new visual stimuli (Logie et al., 2009).

Previous research suggests that change blindness may occur because memory representations are volatile and vulnerable to disruption (Beck & Levin, 2003). The volatile representation hypothesis assumes that bindings are easily overwritten by new feature bindings because they are stored in a particularly volatile state in VWM. Therefore, it is the encoding of new bindings, not the shifts of attention, that cause reduced change detection performance. Furthermore, if binding deficits occur because feature bindings are fragile and easily overwritten in VWM (Allen et al., 2006; Alvarez &

Thompson, 2009; Logie et al., 2009), then binding deficits should not occur if more durable representations of feature bindings can be formed.

We propose that, if the volatile representation hypothesis is correct, then feature bindings should no longer be more vulnerable to disruption than features *if* participants are given the opportunity to create a more durable memory representation. In a typical binding test, study arrays are presented for a very short period of time (150–500 ms; Delvenne et al., 2010; Fougnie & Marois, 2009; Gajewski & Brockmole, 2006; Johnson et al., 2008; Wheeler & Treisman, 2002). This promotes distributed attention and allows only a short encoding time, both of which contribute to poor memory performance (Delvenne et al., 2010; Heubner & Gegenfurtner, 2010; Makovski & Jiang, 2007; Vandenbroucke, Sligte, & Lamme, 2011). Although rapid encoding can lead to complete representations, the representation may be more volatile and more easily overwritten (Alvarez & Thompson, 2009; Vogel, Woodman, & Luck, 2006). In addition to longer encoding time increasing the durability of a representation, orienting attention to an object either covertly (Makovski & Jiang, 2007) or overtly (Heubner & Gegenfurtner, 2010) increases memory performance for that object. Therefore, in the current study we encourage durable binding representations by allowing more encoding time and focused attention.

Makovsi and Jiang (2007) found that distributed attention led to representations that were easily disrupted by new visual information, but focal attention led to more durable representations. After distributed attention encoding of the study array, providing a valid cue to the location of an object, thereby engaging focal attention, prior to the onset of the test object (a retrocue), improved performance for reporting whether the test object was old or new (a typical retrocue effect: Landman, Spekreijse, & Lamme, 2003; Makovski, Sussman, & Jiang, 2008; Sligte, Scholte, & Lamme, 2008). However, if an interference display was presented after distributed attention encoding and prior to the retrocue, the cue advantage disappeared. Therefore, without focal attention prior to interference, volatile representations encoded under distributed attention will be easily disrupted.

Not only does focal attention on a memory representation improve durability of the representation, but focal attention during encoding does as well. Specifically, memory is better for fixated items than nonfixated items when encoding times are short (Heubner & Gegenfurtner, 2010). Participants viewed nine real-world objects in a circle for either a variable amount of time (1000, 3000, or 7000 ms) or a variable number of fixations (three, seven, or 10). Overall performance was higher as encoding time increased, suggesting that longer encoding times allow more durable representations to form. In addition, when encoding time was short (1000 ms or three fixations), memory performance was better for fixated items than nonfixated items. Therefore, when there is not sufficient time to fixate each item, serial shifts of overt attention facilitate durable memory representations for the items that are fixated. Experiments 1 and 3 of the current study encouraged durable memory representations with longer encoding times and focused attention on individual objects.

The goal of the current study was to directly test the attention and volatile representation hypotheses by measuring shifts of attention and varying the durability of memory representations. The attention hypothesis was tested in Experiment 1 by determining *which* object was within the focus of attention and directly testing binding memory for that item (the *attended* object) compared to items that had been attended, but were no longer in the focus of attention (*previously attended* objects) and objects that had never been attended (*unattended* objects). This is similar in motivation to the test of Gajewski and Brockmole (2006), in which an object that was cued in the ISI was considered to be within the focus of attention. According to the attention hypothesis, binding memory should be high for the attended object, but should drop dramatically for previously attended objects; this effect should be larger than the decrease in memory for individual features. Experiments 2 and 3 tested the volatile representation hypothesis by examining binding memory with a test display that should provide the greatest amount of interference (a whole array report) and manipulating whether encoding times were short and attention was distributed, encouraging volatile representations (Experiment 2) or encoding times were long and attention was serially focused on individual items, encouraging durable representations (Experiment 3) during the study array. The volatile representation hypothesis suggests that a whole array test should disrupt binding change detection performance when the representation in memory is volatile (Experiment 2) but not when it is durable (Experiment 3).

Eye movements were used as a measure of shifts in visual attention because eye movements and visual attention are tightly linked (e.g., Hoffman, 1998; Peterson, Kramer, & Irwin, 2004). Although attention can be shifted without moving the eyes (covert shifts of attention), there is a close relationship between shifts of attention and eye movements (Corbetta, 1998; Gutteling van Ettinger-Veenstra, Kenemans, & Neggers, 2009; Rizzolatti, Riggio, Dascola, & Umilta, 1987). People generally fixate where they are attending; a saccade towards a new object is preceded by a shift of attention to it (Belopolsky & Theeuwes, 2009; Deubel & Schneider, 1996; Hayhoe, 2000; Hoffman & Subramaniam, 1995; Land, Mennie, & Rusted, 1999; Peterson et al., 2004). By allowing participants to look directly at objects during the study array, we were able to both monitor the deployment of attention and allow participants to create a more durable memory representation.

