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### **Feature binding in short-term memory and long-term learning**

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## Abstract

In everyday experience we encounter visual feature combinations. Some combinations are learned to support object recognition, and some are arbitrary and rapidly changing so are retained briefly to complete ongoing tasks before being updated or forgotten. However, the boundary conditions between temporary retention of fleeting feature combinations and learning of feature bindings are unclear. Logie, Brockmole, and Vandembroucke (2009) demonstrated that 60 repetitions of the same feature bindings for change detection resulted in no learning, but clear learning occurred with cued recall of the feature names. We extended those studies in two new experiments with the same array of colour-shape-location combinations repeated for 120 trials. In Experiment 1, change detection was well above chance from trial one, but improved only after 40-60 trials for participants who subsequently reported becoming aware of the repetition, and after 100-120 trials for participants reporting no awareness. Performance improved rapidly in Experiment 2 when participants reconstructed the array by selecting individual features from sets of colours, shapes, and locations. All participants subsequently reported becoming aware of the repetition. We conclude that change detection involves a visual cache memory (Logie, 1995; 2003; 2011) that functions from the first trial, and retains feature bindings only for the duration of a trial. In addition, a weak residual episodic memory trace accumulates slowly across repetitions, eventually resulting in learning. Reconstructing feature combinations generates a much stronger episodic memory trace from trial to trial, and so learning is faster with performance supported both by the limited capacity visual cache, and learning of the array.

We constantly encounter complex visual information some of which we must process and learn to form robust and enduring representations that support subsequent object recognition; for example, learning that a box for paper mail in the UK is red and cylindrical, and the flags for the UK and the USA both combine red, white, and blue but in different configurations. However, much of everyday visual information changes rapidly and needs to be retained only briefly to monitor our immediate environment or to complete ongoing tasks. For example, safe driving around town requires continual monitoring and updating of the position and size of nearby traffic, of the current colour of the traffic lights, and of the movements of pedestrians. In these latter cases, it would be a serious disadvantage to maintain an enduring representation of a single visual snapshot of our changing surroundings. The temporary representations of rapidly changing visual information have long been argued to be held in a visual short-term memory system (e.g., Broadbent & Broadbent, 1981; Logie, 1995; Luck & Vogel, 1997; Phillips & Christie, 1977), with some researchers arguing that this comprises a visual cache memory that is separate from, but complementary to visual perception, attention, and episodic long-term memory (e.g., Logie, 1995; 2003; 2011; Logie, Brockmole, & Vandenbroucke, 2009). However, the relationship between long-term associative learning of feature combinations, and short-term memory for temporary bindings between features is unclear, with, for example, some researchers viewing visual short-term memory not as a separate temporary memory system, but as the focus of attention on visual information that is currently activated from long-term memory (e.g. Cowan, Blume, & Saults, 2013; Cowan, Saults, & Blume, 2014; Morey, Morey, Van Der Reijden, & Holweg, 2013). In the experiments reported here, we explored the relationship between temporary bindings and associative learning by investigating the effects on immediate memory

performance of repeated presentation of the same visual array of arbitrary combinations of colours, shapes, and locations.

Visual short-term memory (VSTM)<sup>1</sup> refers to our ability to retain visual information in mind for a short period of time and is very limited in capacity (Cowan, 2001; Logie, 1995, 2003, 2016; Luck & Vogel, 1997; Phillips, 1983; Todd & Marois, 2004). A topic of debate<sup>2</sup> in the literature has been whether VSTM representations comprise individual features temporarily activated from long-term memory, and that memory for temporary bindings between features makes greater demands on attention than remembering individual features (e.g., Cowan, Naveh-Benjamin, Kilb, & Saults, 2006; Wheeler & Treisman, 2002; Zokaei, Heider, & Husain, 2014), or whether VSTM representations consist of integrated bound objects that are not disrupted by attentional distractors any more than are representations of individual features (e.g., Allen, Baddeley, & Hitch, 2006; Gajewski & Brockmole, 2006), particularly for study-test delays beyond 1000ms (Logie, Brockmole, & Jaswal, 2011). For both sides of this debate, with few exceptions (Colzato, Raffone, & Hommel, 2006; Logie et al., 2011; Logie et al., 2009; Rhodes, Parra, & Logie, 2016), the fate of the representations of the bound features, when they are no

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<sup>1</sup> In the literature on visual attention, visual perception, and feature binding, the terms 'visual short-term memory' and 'visual working memory' tend to be used interchangeably. We view visual short-term memory as referring to a set of cognitive functions that support temporary retention of visual information, including verbal labels and semantic knowledge as well as visual codes. We use the term 'visual cache' to refer to a limited capacity domain-specific temporary store for visual codes that is one of several functions of visual working memory within a broader, multi-component working memory. For detailed discussions see Logie (1995, 2003, 2016; Logie & van der Meulen, 2009).

