

## Bound feature combinations in visual short-term memory are fragile but influence long-term learning

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We explored whether individual features and bindings between those features in VSTM tasks are completely lost from trial to trial or whether residual memory traces for these features and bindings are retained in long-term memory. Memory for arrays of coloured shapes was assessed using change detection or cued recall. Across trials, either the same colour-shape (integrated object) combinations were repeated or one feature was repeated while the other varied. Observers became sensitive to the repetition of bindings, but only if it occurred on every trial. Repetition of single features only led to learning in the cued-recall task, and was weak compared to whole-object repetitions. Results suggest that representations in visual short-term memory comprise integrated objects rather than individual features. These representations are readily displaced by new representations formed on subsequent trials. However, when a given representation is not displaced, longer term residual traces can be generated to support long-term learning, and any learning that does occur is based on integrated objects, not individual features.

**Keywords:** Visual short-term memory; Feature binding; Learning.

Close your eyes and try to recall the colours of the books on your shelves. It is likely that you can only remember a few, even though you have looked at these books many times since they were placed on the shelf. What is it about our immediate visual environment that we actually learn? In this paper, we

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attempt to answer this question by examining how the properties of object representations in visual short-term memory<sup>1</sup> (VSTM) constrain learning.

Over the last decade, there has been a debate as to whether VSTM representations comprise primarily integrated objects (e.g., Allen, Baddeley, & Hitch, 2006; Brockmole, Parra, Della Sala, & Logie, 2008; Gajewski & Brockmole, 2006; Johnson, Hollingworth, & Luck, 2008; Luck & Vogel, 1997; Vogel, Woodman, & Luck, 2001) or individual features (e.g., Wheeler & Treisman, 2002; Xu, 2002). The fuel for this debate has been in large part the lack of clarity pertaining to the conditions under which the binding of visual features—such as colour, shape, location, or orientation—occurs. For example, Wheeler and Treisman (2002) proposed that individual features are stored in VSTM automatically, but that the process of binding these features or the maintenance thereof requires extra effort and attention. Gajewski and Brockmole (2006) tested this proposal directly by presenting an exogenous cue during the retention interval that directed attention to a subset of to-be-remembered items. Recall of the features for the cued items was superior to that of uncued items, but the uncued items nevertheless continued to be remembered as integrated wholes: Observers tended to recall all the features of the object or none. Therefore, distracting attention between the study display and the recall probe had no effect on memory for bound features. These results suggest that visual attention is not crucial for maintaining integrated objects in VSTM (see also Yeh, Yang, & Chiu, 2005).

A complementary approach to the same question was taken by Allen et al. (2006), who used a change detection paradigm with arrays of shape–colour combinations. Attention was manipulated through the use of secondary tasks, such as generating random sequences of numbers, during the presentation of both the study and the test arrays. The secondary task load affected overall performance but had no greater effect on memory for bound features than it did on memory for individual features (see also Johnson et al., 2008). Again, attention did not seem to be essential for maintaining bindings. In the same series of experiments, however, they found that memory for the binding of features was poorer when objects were presented in a rapid sequence rather than simultaneously. Memory for individual features did not show this same drop in performance with sequential presentation. Allen et al. concluded that although maintaining bindings in working memory does not appear to require attention or

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<sup>1</sup> Many vision researchers use the terms *visual working memory* and *visual short-term memory* interchangeably, whereas researchers in working memory view the latter as comprising one of a range of functions of the former (e.g., Logie & van der Meulen, in press). In this paper, we are primarily concerned with representations stored over the short term (within trials) and long term (across trials), and hence we will refer to visual short-term memory without implying a theoretical contrast with visual working memory.

executive functions, the bindings are vulnerable and items early in the sequence may be overwritten by items later in the sequence.

These studies suggest that as long as an object is represented in VSTM, the maintenance of the feature bindings for that object is largely automatic. However, what happens to these bindings once they are no longer immediately relevant to the task of the observer? In most studies of visual feature binding, the combinations of features are randomly varied from trial to trial, but the pool of features on which these combinations are based typically remains the same throughout the experiment. So, for example, on one trial the stimuli might comprise a red triangle, a blue circle, and a green square each in a specific location. On the following trial, one or more of the same locations might be used for a green circle, a red diamond, and a blue triangle. In order to maintain adequate levels of performance throughout the sequence of trials in an experiment, the bindings formed on one trial would have to break apart to allow the formation of a new set of bindings on the next trial. We are aware of only two studies that have systematically investigated whether or not there is any residual trace of the bindings maintained from trial to trial.

One preliminary, but unpublished, study by Dishon-Berkovits and Treisman (described in Treisman, 2006) examined whether particular colour–shape pairings repeated on 80% of trials can be learned and whether participants subsequently benefit from this learning in a VSTM task. The results showed that participants performed better than chance on a surprise postexperiment questionnaire for the combinations that were shown frequently in the VSTM task, but that the performance on the VSTM task itself did not benefit from repeating the same colour–shape configurations. They concluded that bindings were stored in LTM, but that this information from LTM wasn't used in the VSTM task.