EXPERIMENT 1

In Experiment 1, the attention hypothesis was tested by encouraging shifts of attention during the study array and manipulating whether the test object was within the focus of attention. This was accomplished by creating a study array composed of small objects in a large circle, forcing participants to fixate on individual objects. In addition, the presentation time of the study array was dependent on the amount of time it took participants to fixate on four objects, and saccade towards a fifth. As soon as a saccade was detected within 3.8° of the fifth object, the array disappeared.

Research has demonstrated that with the initiation of a saccade, the focus of attention has moved to the saccade target; therefore, this fifth object was considered to be the *attended* object (Deubel & Schneider, 1996; Garavan, 1998; McElree, 1998, 2001; Oberauer, 2003; Peterson et al., 2004). The four objects fixated prior to the attended object were *previously attended* objects. Any object that was not fixated was an *unattended* object. Following the ISI, a test screen was presented that contained a single object in the centre of the screen that was generated based on the order of fixations on the study array. The attention hypothesis predicts that binding change detection performance should be as good as single feature change detection for the object within the focus of attention, but poorer for all objects that are not within the focus of attention at the onset of the change.

Method

Participants. Eighteen students, 13 undergraduate students, and five graduate students, including the first author (12 female, six male, average age 22 years), participated in this experiment. Undergraduate students received course credit for participation. All participants had normal colour vision and normal or corrected to normal vision.

Apparatus. An Eyelink II head-mounted eyetracker was used to track eye movements and a chinrest was used to prevent head movements. Before every block, calibration and validation procedures were conduced and drift corrections were conducted between each trial. The SR Research Experiment Builder program was used to create and run the experiment.

Stimuli. Ten shapes (see Figure 1), in 10 highly discriminable colours (red, green, yellow, blue, purple, white, black, brown, pink, and orange) were used to create study arrays of eight objects. The same shapes and colours were used as in the Wheeler and Treisman (2002) experiment, with the addition of two colours and two shapes to accommodate an eight object set size. Each shape and colour within an array was unique. Each object subtended a visual angle of approximately 0.73° (from a viewing distance of 45 cm) and

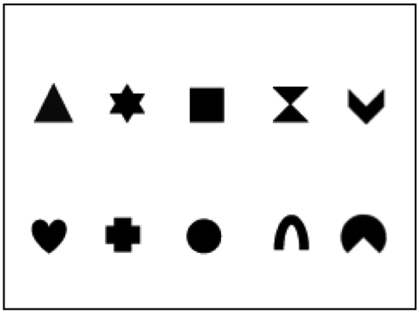

Figure 1. Shapes used in all experiments. Ten shapes and 10 colours were used to create a set of 100 objects. No two objects with the same shape or colour appeared within an array.

was presented in a circle subtending 13.7° visual angle from the centre of the screen.

Procedure. Participants viewed an array of eight objects, followed by a 900 ms ISI, then a test object. Presentation time of the study array was dependent upon fixations. Participants fixated on four objects, and once a saccade was detected in the interest area (a square 3.8° visual angle around the object) of the fifth object, the array disappeared (see Figure 2). After a 900 ms ISI, a test object was presented in the centre of the screen. The test object was selected based on the order in which objects were fixated (lags 0,

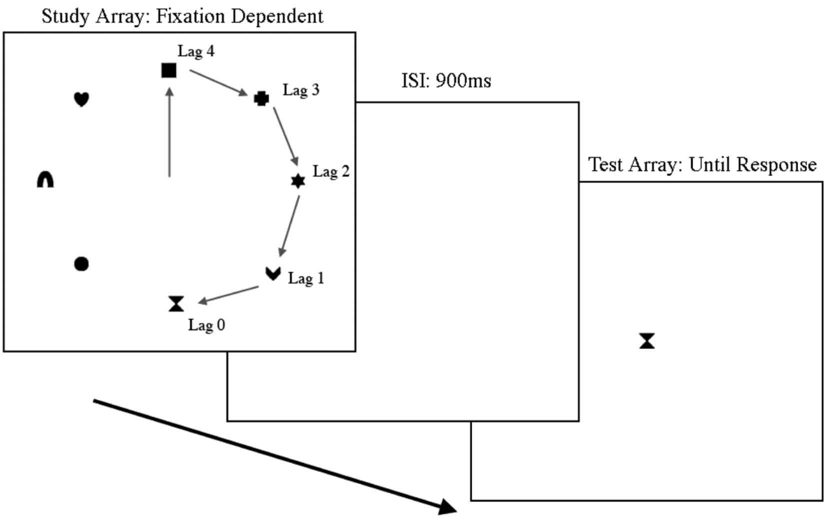

Figure 2. Procedure in Experiment 1. The dotted lines represent eye movements and each frame represents a fixation on a new object on the study array. Participants viewed the study array until an eye movement was detected within the interest area of the fifth object (lag 0). The attended object (lag 0) is presented on the test array.

1, 2, 3, 4, and unattended). The lag 0 object (the attended object) was the object that a saccade was detected within the interest area of prior to the onset of the ISI. The lag 1 object was the object fixated prior to lag 0, etc. All objects that were never fixated were considered to be unattended. Participants indicated whether they detected a change by pressing one of two buttons on a controller.