<sup>2</sup> We are fully aware that there is another, related debate as to whether the limitation on visual short-term memory capacity is based on the precision of the visual representation or the number of items retained. A discussion of that debate is out of the scope of the current studies. Our research goal here was to focus on the conditions under which visual information is lost from memory trial to trial or leads to long-term learning, and the cognitive mechanisms that support temporary and long-term visual representations.

longer task-relevant, has not been systematically examined and therefore remains less well understood.

In a preliminary study, Dishon-Bercovits and Treisman (cited in Treisman, 2006) examined whether participants learned particular colour-shape pairings that were repeated on 80% of trials and whether this learning benefitted performance on a surprise post-experiment questionnaire regarding those pairings. Findings showed that although repeating the pairings did not improve performance on the VSTM task, participants performed better than chance on the questionnaire, indicating that the binding of the pairings yielded residual traces that were stored in long-term memory (LTM), but the stored information was not used in the VSTM task. Colzato et al. (2006) found faster performance for repeated colour-shape pairings than for non-repeated pairings, indicating some learning of the binding of the paired features in the VSTM task. However, performance for the repeated pairing was not improved in a subsequent memory test. Based on these results, Colzato et al. (2006) suggested that temporary memory for binding of features and learning of feature combinations are independent mechanisms.

Incorporating a variant of the Hebb repetition paradigm (e.g., Couture & Tremblay, 2006; Hebb, 1961; Lee, 1976; Page, Cumming, Norris, Hitch, & McNeil, 2006; Szmalec, Duyck, Vandierendonck, Mata, & Page, 2009), Logie et al. (2009) found that repetition of exactly the same array of colour-shape-location bindings on every third trial across 72 trials failed to show any improvement in change-detection performance over trial blocks. This was in striking contrast with clear effects of learning with just 8 repetitions across 24 trials in the original Hebb (1961) study and with 8-12 repetitions in subsequent studies, cited above, that used a wide range of different types of material, including visual dot patterns (e.g., Couture & Tremblay, 2006).

In the Logie et al., (2009) study, a significant but very small improvement in performance in change detection for colour-shape-location bindings was observed when the repetition occurred on every trial of 60 trials (90 presentations to include presentations on the no-change test arrays), but there was no evidence that participants learned bindings of repeated colour-location pairings when colour-shape combinations changed across trials, or of repeated shape-location pairings when shape-colour combinations changed across trials. Learning was observed only for repeating integrated objects, not for repeating individual features. Most remarkable is that the improvement in performance for integrated objects was less than 10%, was well below ceiling, only appeared after repeating the same array for 40 trials, and over the final 20 trials (out of 60) performance dropped back to the same level observed over the first 20 trials, reversing any evidence for learning. In a third experiment, Logie et al. (2009) again repeated the same colour-shape-location array across 60 trials, but tested memory by presenting a visual location cue for spoken recall of the names of the colour and shape presented in that location (e.g., green star or blue cross). This cued recall paradigm was closer to that used to demonstrate Hebb type learning in other studies with verbal material. In this third experiment, there was evidence of substantial learning with an increase of 40% in accuracy of recall across trials. However, even here, repetition of colour-location and shape-location arrays showed very little evidence of learning, and performance was poorer overall than for integrated objects. These findings led the authors to conclude that, for change detection, there is little evidence of a residual trace of an array from trial to trial, with each stimulus array replacing the immediately preceding array in VSTM, even though the arrays are identical. Clear evidence of learning from repeated arrays only appeared in Experiment 3 when participants had to generate the names of integrated objects in response to a location cue. Because there was no learning for repetitions of colour only or of

shape only, it was proposed that the integrated objects, not individual features, were the basis for learning when this occurred. It was also proposed that change detection relies on a short-lived representation in VSTM that functions separately from learning and long-term memory, consistent with the findings from Colzato et al. (2006), and Treisman (2006). Learning was thought to arise from repeated use across trials of the verbal labels for the integrated objects, not from the repeated presentation of the same visual array. Evidence that learning might occur in a reconstruction paradigm without reliance on verbal labels was reported by Brady, Konkle, and Alvarez (2009) who demonstrated that when participants were presented with a location cue and asked to select a target colour from a range of colours displayed at test, then learning occurred for colour combinations within only part of the study array that were repeated around 130 times randomly amongst a total of 600 trials, the remainder of which involved novel colour combinations on each trial.