In another study about the learning of bound objects, Colzato, Raffone, and Hommel (2006), asked participants to respond to a particular shape with a keypress. The shapes were paired with colours, and to see whether the binding between the colour and the shape could be learned, some colour–shape configurations were repeated more often than others. Colzato et al. predicted that participants would respond faster for repeated colour–shape pairings than for nonrepeated pairings. This effect was found, even though participants only had to respond to a shape regardless of its colour. However, there was no evidence of better memory for the repeated colour–shape pairings in a subsequent memory test. Colzato et al. therefore concluded that binding and learning mechanisms are independent.

From this work, it therefore appears that there is scant evidence for long-term learning of feature bindings within integrated objects. However, each of these studies is limited in important ways. In the Dishon-Berkovits and Treisman (Treisman, 2006) study, each object was repeated in a different

location every time it was shown. It could be that location is an important factor when it comes to feature binding (Treisman & Zhang, 2006) and that no benefit was found in the VSTM task as a result (see also Logie, Brockmole, & Jaswal, 2008). In the Colzato et al. (2006) study only one of the visual features was task relevant and binding was not required, perhaps also leading to a limited ability to detect long-term learning of bindings.

The purpose of the experiments reported here, therefore, was to directly address the extent to which bindings created in VSTM leave a longer term memory trace after they are no longer relevant. In each experiment, we adopted a variant of a technique that is referred to as the Hebb (1961) learning paradigm. This technique has been applied primarily to investigate learning of sequences of numbers, words, or letters, and typically involves presenting sequences that exceed short-term verbal memory span (e.g., 16 item lists) for immediate recall. Unknown to the participant, one particular sequence of items is repeated, for example on every third trial. The usual finding is that recall of these repeated lists gradually improves across repetitions compared with recall of the lists that are novel on all other trials (e.g., Caird, 1964; Cunningham, Healy, & Williams, 1984; Hitch, Fastame, & Flude, 2005; Page, Cumming, Norris, Hitch, & McNeil, 2006). A few studies have used a Hebb-type paradigm to investigate learning of sequences of nonverbal items presented visually (e.g., Couture & Tremblay, 2006; Gagnon, Foster, Turcotte, & Jongenelis, 2004; Page et al., 2006; Turcotte, Gagnon, & Poirier, 2005). As with verbal sequences, all of these studies have shown that when the same sequence of pictures or order of appearance of dots is shown repeatedly on some of the trials, participants show improvement in the recall of the repeated sequence compared with the novel sequences on the interpolated trials. This kind of evidence suggests that, although participants expect a series of novel sequences, nevertheless they retain a trace of each sequence after every trial, allowing a strengthening of the trace every time a particular sequence is repeated.

In studies of feature binding, performance is typically based on simultaneous presentation of multiple objects. Our aim here was to use a version of the Hebb repetition paradigm in which these arrays were presented repeatedly. We present three experiments that explore whether individual features and bindings between those features in VSTM tasks are lost from trial to trial or if they show evidence of learning across trials. Across three experiments, observers were to remember an array of multi-feature objects across short retention intervals. Each experiment used a Hebb-type learning procedure where aspects of these to-be-remembered arrays were consistently repeated across trials. In the *repeat-all* condition, the repeated arrays retained the exact same combinations of shapes, colours and locations (i.e., they were identical). In the *repeat-colour* condition, the repeated arrays were composed of the same combination of colours and

locations while the shapes in the display were varied across trials. Finally, in the *repeat-shape* condition the repeated array showed the same combination of shapes and locations while the colours in the display varied across trials. If bindings are robust only until the end of a trial, observers should be insensitive to this repetition and show no increase in memory performance over the course of the experiment. This result would be consistent with the findings of Allen et al. (2006) which indicate that bindings in VSTM are fragile and break apart easily, even if they do not require attention for their maintenance. It would also be consistent with the conclusion drawn by Dishon-Berkovits and Treisman (Treisman, 2006; see also Logie, 1995, 2003; Logie & van der Meulen, in press) for a VSTM store that functions rather separately from LTM. On the other hand, any improvement in performance across trials on which the stimulus array is repeated would suggest that some object information is retained across trials. If learning only occurs for bound objects, performance should only improve when the repeated display consists of exactly the same combinations of colour, shape, and location, but performance would not improve when only one of the features is repeated. This pattern of findings would be consistent with the view that integrated objects rather than individual features form the basis for long-term learning.

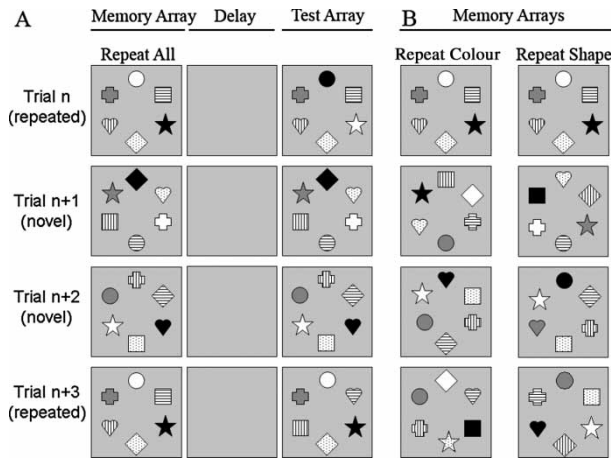
## EXPERIMENT 1

The purpose of Experiment 1 was to examine whether long-term memory traces of repeatedly presented multifeature objects are generated despite the fragility of bound object representations in VSTM. Observers engaged in a change detection task in which they judged whether two sequentially presented arrays were the same or different. When changes were incorporated into the test array, the features of two objects swapped across locations. Repeat-all, repeat-colour, and repeat-shape trials were blocked and the repetitions occurred on every third trial (see Figure 1). The memory arrays on the two intervening trials were completely novel and none were repeated within the experiment.