Changes were grouped into four blocks: Colour changes, shape changes, two-feature (colour or shape changes randomly mixed) and binding changes. Participants indicated whether the test object was present in the study array by pressing one of two buttons on a controller. On the test screen, participants were asked whether the colour, shape, or colour–shape combination of the test object was present in the first screen, which included instructions about which change type may have occurred. For example, in the colour block, the test array contained the instructions "Did you see this colour in the first array? Press the left button for yes the right button for no." In the two-feature block, participants were either given shape instructions or colour instructions, depending on the trial type. Each block contained 82 trials: 10 practice trials and 72 test trials (12 at each lag, half change and half no change for each lag), for a total of 328 trials. In the two-feature block, half of the trials at each lag were colour trials and half were shape trials.

Participants performed a verbal suppression task to prevent verbal coding of the stimuli. A verbal suppression task similar to Luck and Vogel (1997) was used except that we used a subvocal suppression task to prevent head movements while talking. Participants were presented with three random numbers (0–9) before each trial and were asked to silently repeat them during the trial. At the end of the trial, a screen was presented with the numbers 0–9 displayed in black. When participants looked at a number, it changed to red. To report the numbers, participants looked at the number and once it turned red, pressed a button on a controller (a different button from the ones used to indicate a change or no change).

Results

Overall accuracy for the verbal load task was very good ($M = 0.91$, $SD = 0.07$). All of the participants performed above 75% on this task.

A 6 × 4 repeated measures ANOVA with lag (0, 1, 2, 3, 4, and unattended) and change type (colour, shape, two-feature, and binding) as within-subjects factors revealed a main effect of change type, $F(3, 51) = 20.86$, $p < .01$, $\eta_p^2 = .55$, and a main effect of lag, $F(5, 85) = 16.51$, $p < .01$, $\eta_p^2 = .49$ (see Figure 3). The Lag × Change type interaction was not significant, $F(15, 255) = 1.43$, $p = .13$ $\eta_p^2 = 08$. Pairwise comparisons revealed that performance in the colour block ($M = 0.78$, $SD = 0.14$), was higher than the three other blocks, all ps $< .01$. In addition, performance in the two-feature block

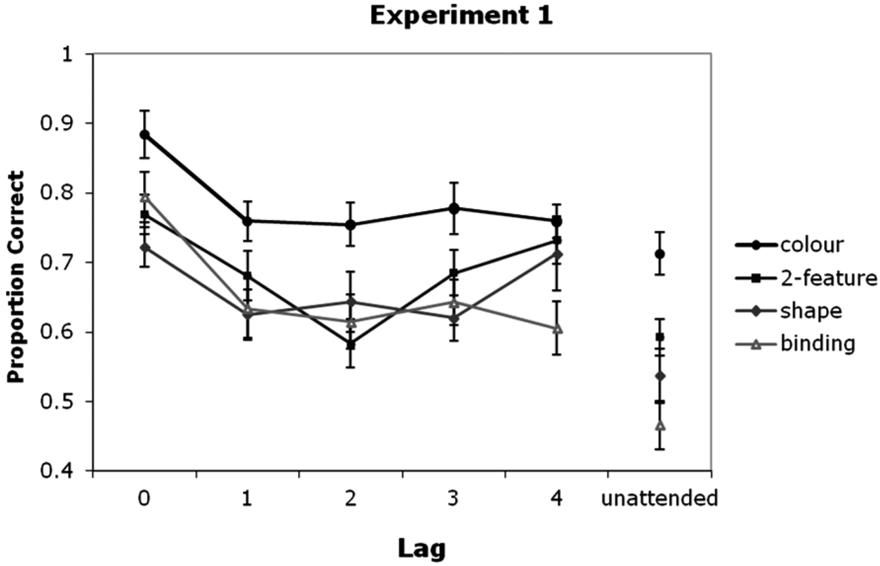

Figure 3. Results from Experiment 1. Proportion correct for each block type at each lag. Error bars represent standard error of the mean.

($M = 0.68$, $SD = 0.15$), was higher than the binding block ($M = 0.63$, $SD = 0.18$), $p < .05$, but not the shape block ($M = 0.64$, $SD = 0.18$). Finally, performance in the shape and binding blocks did not differ from each other, $p = .41$, $\eta_p^2 = .03$.[1]

Because the primary comparison of interest was between shape and binding changes from lag 0 to lag 1, an additional 2 (change type) × 2 (lag) ANOVA was conducted on binding and shape changes at lags 0 and 1 in order to maximize sensitivity for finding a binding deficit. The results of this ANOVA yielded no main effect of change type, $F(1, 17) = 0.77$, $p = .39$, $\eta_p^2 = .04$, but a significant effect of lag, $F(1, 17) = 14.36$, $p < .01$, $\eta_p^2 = .46$. Performance was higher at lag 0 ($M = 0.76$, $SD = 0.17$) than at lag 1 ($M = 0.63$, $SD = 0.17$). Finally, there was no interaction between change type and lag: $F(1, 17) = 0.68$, $p = .42$, $\eta_p^2 = .04$.

Pairwise comparisons also revealed that overall performance at lag 0 (the attended object) was higher ($M = 0.79$, $SD = 0.16$) than all other lags, all *p*s $< .01$. In addition, performance for all attended items (lags 0–4) was better than performance for unattended items ($M = 0.58$, $SD = 0.16$), all *p*s $< .01$. Performance at lag 4 ($M = 0.70$, $SD = 0.15$) was better than

[1] Participants made revisits to an object on 22% of all trials. If the object probed at test was revisited, these results were excluded in a separate analysis. This produced the same results as the original analysis. Therefore, the original analysis with no trials excluded was reported.

performance at lag 2 ($M = 0.65$, $SD = 0.15$), $p < .05$, but not at lag 3 ($M = 0.68$, $SD = 0.17$), or lag 1 ($M = 0.68$, $SD = 0.16$).