One hypothesis, based on the above findings, is that object representations are retained in a domain-specific short-term visual memory store or ‘visual cache’, which is separate from LTM, is separate from verbal short-term memory, and the contents of which are replaced by new representations derived from a subsequent stimulus array. A detailed description of the concept of the visual cache and evidence for its characteristics is beyond the scope of the current paper, and detailed treatments are provided elsewhere (Logie, 1995, 2003, 2011, 2016; Logie et al., 2009; Logie et al., 2011; Logie & van der Meulen, 2009). In summary, the visual cache is thought to be a passive store that retains a limited amount of visual information for periods of a few seconds after stimulus removal until replaced/updated with a new stimulus. It is argued that a participant is not aware of the contents of the visual cache unless these contents are retrieved for the ongoing task. Because its contents are outside of awareness, the visual cache is argued to



be separate from generating and maintaining a visual mental image (Borst, Niven, & Logie, 2012; van der Meulen, Logie, & Della Sala, 2009), and separate from visual attention (Allen et al., 2006; Gajewski & Brockmole, 2006; Logie et al., 2011). Given its characteristics as a domain-specific temporary store, the visual cache is distinct from the concept of the domain-general and cross-modal episodic buffer proposed by Baddeley (2000). It is also distinct from the earlier concept of a visuo-spatial scratch-pad (Baddeley, 1986) that was thought to support both visual mental imagery and visual short-term memory. A domain-specific visual cache would provide the brain with the flexibility to continually update representations of rapidly changing visual information in the environment, and to retain adequate levels of performance without being prone to interference from previously presented visual or related semantic information. In the experiments reported here, we explored the conditions under which temporary visual representations are, or are not overwritten by new information, even when the new information is identical to what was previously retained. This has important implications for understanding how longer term traces are generated and how these can in turn facilitate long-term learning, as well as for understanding the functioning of VSTM and its relationship with LTM.

More specifically, we aimed to investigate whether individual features and multi-feature bound objects generate residual memory traces that subsequently lead to learning, and whether the presence or absence of these residual traces depends on the mode by which memory is tested. Healthy adult participants were asked to remember an array of coloured objects across short retention intervals. To investigate the extent to which these integrated objects would generate longer term memory traces, we employed a version of the Hebb-type (Hebb, 1961) repeated presentation technique used by Logie et al. (2009) in which the to-be-remembered arrays of feature combinations of colours, shapes, and locations were consistently repeated across all

trials. A limitation of Experiments 1 and 2 in Logie et al. (2009) was the finding of essentially null results, and 60 trials might not have been sufficient to detect clear effects of learning with a change detection paradigm. Therefore, here we doubled the number of trials in order to examine whether learning of visual arrays in a change detection paradigm requires more repetitions than were used in the previous study. A second limitation of the previous study was that a fixed array size with six objects was used in all three experiments. This might have been too large a number of objects to facilitate learning from repetition. Therefore, in Experiment 1, we manipulated array size to investigate whether longer-term learning is constrained by the number of items participants have to encode and retain on every trial. A third limitation of the earlier study was the use of the same combinations of colours, shapes, and locations for repeated presentation to every participant and this particular set of combinations might have been particularly difficult to learn. So, in the new experiments, the array for repetition was different for each participant. In the first experiment, we used a change-detection task to examine participants' learning over time.

There were two further limitations of Logie et al. (2009), one of which was the sample sizes in each experiment, with 12 participants in Experiment 1 and 3, and 24 participants in Experiment 2. These participant numbers might not have allowed for sufficient statistical power to detect what might have been a rather weak effect of learning in those previous first two experiments. Also, Experiment 3 in Logie et al. (2009) involved spoken, verbal responses that would make the task a less pure measure of memory for visual representations. In the second experiment reported here, we used visual reconstruction to test visual memory by asking participants to select, from the set of possible stimuli, the colour-shape-location combinations that were shown in the memory array. This would not prevent participants from naming the features, but it avoided the need to use the names explicitly to perform the task. Moreover, in

both experiments, participants were asked to repeat aloud two irrelevant digits (articulatory suppression) as a means to reduce the possible contribution of feature names in memory for the study array.