### Method

*Participants.* Twelve students from the University of Edinburgh participated and were compensated with £6. In this and subsequent experiments, all participants had normal or corrected-to-normal vision.

*Stimuli and apparatus.* Stimuli consisted of arrays of six objects positioned every 60° around an imaginary circle with a diameter of 8.8 cm. Each object was created by randomly combining six colours and six shapes without replacement from a set of eight colours (black, blue, cyan,



**Figure 1.** (A) The procedure used in Experiment 1 in the repeat-all condition. On each trial observers judged whether a test array was the same as a memory array. Changes were inserted by swapping either colour (see trial  $n$ ) or shape (see trial  $n+3$ ) features across locations. (B) Example memory arrays used on trials  $n$  through  $n+3$  of the repeat-colour and repeat-shape conditions. The properties of the delay and test array displays were the same as that illustrated in Panel A. Stimuli were shown in full colour and are not drawn to scale. Experiment 2 used a similar procedure with repetition occurring on every trial.

green, purple, red, white, and yellow) and eight shapes (arrow, circle, diamond, heart, plus, square, star, and triangle). On average, the objects subtended 1.8 cm horizontally and vertically. Stimuli were presented against a grey background on a cathode ray tube (CRT) monitor. Viewing distance was not constrained.

*Design and procedure.* The experimental procedure is illustrated in Figure 1. To suppress verbal rehearsal, each trial began with the presentation of two digits that the observer vocally repeated throughout the trial. After 1500 ms, a fixation cross appeared for 1000 ms, which was then replaced by the memory display for 200 ms. After a further 2000 ms delay, the test display was presented. On half of the trials, the memory and test displays were identical. On the other half of the trials, changes were made to two of the six objects. On half of these change trials, the colour of two objects were swapped; on the other half of change trials, the shape of two objects were swapped. The test array remained visible until this response was made and the inter trial interval was 2000 ms.

Orthogonal to the no change and change manipulation, two further types of trials were created. A *novel* trial presented a memory array that had not been previously shown in the experiment. A *repeated* trial, however, presented a memory array that contained information that was previously

shown to observers. Repeated trials occurred every three trials beginning with the third trial in the experiment (i.e., Trial 3, 6, 9, . . .). The proportion of change and no change trials (see earlier) was the same for both novel and repeated trials.

The experiment was divided into three conditions completed in counter-balanced order across participants. Within each condition the nature of the repeated trials was manipulated. In the *repeat-all block*, repeated memory displays were identical. In the *repeat-colour block*, the same colour-location pairings were used while the shape of each object was randomly selected on each repeated trial. Finally, in the *repeat-shape block*, the shape-location pairings were the same in all repeated memory displays while the colour of each object was randomly selected on each trial. Breaks were provided between each condition, but no information regarding condition structure or the repetition of object information was given to observers. Each condition included 72 trials. The experimental session lasted less than 30 min.

## Results and discussion

Change detection performance was analysed with a 2 (repetition)  $\times$  3 (condition) repeated measures ANOVA using both percentage correct and  $A'$  as dependent variables. Results are entirely consistent across these measures. No reliable effects were observed (all  $F_s < 1$ ). For novel trials, change detection accuracy averaged 68%, 67%, and 68% ( $A' = .76, .77, .75$ ) in the repeat-all, repeat-colour, and repeat-shape conditions, respectively. For repeated trials, accuracy averaged 68%, 70%, and 67% ( $A' = .76, .79, .75$ ) in the repeat-all, repeat-colour, and repeat-shape conditions, respectively.

The performance levels obtained show that participants could retain visual information within each trial. However, Experiment 1 provided no evidence that the frequent repetition of object information, whether in part or in whole, leads to better change detection performance (cf. Olson & Jiang, 2004; Wolfe, Oliva, Butcher, & Arsenio, 2002). This finding is consistent with the hypothesis that bindings between features are held as temporary representations for the duration of a single trial, but are lost across two intervening trials in a change detection paradigm. That is, each new array displaces any representations of the previous array, and therefore there is no residual trace when the repetition occurs to allow for long-term learning. Therefore, repeating an array on every third trial was insufficient to allow learning even if this frequency of repetition commonly leads to learning in previous studies using the Hebb-type learning paradigm. To explore this possible interpretation of our data, in Experiment 2 we minimized the possible disruption of temporary representations from trial to trial by repeating the same array on every trial. This should maximize the

possibilities for learning of feature bindings that lead to improvements in change detection performance.