Discussion

Across all blocks, performance dropped rapidly from lag 0 to lag 1, after which performance remained steady until lag 4. This suggests that memory for both the features and bindings are best for an object that was attended at the onset of the change. However, there was no difference in performance between the binding and the shape blocks. Therefore, there was no evidence to suggest that attention was required to maintain feature bindings. If shifts of attention necessarily disrupt binding memory, the shifts of attention during encoding should have impaired memory for the feature bindings of the previously attended items. However, feature bindings were maintained despite several serial shifts of attention. These results do not support the attention hypothesis; therefore, the next two experiments test the volatile representation hypothesis.

EXPERIMENT 2

Experiment 2 tested the volatile representation hypothesis by promoting volatile binding representations with a very short encoding time and encouraging overwriting with a whole array test. Specifically, we replicated the design of Wheeler and Treisman (2002): A 150 ms encoding time was used, and a whole array was presented at test. One change was made to the design: Arrays with set sizes of four, six, and eight objects were used instead of two, four and six. Wheeler and Treisman found that all types of changes were detected equally well at set size two, and binding performance was poorer than shape performance only at larger set sizes. Therefore, larger set sizes were used to increase sensitivity for detecting binding deficits. According to the volatile representation hypothesis, because distributed attention during encoding (this was confirmed with eye tracking) and short encoding times lead to volatile binding representations, binding change detection performance should be lower than shape change detection performance, especially at larger set sizes.

In addition, this experiment allowed us to test the hypothesis that selective binding deficits never occur (*equal representation hypothesis*; Johnson et al., 2008). Specifically, Johnson et al.'s (2008) attempt at replicating Wheeler and Treisman's (2002) study revealed that binding changes were not more difficult to detect than shape changes with a whole array test. Experiment 2 tested this hypothesis with a design most likely to reveal binding deficits: A short encoding time and a whole array test. No binding impairment at this point would suggest that binding deficits should never occur, under any hypothesis, contrary to the results of prior data (Brown & Brockmole, 2010; Fougnie & Marois, 2009; Wheeler & Treisman, 2002). However, a binding deficit would support the volatile representation hypothesis and would suggest that, although shifts of attention do not necessarily disrupt binding memory (Allen et al., 2006; Delvenne et al., 2010; Gajewski & Brockmole, 2006; Johnson et al., 2008), binding representations may be particularly volatile.

Method

Participants. Nineteen undergraduate students and one graduate student (nine female, seven male, average age 20) participated in this experiment. Undergraduate students received credit in psychology courses. All participants had normal or corrected to normal vision and normal colour vision.

Stimuli. The same objects were used as in Experiment 1. To create the study arrays, objects were presented in one of eight possible locations of a 3×3 grid (the centre position never containing an object) subtending an $8.6^\circ \times 8.6^\circ$ region on a grey screen.

Test arrays for the change trials were created by changing two objects in the study array. In the colour change test arrays, two of the objects in the test array changed to new colours not present on the study array. In the shape change test arrays, two objects changed to new shapes not present on the study array. In the binding change test arrays, two of the objects traded features. For example, a blue circle and an orange square in the study array could change to an orange circle and a blue square in the test array. All of the objects swapped locations from the study array to the test array to prevent the use of location binding as a strategy for completing the task.

Procedure. Participants completed four blocks of trials, in a random order, with different types of changes occurring in each block (colour, shape, two-feature, binding; see Figure 4). Prior to the start of each block, participants were told which change type to detect. Each block contained 144 trials and 32 practice trials for a total of 576 test trials and 128 practice trials. In all four blocks, half of the trials were change trials and half were no change trials. Set sizes of the arrays were randomly distributed within blocks (48 trials, half change and half no change, for each set size). In the two-feature block, half of the trials were colour trials and half were shape trials.

On each trial, a study array was displayed for 150 ms, followed by a 900 ms ISI, and then a test array until a response was given. Participants indicated whether they detected a change to any of the objects by pressing one of two buttons on a controller. On the test array, participants were asked if they detected a change, which included instructions about which change type may have occurred. For example, in the colour block, the test change array contained the instructions "Press the left button if you saw a colour change