## EXPERIMENT 2

In Experiment 2 we excluded novel trials from the design and repetitions of individual features or of bindings occurred on every trial. This maximized exposure to the repeated arrays (i.e., signal) and minimized any potential distraction from novel arrays (i.e., noise). This provided a scenario in which learning effects within a change-detection task should be optimized. In the absence of novel trials to establish a baseline for comparison, the trial sequence within each condition was divided into three blocks to assess the extent of learning. If observers are sensitive to the across-trial repetition of stimulus information, then change detection accuracy should improve across blocks.

### Method

*Participants.* A new sample of 24 students from the University of Edinburgh participated. They were offered an honorarium of £6. An additional two participants completed the study but were excluded from analysis due to either technical problems or failure to complete the task with above-chance performance.

*Stimuli and apparatus.* The stimuli and apparatus were the same as in Experiment 1.

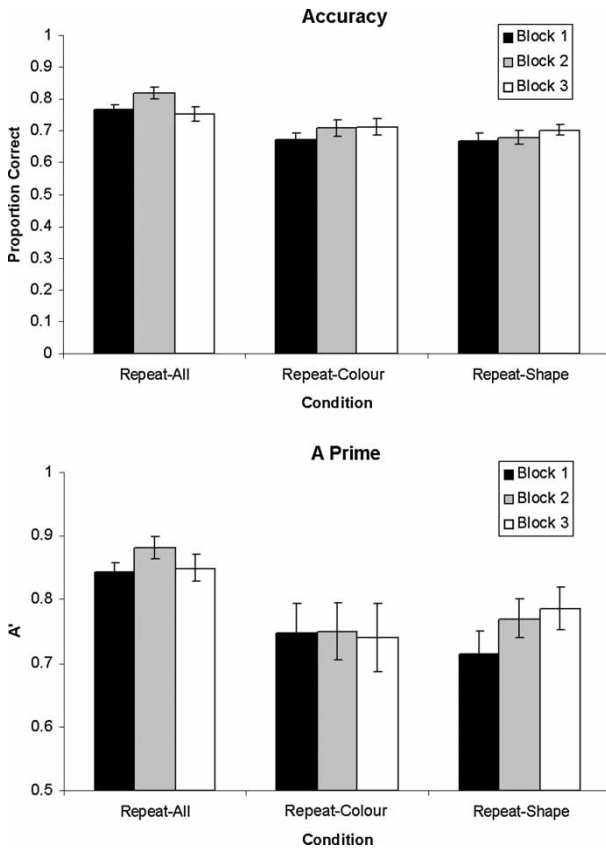
*Design and procedure.* The general procedure replicated that of Experiment 1, except that novel trials were excluded from the design, and the number of trials in each condition (repeat-all, repeat-colour, and repeat-shape) was reduced to 60. The experimental session lasted less than 30 min.

### Results and discussion

For analysis, the trial sequence within each condition was divided into three blocks. Change detection performance was analysed with a 3 (condition)  $\times$  3 (block) repeated measures ANOVA using both percentage correct and  $A'$  as dependent variables (see Figure 2). Results are entirely consistent across these measures and, in the interest of exposition, analyses are only reported for percentage correct.

In contrast to Experiment 1, a main effect of condition was observed,  $F(2, 46) = 21.5$ ,  $p < .001$ . Planned comparisons demonstrated that performance





**Figure 2.** Change detection performance as measured by percentage correct and  $A'$  across blocks of trials in repeat-all, repeat-shape, and repeat-colour conditions in Experiment 2. Error bars represent standard error.

was better in the repeat-all condition relative to both the repeat-colour,  $F(1, 23) = 24.4$ ,  $p < .001$ , and repeat-shape blocks,  $F(1, 23) = 32.2$ ,  $p < .001$ . In addition, within the repeat-all condition, accuracy was reliably superior to that of the novel trials in Experiment 1 ( $p < .001$ ), suggesting that the increased frequency of repetition led to long-term learning when whole objects were repeated from trial to trial. Performance on the repeat-colour and repeat-shape conditions did not differ,  $F(1, 23) < 1$ , and within both these conditions, performance in Experiment 2 was not reliably different from that on the novel trials in Experiment 1 (colour condition:  $p = .42$  shape condition:  $p = .94$ ), suggesting that more frequent repetition did not affect performance in these partial repetition conditions. The main effect of block was not reliable,  $F(2, 46) = 1.70$ ,  $p = .20$ , nor did the factors interact,

$F(4, 92) = 1.51, p = .21$ . This lack of an interaction is curious given that performance in the repeat-all condition was superior to that in the repeat-colour and repeat-shape conditions, an effect that one would expect to emerge across trials.

To help resolve this ambiguity and to examine more closely the performance trends in the repeat-all condition over trials, we further decomposed this condition into six blocks of trials ( $M = 0.77, 0.76, 0.79, 0.85, 0.76, \text{ and } 0.74$  in Blocks 1–6, respectively) and analysed change detection performance with a one-way repeated measures ANOVA. The main effect of block was reliable,  $F(5, 115) = 2.50, p < .05$ , and single degree of freedom polynomial tests indicated a reliable quadratic trend in the data,  $F(1, 23) = 6.31, p < .05$ , suggesting that performance improved from Block 1 to Block 4, but declined thereafter. This pattern of performance presents a bit of a puzzle. While the increase in performance across Blocks 1–4 is consistent with learning, what mechanism accounts for the subsequent decline? Although a complete account of this effect is beyond the scope of this paper, we think that it is possible that the diminished repeat-all performance for the later trials may have resulted from a build-up of interference from the varying test arrays on the change trials. However, a post hoc analysis separately comparing change detection accuracy on same and different trials across blocks showed the interaction was not statistically reliable ( $F < 1$ ), so this is a somewhat speculative account, and other explanations may also be possible.

What we can conclude is that Experiment 2 showed some evidence of learning when the study array was repeated on every trial with better overall performance for the repeat-all condition compared to the repeat-colour and repeat-shape conditions in which a set of single features was repeated across trials. This suggests that there is a residual memory trace that carries over from trial to trial, but in contrasting the results of Experiments 1 and 2, it is clear that this learning only occurred when no novel study arrays intervened between repetitions. The fact that learning only occurred for the repeat-all condition also provides evidence consistent with the hypothesis that feature bindings form the VSTM representations used in change detection tasks, and that those bindings can be retained from trial to trial, when no novel arrays intervene. However, the advantage obtained from repeating exactly the same array on every trial was far from dramatic (an increase in accuracy of  $< 10\%$ ), and performance remained well below ceiling even after repeating the same memory array across 60 consecutive trials. Furthermore, the learning effect from repeating the same study array on every trial might not be as robust as suggested from the overall performance levels given that performance started to decline in the repeat-all condition in the last third of the trials. In other words, repeating a stimulus array—even on every trial—yields a very modest impact on change detection performance.

### EXPERIMENT 3

The lack of strong evidence from Experiments 1 and 2 that feature bindings are maintained from trial to trial is intriguing, particularly when we consider the evidence from previous studies that feature bindings appear to comprise the representations on which participants base their detection of changes in object arrays. The evidence from Experiments 1 and 2 favours the view that the bindings are maintained for as long as needed and then are discarded in favour of a new set of bindings. However, studies using Hebb-type learning paradigms typically use a measure of recall to test the effect of repetitions, and the limited learning that we observed in Experiment 2, even with repetition on every trial, might stem from our use of change detection to test VSTM (e.g., the test displays which incorporate feature changes on 50% of trials might be a source of interference). Therefore in Experiment 3, we adopted a probed recall procedure (Brockmole et al., 2008; Gajewski & Brockmole, 2006). This also allowed us to look at the impact of repeating stimulus arrays separately on memory for feature bindings and memory for individual features.

#### Method

*Participants.* A new sample of 12 University of Edinburgh undergraduate students participated in exchange for course credit.

*Stimuli and apparatus.* The memory displays were constructed as in Experiments 1 and 2. Memory was probed by placing a white square frame subtending 2 cm at one of the six locations that previously housed an object.

*Design and procedure.* As in previous experiments, to suppress verbal rehearsal, each trial began with the presentation of two digits that the observer vocally repeated throughout the trial. After 1500 ms, a fixation cross appeared for 1000 ms, which was then replaced by the memory display for 250 ms. After a further 2000 ms delay, a test probe was presented in a location that was previously occupied by one of the objects in the memory display. Observers then ceased repeating digits and verbally reported to the experimenter the colour and shape of the probed item. The test probe remained visible until this response was made and the intertrial interval was 2000 ms. As in Experiments 1 and 2, the experiment was divided into repeat-all, repeat-colour, and repeat-shape conditions, counterbalanced across participants. As in Experiment 2, the experiment employed repeated trials only. Within each condition, each item was probed an equal number of times, and each condition contained 60 trials. The experimental session lasted less than 30 min.