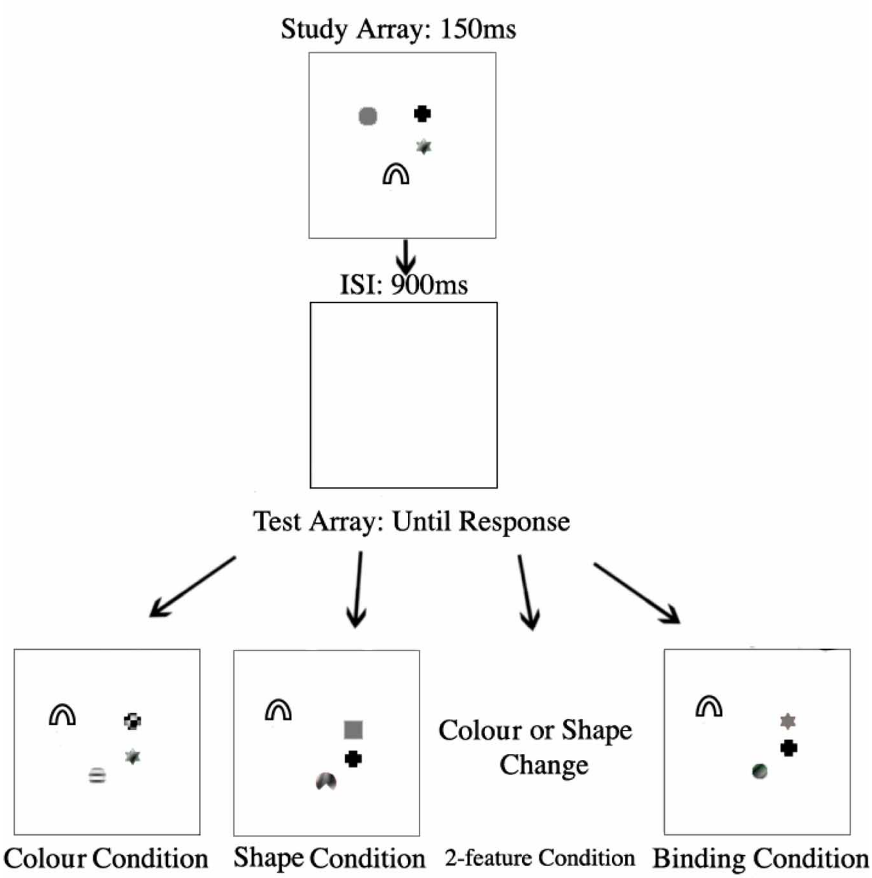

Figure 4. Procedure and types of changes for Experiment 2. All objects switched locations from the study array to the test array. In the colour condition, two objects changed to two colours not present on the study array; in the shape condition, two objects changed to shapes not present on the study array; in the two-feature condition, half of the trials were colour changes and half were shape changes; in the binding condition, two objects traded features from the study array to the test array.

and the right button if you did not see a change." In the two-feature block, participants were either given shape instructions or colour instructions, depending on the trial type. As in Experiment 1, participants performed a subvocal verbal suppression task to prevent verbal coding of the stimuli.

Results

Accuracy for the verbal suppression task was very good ($M = 0.92$, $SD = 0.05$). All participants performed above 75% on this task. In addition, eye movements on the study array suggest that participants distributed attention across all objects: Participants looked away from the centre of the array on only 5% of all trials.

A 4 × 3 repeated measures ANOVA with change type (colour, shape, two-feature, and binding) and set size (four, six, and eight) as within-subjects factors revealed a main effect of set size, $F(2, 36) = 40.25$, $p < .01$, $\eta_p^2 = .69$, and change type, $F(3, 54) = 46.01$, $p < .01$, $\eta_p^2 = .72$, but no interaction, $F(6, 108) = 1.78$, $p = .11$, $\eta_p^2 = .09$ (see Figure 5). Post hoc pairwise comparisons revealed that performance in the colour block ($M = 0.83$, $SD = 0.12$), was significantly higher than all other blocks, all *p*s $< .01$. Two-feature performance ($M = 0.70$, $SD = 0.09$), was higher than both shape performance ($M = 0.66$, $SD = 0.09$) and binding performance ($M = 0.62$, $SD = 0.10$), all *p*s $< .01$. Critically, shape performance was higher than binding performance, $p < .05$.

Pairwise comparisons revealed that performance at set size four ($M = 0.76$, $SD = 0.12$) was better than performance at set size six ($M = 0.69$, $SD = 0.13$), $p < .01$, which was significantly higher than performance at set size eight ($M = 0.65$, $SD = 0.10$), $p < .05$.

Discussion

The results of Experiment 1 replicated those of Wheeler and Treisman (2002): Colour changes were the easiest to detect, followed by the two-feature changes,

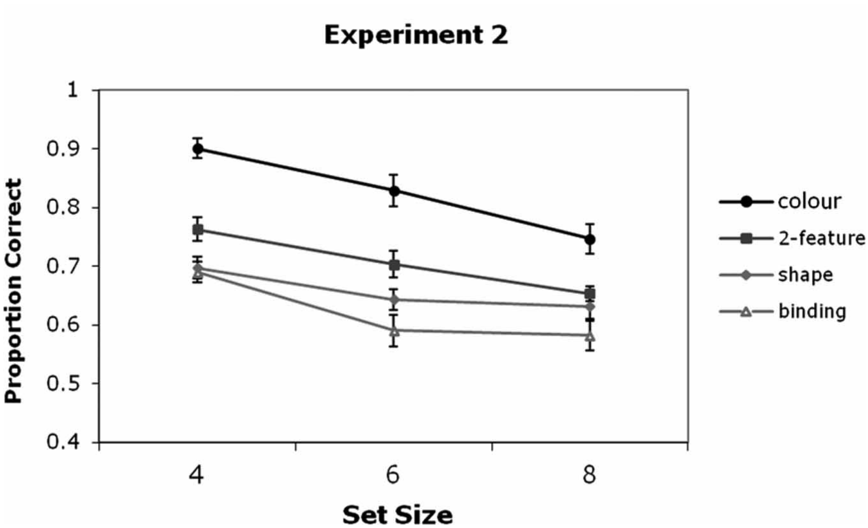

Figure 5. Results of Experiment 2. Proportion correct for each block type at each set size. Error bars represent standard error.

then shape changes. Critically, it was more difficult for participants to detect changes to bindings than shapes. These results are inconsistent with the equal representation hypothesis. Rather, they suggest that when volatile representations are encouraged at encoding (through short encoding times and distributed attention), feature bindings are likely to be disrupted by a whole array test, in line with the volatile representation hypothesis. Furthermore, participants rarely (5% of the trials) moved their eyes away from the centre of the screen on the study array, supporting the assumption that a brief encoding time leads to distributed attention. Experiment 2 supported the prediction of the volatile representation hypothesis that the whole array test overwrites binding representations when encoding conditions make it difficult to form a durable memory representation. However, the volatile representation hypothesis also predicts that a whole array test should no longer disrupt feature bindings if participants are encouraged to form durable memory representations for each item. This was tested in Experiment 3.