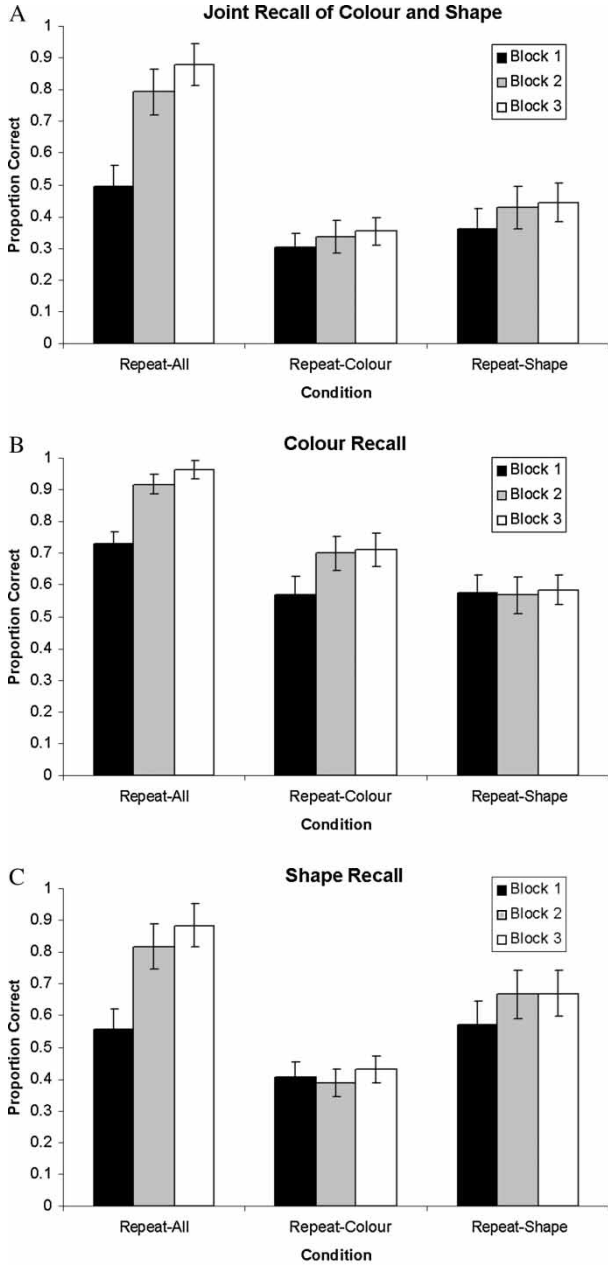
## Results and discussion

Separate analyses considered the accuracy (expressed as percentage correct) with which colour and shape combinations were recalled correctly, and the accuracy with which colour or shape were recalled as individual features. In order to assess learning across trials, the 60 trials in each condition were collapsed into three 20-trial blocks.

*Feature binding recall.* The accuracy of recalling both colour and shape at the probed location was submitted to a 3 (condition)  $\times$  3 (epoch) repeated measures ANOVA (see Figure 3a). The main effect of condition was reliable,  $F(2, 22) = 20.7, p < .001$ . Consistent with Experiment 2, feature recall was more accurate in the repeat-all condition than in both the repeat-colour,  $F(1, 11) = 43.6, p < .001$ , and repeat-shape condition,  $F(1, 11) = 18.0, p < .001$ , while performance did not differ between the repeat-colour and repeat-shape conditions,  $F(1, 11) = 1.85, p = .20$ . A main effect of block was also observed,  $F(2, 22) = 31.3, p < .001$ . The factors interacted,  $F(4, 44) = 6.65, p < .01$ . To explore the nature of this interaction we conducted three separate one-way ANOVAs to assess the effect of block within each condition.

In the repeat-all condition, accuracy reliably varied across epochs,  $F(2, 22) = 29.4, p < .001$ . Single degree of freedom polynomial tests revealed both positive-slope linear,  $F(1, 11) = 41.7, p < .001$ . and quadratic trends,  $F(1, 11) = 7.48, p < .05$ . across blocks. Accuracy did not vary reliably across epochs for the repeat-colour,  $F < 1$ , or the repeat-shape conditions,  $F(2, 22) = 1.22, p = .32$ . These results suggest a strong effect of learning when entire objects are repeated across memory arrays that is absent when only single features are repeated. To obtain a more precise measure of this improvement, we further decomposed the repeat-all condition into six 10-trial blocks ( $M = 41\%, 58\%, 72\%, 86\%, 88\%$ , and  $87\%$  in Blocks 1–6, respectively). It is clear from these data that accuracy improved in a linear fashion from Block 1 to Block 4 (on average, accuracy increased 15% per block), after which an asymptotic level of performance (87%) was achieved.

*Colour recall.* The accuracy of colour recall, regardless of whether or not shape was recalled correctly, was submitted to a 3 (condition)  $\times$  3 (epoch) repeated measures ANOVA (see Figure 3b). The main effect of condition was reliable,  $F(1, 22) = 20.3, p < .001$ . Consistent with Experiment 2, feature recall was more accurate in the repeat-all condition than in both the repeat-colour,  $F(1, 11) = 20.3, p < .001$ , and repeat-shape conditions,  $F(1, 11) = 44.6, p < .001$ , while performance did not differ between the repeat-colour and repeat-shape conditions,  $F(1, 11) = 2.65, p = .13$ . A main effect of block was also observed,  $F(2, 22) = 23.5, p < .001$ . Interestingly, however, the



**Figure 3.** Recall performance across trial blocks in the repeat-all, repeat-colour, and repeat-shape conditions in Experiment 3. (A) Recall of shape and colour combinations. (B) Recall of colour independent of shape. (C) Recall of shape independent of colour. Error bars represent standard error.

factors interacted,  $F(4, 44) = 3.41$ ,  $p < .05$ . To explore the nature of this interaction we conducted three separate one-way ANOVAs to assess the effect of block within each condition.

In the repeat-all condition, accuracy reliably varied across epochs,  $F(2, 22) = 28.4$ ,  $p < .001$ . Single degree of freedom polynomial tests revealed both positive-slope linear,  $F(1, 11) = 33.1$ ,  $p < .001$ , and quadratic trends,  $F(1, 11) = 13.3$ ,  $p < .01$ , across blocks. In the repeat-colour condition, accuracy also reliably varied across epochs,  $F(2, 22) = 28.4$ ,  $p < .001$ . This variance was again explained by both positive-slope linear,  $F(1, 11) = 8.72$ ,  $p < .05$ , and quadratic trends,  $F(1, 11) = 6.99$ ,  $p < .05$ , across blocks. However, in the repeat-shape condition, no reliable effect of block was observed,  $F(2, 22) < 1$ . Considering colour recall independent of shape recall, we therefore obtained some evidence that the repetition of a single feature can be learned. However, this rate of learning was smaller (increase in accuracy of 14% over the course of the experiment) compared to cases where both an object's colour and shape repeat across trials (23% increase over the experiment).