EXPERIMENT 3

Experiment 3 tested the final prediction of the volatile representation hypothesis: When durable representations of bindings can be encoded (due to longer encoding time and focused attention), a whole array test will not overwrite the binding representations and there will be no binding deficit. Experiment 3 used the same study array design as Experiment 1, but a whole array test (like Experiment 2). At test, the objects were presented in a small circle in the centre of the screen. This circle was approximately the same size as the grid used in Experiment 2. Finally, the results from Experiments 1 and 2 were consistent with previous research that demonstrated that the theoretical comparisons of interest were between the shape and binding blocks (Johnson et al., 2008; Wheeler & Tresiman, 2002); therefore, in this experiment, participants completed the shape and binding blocks only.

Method

Participants. Fifteen students participated in this experiment (four male, 11 female, average age = 19.5) for credit in their undergraduate psychology courses. All students had normal vision and normal colour vision.

Stimuli and apparatus. The same stimuli and apparatus were used as in Experiment 1, except that only the shape and binding blocks were used.

Procedure. The procedure was the same as Experiment 1, except that a whole array test was used (see Figure 6). At test, all eight objects were

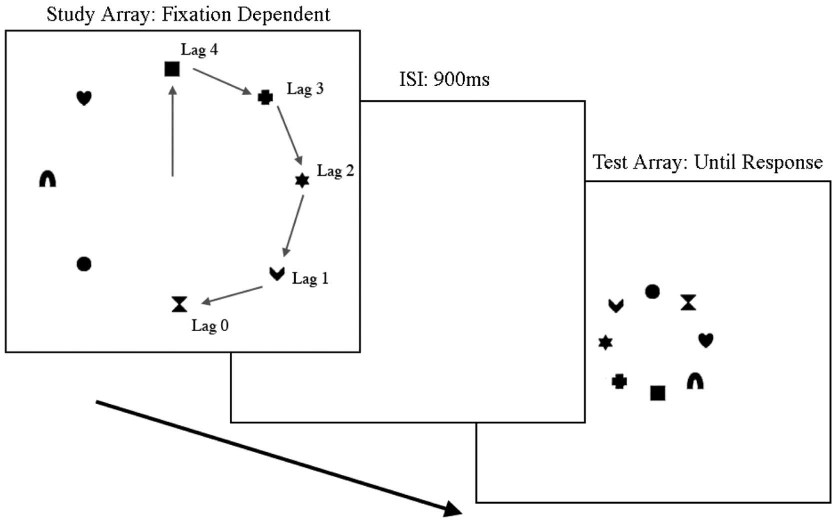

Figure 6. Procedure for Experiment 3. Participants viewed the study array until an eye movement was detected within the interest area of the fifth object (lag 0). A whole array was used at test.

presented in a small circle in the centre of the screen (similar to Experiment 2). Each object was presented approximately 4.3° from centre. On the change trials, two objects always changed: Lag *n* and lag *n+1* (e.g., lags 0 and 1, 1 and 2, etc.). When the lag 4 object changed, an unattended item changed also; on the unattended change trials, two unattended items changed. Participants were asked if they detected a shape or binding change, depending on the block. The order of the blocks was counterbalanced across participants. Each block contained 82 trials; 10 practice trials and 72 test trials (12 at each lag, half change and half no change for each lag), for a total of 164 trials. Participants viewed the same instructions at test as in Experiment 2. The same subvocal suppression technique was used as in Experiments 1 and 2.

Results

As in Experiments 1 and 2, verbal load performance was very good ($M = 0.95$, $SD = 0.05$). All participants performed above 75% on this task.

A 6 × 2 repeated measures ANOVA with lag (0 and 1, 1 and 2, 2 and 3, 3 and 4, 4 and unattended, and unattended) and change type (shape and binding) as within subjects factors revealed a main effect of lag, $F(5, 70) = 9.99$, $p < .01$, $\eta_p^2 = .42$, but no main effect of change type, $F(1, 14) = .66$, $p = .43$, $\eta_p^2 = .05$ (see Figure 7). The Lag × Change type interaction was not significant, $F(5, 70) = 0.70$, $p = .63$, $\eta_p^2 = .05$.