*Shape recall.* The accuracy of shape recall was submitted to a 3 (condition)  $\times$  3 (epoch) repeated measures ANOVA (see Figure 3c). The main effect of condition was reliable,  $F(1, 22) = 16.6$ ,  $p < .001$ . Consistent with Experiment 2, feature recall was more accurate in the repeat-all condition than in both the repeat-colour condition,  $F(1, 11) = 37.1$ ,  $p < .001$ . The repeat-all condition was not, on average, different from the repeat-shape condition,  $F(1, 11) = 2.73$ ,  $p = .13$ . Shape recall was reliably better in the repeat-shape condition compared to the repeat-colour condition,  $F(1, 11) = 17.8$ ,  $p < .001$ . A main effect of block was also observed,  $F(2, 22) = 14.6$ ,  $p < .001$ . Interestingly the factors interacted,  $F(4, 44) = 4.10$ ,  $p < .01$ . As with colour recall, to explore the nature of this interaction we conducted three separate one-way ANOVAs to assess the effect of block within each condition.

In the repeat-all condition, accuracy reliably varied across epochs,  $F(2, 22) = 21.0$ ,  $p < .001$ . Single degree of freedom polynomial tests revealed both positive-slope linear,  $F(1, 11) = 27.2$ ,  $p < .001$ , and quadratic trends,  $F(1, 11) = 7.08$ ,  $p < .05$ , across blocks. In the repeat-shape condition, although shape recall improved by 10%, the effect of block was not reliable,  $F(2, 22) = 1.24$ ,  $p = .31$ . In the repeat-colour condition, no reliable effect of block was observed,  $F(2, 22) < 1$ . Thus, independent consideration of shape recall provides no evidence that repetition of a single feature leads to robust learning.

## Summary

To summarize, when using a probe recall procedure and repeating the complete stimulus array on every trial, improvements in recalling bindings between colour and shape can be obtained across trials. Indeed, performance approaches ceiling, but only after 40 trials. Small effects of learning on recall of colour were found for repeating colours, but there was no equivalent effect on shape. These results are consistent with the hypothesis that bound object representations in VSTM are the primary determinant of long-term learning.

## GENERAL DISCUSSION

In the present study, we examined how long-term memory traces for repeatedly presented multifeature objects are generated, and whether these traces are constrained by the representational format of VSTM. Across three experiments, observers were asked to remember an array of coloured shapes across a short retention interval. Previous work has suggested that in such tasks objects are stored in VSTM as integrated, singular, bound units rather than as caches of individual features (Allen et al., 2006; Gajewski & Brockmole, 2006; Johnson et al., 2008; Luck & Vogel, 1997; Vogel et al., 2001). As such, one might expect that bound object representations may serve as the basis for long-term learning. Using a Hebb-type learning procedure, object features were consistently repeated across trials. To the extent that observers are sensitive to this repetition, performance on the short-term memory task should improve over trials. In separate conditions, repetitions involved colour (repeat-colour), shape (repeat-shape), or the combination of colour and shape (repeat-all). If the contents of VSTM constrain learning and learning only occurs for bound objects, performance should only improve when the repeated display consists of exactly the same combinations of colour and shape.

Experiment 1 adopted a change detection paradigm and memory arrays were repeated on every third trial. Change detection performance was well above chance, but was no better on the repeated trials than on the intervening novel trials, suggesting that neither the repetition of individual features nor bindings were learned. By increasing the frequency of repetition to every trial in Experiment 2, change detection performance in the repeat-all condition improved, an effect that was absent in the repeat-colour and repeat-shape conditions. The amount of learning was very modest, however, and was not consistent for the later trials. Much clearer evidence of learning of repeated object information was observed in Experiment 3 in which the study array was presented on every trial and memory was tested using a

probed recall method. Learning was most robust when colour–shape bindings were repeated, but developed rather slowly as performance improved linearly over the course of 40 repetitions before reaching asymptote. There was some evidence that repeating a set of colours while varying shape from trial to trial led to modest improvements in colour memory, but there was not an equivalent effect on recalling shape when shape information was held constant across trials.

Collectively, these experiments support the following conclusions. First, our results are broadly consistent with previous demonstrations that bindings in VSTM are fragile as they are susceptible to interference generated by the creation of new multifeature object representations in VSTM (Allen et al., 2006). When novel objects arrays were interleaved between repeated arrays, no learning was obtained. The fact that some learning is possible when repetitions occur on every trial suggests that the fragility arises from overwriting of the contents of VSTM. This result is consistent with the view that VSTM can support temporary representations required for performance on a trial by trial basis, and functions separately from long-term memory.

Second, despite their fragility, feature bindings created in VSTM influence the nature of long-term learning. Due to the complexity of visual objects and the myriad features that define and discriminate them, representations in VSTM combine multiple features into singular object representations. It appears from our experiments that this representational format of VSTM constrains long-term learning about objects and features that we encounter many times. Across experiments, learning effects were generally absent in the repeat-colour and repeat-shape conditions, and when present, they were much smaller than learning effects in the repeat-all conditions. This pattern of data suggests that integrated objects are more likely to be transferred into long-term memory than individual object features.

Third, location might be an important feature of objects. In a study with similarities to our own, Dishon-Berkovits and Treisman (reported by Treisman, 2006) found no evidence that long-term memory for feature bindings improves change detection within trials. However, repeated objects were not always presented in the same spatial location. In contrast, presenting repeated visual features in the same locations on each trial, we did obtain short-term memory benefits from longer term learning, at least for colour-shape conjunctions, in both change detection and cued-recall. Therefore, our data suggest that bound representations that include location along with shape and colour can be the basis for long-term learning, although these results do not suggest that location must be a prerequisite for learning of bindings to occur. Moreover, recent evidence from our own and other laboratories has suggested that if location cannot function as a



memory cue, then it does not play any special role in binding once bound object representations are generated in VSTM (Logie et al., 2008; Treisman & Zhang, 2006). The role of location in long-term learning therefore remains an interesting question for future research.

Fourth, although short-term memory and long-term memory may be regarded as separate constructs (e.g., Baddeley, 1986, 2000; Logie, 1995, 2003; Logie & van der Meulen, in press), the present results suggest ways in which they are related. Observers' learning of repeated objects reciprocally benefited short-term memory for those objects. This is consistent with the notion that acquired knowledge can influence short-term visual memory. This is analogous to the well-established finding that verbal short-term memory for letter sequences is better for sequences that resemble real words represented in long-term memory (e.g., Baddeley, 1971). Returning to our own data, the finding that bound objects constrain both VSTM and long-term learning further suggests that VSTM and visual long-term memory share a common representational format. The results of the present study are not, however, consistent with the hypothesis that VSTM is merely a temporarily activated subset of LTM (Anderson, 1983; Cowan, 1995, 1999; Postle, 2007; Ruchkin, Grafman, Cameron, & Berndt, 2003). Performance on the VSTM tasks was well above chance levels even when no evidence for learning was obtained in Experiment 1, and it is extremely unlikely that there were representations in long-term memory of the specific combinations of features used in our experiments that could be used to support performance. Both of these facts suggest that VSTM can operate independently of LTM. Indeed, based on the activated LTM hypothesis, one could reasonably predict that more robust learning should have been present in the single-feature repetition conditions: LTM would hold representations for the individual colours and shapes used in the study, each presentation of a particular colour or shape should lead to repeated activation of those representations, and this in turn should lead to evidence that access to the representations was facilitated across trials. There was some evidence that this might have occurred for colour in Experiment 3, but the evidence for learning was much stronger for representations of feature bindings that would have been encountered for the first time on starting the experiment.

In addition to refining our understanding of the relationship between VSTM and LTM, the current experiments raise new and interesting questions for future research. First, despite identical memory arrays and retention intervals, the strength of long-term learning depended on the manner in which short-term memory was tested with location-cued recall in Experiment 3 resulting in much stronger evidence for long-term learning than did change detection. Why might this have occurred? In general terms, this result suggests that learning is not simply a product of repeated generation of similar VSTM representations, but is also affected by the way

in which those representations are subsequently interrogated. With specific reference to the tasks used in this study, one possible explanation for the observed task-discrepancies is that the test displays used in change detection tasks are a source of interference which is not present in the cued recall procedure. Another possibility is that performance in the cued-recall task was driven not only by visual memory for the objects, and the use of location as a cue, but also memory for the verbal responses made during the recall process. Future research will be required to disentangle these (and potentially other) possibilities in an effort to systematically characterize the role of task constraints on the quality of both short- and long-term memory representations.

A second issue for future research concerns the role of explicit memory and awareness in the learning mechanisms tapped in this study. In other visual processing domains such as visual search, researchers have shown that observers become sensitive to target location probabilities as well as repeated covariation between a particular search target and its surrounding context. Several researchers have suggested that these contingencies are represented implicitly in long-term memory (e.g., Chun & Jiang, 1998; Geng & Behrmann, 2005; Walthew & Gilchrist, 2006). The extent to which learning in the change detection and cued recall tasks used in this study depends on explicit memory is therefore an interesting question. Although we did not formally assess the extent to which observers were aware of our manipulations, at the conclusion of each experiment we asked observers whether they noticed anything unusual about the displays. In Experiment 1 (no learning), none of the participants had noticed that certain displays repeated over trials. In Experiment 2 (limited learning), fewer than half of the participants noticed the repetition. In Experiment 3 (robust learning), almost all observers noticed the repetitions. These trends suggest a possible correlation between awareness and learning, and that awareness might arise when there is a residual trace from a previous trial against which the current trial can be compared. If there is no residual trace, then there would be no basis on which to build an awareness of the repetition. However, we were not able to identify any obvious performance differences between observers that were and were not aware of repetitions. A focused and systematic investigation into the role of awareness in the long-term learning of repeated objects is therefore an important avenue for future consideration.

In summary, the results of three experiments suggest that representations in visual short-term memory comprise integrated objects rather than individual features. These representations are readily displaced by new representations formed on subsequent trials. However, when a given representation is not displaced, longer term residual traces can be generated to support long-term learning, and any learning that does occur is based on integrated objects, not individual features.

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