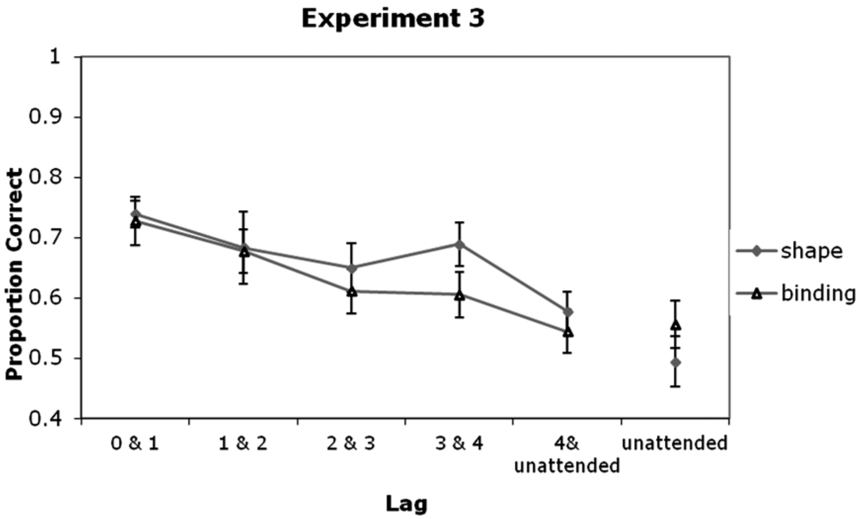

Figure 7. Results from Experiment 3. Proportion correct for each block type at each lag. Error bars represent standard error of the mean.

Post hoc pairwise comparisons revealed that performance was not different at lag 0 and 1 ($M = 0.73$, $SD = 0.12$) and lag 1 and 2 ($M = 0.68$, $SD = 0.15$). This is likely because memory for the lag 1 item was included in both measures, reducing overall performance for lag 0 and 1 compared to lag 0 alone. However, performance was better at lag 0 and 1 than all other lags, all *p*s $<.05$. In addition, performance for unattended items ($M = 0.53$, $SD = 0.15$) was significantly less than all attended items (lags 0 and 1–3 and 4), all *p*s $<.05$, except lag 4 and unattended items ($M = 0.56$, $SD = 0.13$).

Discussion

Experiment 3 revealed no difference in performance between the shape and binding blocks. This suggests that when durable binding representations are encouraged through focused attention and longer encoding times, interference caused by the whole array test is reduced. Furthermore, when durable binding representations were not encouraged (Experiment 2), the effect size of the binding deficit (the difference between shape and binding performance) was $\eta_p^2 = .23$, but when durable binding representations were encouraged (Experiment 3) the effect size was only $\eta_p^2 = .05$. These results support the volatile representation hypothesis, which suggests that feature binding performance is reduced when the memory representation is volatile and new feature bindings are formed at test. When a more durable representation is formed (though serial shifts of attention and longer encoding times), the test array no longer disrupts the feature binding memory.

GENERAL DISCUSSION

The three experiments combined support the volatile representation hypothesis. First, Experiment 1 demonstrated that even after several shifts of serial attention, binding performance remained as high as shape performance, inconsistent with the attention hypothesis. Experiment 2 showed that when volatile binding representations were encoded (based on shorter encoding times and distributed attention) and overwriting was possible (a whole array test was used), binding performance was lower than shape performance. These results are contrary to the equal representation hypothesis and confirm that, under particular encoding conditions, binding memory may be more vulnerable to interference than individual features. We hypothesized that this interference from the whole array test occurs when binding representations are volatile in memory. Consistent with this hypothesis, the results of Experiment 3 showed that binding and shape performance were equal when durable binding representations were encouraged, even when a whole array test was used.

We propose that there are two factors that determine whether a binding deficit is likely to occur: The ability to create a durable representation (through longer encoding times and focused attention) and the probability of interference created by the test array. Whether a binding deficit will occur is likely probabilistic, depending on the durability of the representation and likelihood of interference caused by new visual stimuli.

Experiments 1 and 3 show that, when encoding time is longer and attention is focused on individual objects, a binding deficit does not occur, regardless of whether the test array is likely to cause a large (Experiment 3) or small (Experiment 1) degree of interference. In contrast, a binding deficit does occur when encoding time is short and attention is distributed across all objects during encoding and when the test array is likely to cause interference (Experiment 2).

Previous examples of binding deficits can also be explained within this framework. For example, Brown and Brockmole (2010) introduced a backwards counting task throughout the entire trial period, including the encoding phase. Given the important role in attention in the formation of feature bindings (Treisman & Gelade, 1980), we proposed that dividing attention during encoding in this manner may have increased the probability of creating a volatile representation, created by a thinner distribution of resources during encoding.

Fougnie and Morois (2009) found a binding deficit when participants were required to track moving targets during the ISI of a change detection task. Although the tracking task was not relevant to the change detection task, even task-irrelevant visual stimuli can create disruption when attention is distributed at encoding (Makovski & Jaing, 2007). Therefore, the MOT task likely created a similar disruption of the change detection stimuli, creating a binding deficit. In contrast, the visual search task that participants completed during the ISI of a change detection task in Johnson et al. (2008) reduced change detection performance overall, but no more for bindings than orientation. However, the search task was completed in a different location of the screen than where the change detection task occurred, the search this task itself was shorter than the tracking task and likely less difficult, and the objects did not swap locations at test. All of these factors may have made it less likely for the test array to create greater interference for bindings. Although these explanations have not been empirically tested, this framework proposes an alternate explanation for the diversity of results on this topic that best explains the widest range of data.

In light of the present results, future research examining binding deficits should consider whether the presentation parameters of the study array encourage durable or volatile binding representations. As noted previously, encoded binding representations may be more volatile because of distributed attention and/or shorter encoding times. Eye movement analysis revealed that there were differences between experiments in the number of fixations on objects during encoding. Specifically, few fixations were made on objects in Experiment 2, but fixations were made on several objects in Experiment 1 and 3. Encoding times also varied across experiments. In Experiment 3, participants spent, on average, 200–300 ms looking at each object, approximately 1000 ms in total. Within a small range of *short* encoding times, the duration of the study array is not necessarily predictive of binding performance—in both Johnson et al. (2008) and Gajewski and Brockmole (2006) participants were allowed less than 150 ms per object and neither of these studies demonstrated binding deficits. However, longer encoding times may encourage more durable representations (Beck & van Lamsweerde, 2011). Heubner and Gegenfurtner (2010) demonstrated that, for encoding times of 1000 ms, fixated items are remembered better than nonfixated items; however, when encoding time was longer (3000 or 7000 ms), fixated items were not remembered better than nonfixated items. Therefore, total encoding time and focused attention likely both play an important in the formation of a more durable representation; when encoding times are longer, directly fixating an item may not be required to increase memory performance. In the current study, both longer encoding times and focused attention served the same purpose: Allowing participants to form a more durable memory representation, which decreases the likelihood of interference from the test array.

Next we consider possible limitations or alternative explanations for the results from the current study. First, it is important to note that while the ISIs of Experiments 1 and 3 were equal to that of Experiment 2, the total maintenance time for each individual object varied, depending on the order of fixations. When objects trade places at test and the ISI is short, the ability to detect colour–shape binding changes is reduced compared to a test in which the objects remain in their original spatial locations; however, when the ISI is longer than 1500 ms, presenting test objects in a new spatial arrangement has no effect (Logie, Brockmole, & Jaswal, 2011). Although the ISI was only 900 ms in the current experiments, the total maintenance time (the time between fixating an object and the onset of the test array) was generally longer than 1500 ms for all but the last attended object. Therefore, the location swaps may have been more disruptive to change detection performance in Experiment 2 than in Experiments 1 and 3. However, the idea that longer maintenance periods reduce the disruptive effect of swapping object locations at test is consistent with the hypothesis that longer time periods allow participants to create a more stable representation prior to the onset of the test array. If this is this case, both longer encoding and maintenance periods may promote durable representations.

Next, the last fixated item was designated as the item within the focus of attention. Although it is very likely that this was true while the study array was still present, given the link between eye movements and attention (Corbetta, 1998; Gutteling et al., 2009; Rizzolatti et al., 1987), it is possible that shifts of attention could have been made after the offset of the study array, during the maintenance period. Therefore, the last fixated item would no longer be the item within the focus of attention. However, our overall highest performance at lag 0 compared to all other lags suggests that this is unlikely. Namely, binding performance was very high at lag 0, equal to shape performance. If attention had shifted between items in memory during the maintenance phase, this should have resulted in a decrease in binding performance at lag 0, under the assumptions of the attention hypothesis. Therefore, even if the lag 0 item was no longer within the focus of attention, the results of the current study argue against the attention hypothesis.

Third, as noted in the introduction, in addition to the attention hypothesis and the volatile representation hypothesis, it is also possible that feature bindings are not encoded as completely as individual features. Furthermore, it is possible that shorter encoding times and distributed attention do not promote a more volatile representation, but rather a less complete, but sable, representation. This would suggest that the binding deficit found in Experiment 2 is not caused by a more volatile representation, but rather by a failure to encode a complete representation due to insufficient encoding times. However, previous research demonstrates that complete binding representations may be formed with a short encoding time, but that this is not always reflected in performance when a change detection task is used (Alvarez & Thompson, 2009; Gajewski & Brockmole, 2006; Logie et al., 2009; Wheeler & Triesman, 2002). For example, free and cued recall tests show high binding memory, even if change detection is low

(Alvarez & Thompson, 2009; Gajewski & Brockmole, 2006), which suggests that a complete representation is formed. In addition, research has shown that the consolidation rate for feature bindings is equivalent to the slower to encode feature (Woodman & Vogel, 2008). Therefore, any binding representation should be as complete as the shape representation. We therefore believe that the more likely explanation for the current set of data is that distributed attention (or inadequate encoding time) creates a more volatile binding representation that is easily overwritten.

Finally, it could be argued that shifts of attention do disrupt binding memory, but only when attention is distributed during encoding (a modification of the attention hypothesis). That is, the whole array test shifts attention from the objects in memory as suggested in Wheeler and Treisman (2002), but this shift is only disruptive because of the distributed attention during encoding (encouraging a volatile representation). Although this is possible given the results of the current study, this account is inconsistent with previous research. Specifically, Gajewski and Brockmole (2006) found that when attention was shifted during maintenance (following distributed attention during encoding), no binding deficit emerged. This suggests that simple shifts of attention do not disrupt binding memory; rather, the durability of the representation is specifically beneficial in the face of new visual information.

The question that remains for future research is *why* memory for bindings is more fragile than memory for individual features. We believe the answer here s most likely to lie in the role of attention in the perception of feature bindings (Treisman & Gelade, 1980), although this still needs to be empirically determined. In sum, although feature bindings are more volatile in VWM than individual features in some situations, sustained attention is not required to maintain feature binding representations. When encoding times are short and attention is distributed at encoding, a whole array test creates interference that is especially detrimental to maintaining feature bindings. However, the effects of interference are reduced when encoding times are longer and attention is focused on individual items during encoding, encouraging a more durable representation.

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