By manipulating the response mode across experiments (change detection versus visual reconstruction), we aimed to gain additional insight into the conditions under which repeated presentation generates residual traces in episodic long-term memory that are carried over from trial to trial in support of learning. In other words, we are assuming that participants use the visual cache to support performance in temporary feature binding tasks in which the stimulus array changes from trial to trial. However, when the stimulus array is repeated, there is an additional, residual trace in episodic long-term memory that can accumulate across repetitions, and as learning of the array progresses, there is increasing support for performance from episodic long-term memory in addition to the contents of the visual cache on each trial. In a change detection paradigm the episodic trace is very weak and therefore requires a large number of repetitions of the same stimulus array before learning results in an improvement in performance. So, in Experiment 1, with change detection and six-item arrays, we expect results similar to those in Logie et al. (2009) Experiment 2, but with some evidence of learning because of the larger number of repetitions, the increase in participant numbers, and the other changes to the procedure outlined above. With four item arrays we expect faster performance improvements because there is less material to learn. However, based on previous estimates that the capacity of visual short-term memory is around 3-4 items (Cowan, 2001; Luck & Vogel, 1997), we might also see performance close to ceiling from the start because the whole array may be retained in the visual cache during a trial, and no learning will be needed. In Experiment 2 reported here, the act of selecting each feature for the correct combination during reconstruction of items that are

repeated across trials may greatly strengthen a weak episodic trace from the array presentation. Unlike Brady et al. (2009), the whole array was repeated on every trial. So, we expect that there would be rapid learning of the repeated array and participants would then draw on both the contents of their visual cache, and a rapidly strengthening episodic trace resulting in clear improvement in performance across trials. This would build on the results from Logie et al. (2009) Experiment 3, which demonstrated rapid learning when memory for six-item arrays was tested using reconstruction of the combinations of verbal labels for the visual features in the repeated array.

Finally, the Logie et al. (2009) study did not consider whether or not the participants were aware of the repetition of the array across trials. Hebb (1961) reported that learning of recalled digit sequences occurred even for participants who reported not being aware of the repeated sequence. However, it is possible that awareness of the repetition of a visual array in a change detection paradigm may be associated with more rapid improvements in performance across trials. Therefore, at the end of the whole test session, participants were asked whether or not they had been aware that they had seen the same array on every trial. Although retrospective reports from participants should be treated with caution, this offered the opportunity to investigate any systematic differences in performance between those who subsequently reported awareness of the repetition and those who did not.

## Experiment 1

In the first experiment we explored the impact on change detection performance of repeating the same array of colour-shape-location combinations with two different array sizes.

### Methods

#### *Participants*

Thirty-one healthy adults (8 males and 23 females), aged 18 to 33 years old ( $M = 23.8$  years old,  $SD = 3.72$ ), with normal or corrected-to-normal visual acuity and normal colour vision, participated in Experiment 1. Participants were recruited from among students at the University of Edinburgh who received £10 for their participation. All participants signed a consent form prior to testing and were debriefed afterwards. Ethical approval for the study was provided by the Psychology Research Ethics Committee of the University of Edinburgh. In order to ensure adequate statistical power, we carried out power analysis using G\*Power 3 (Faul, Erdfelder, Lang, & Buchner, 2007) to calculate a priori the minimum required sample size. Based on the  $F$  value of a significant effect for repeated-arrays reported in Logie et al (2009), we estimated the lower and upper limit on partial eta square. Both limits were very high (0.39 and 0.75 respectively), therefore we opted to adopt a stricter criterion. Specifically, we carried out the power analysis based on a  $\eta_p^2$  of .06, which represents a medium size effect. To achieve power of 0.95 to detect a medium effect size of  $\eta_p^2 = .06$  with a significance level of  $\alpha = .05$ , the estimated required number of participants was 28.

#### *Apparatus and Stimuli*

The task, the sequence of events on each trial, and the durations for each phase of the trial are presented in Figure 1. On each trial, participants viewed a study array of either six objects or

four objects for 200ms, followed by a blank screen for 2000 ms, and then a test array. They were asked to respond whether or not a change occurred between the study and test array within the trial by pressing two keyboard buttons for a change/no-change response (“m” / “z” respectively). When a change occurred this could be either in colour (i.e., the colours of two objects were swapped with all shapes staying in the same location) or in shape (i.e., the shapes of two objects were swapped with all colours staying in the same location). The study array was different for every participant but each participant saw their allocated array repeated throughout the duration of the task, i.e., the precise combinations of colour, shape, and location for each of the objects in the array were identical on every trial; however, participants were not informed about this repetition. At the beginning of each trial participants were presented with two digits (1 to 10) displayed for 1500 ms. These digits were randomly generated by the computer on every trial, and participants were asked to repeat the digits aloud (articulatory suppression) at a rate of two per second throughout the trial and until the test array onset. Articulatory suppression was intended to discourage participants from supporting their memory performance by subvocal rehearsal of the names of the colours, shapes, or locations for the study array objects during encoding or the 2000 ms retention interval. Participants were monitored by the experimenter, who ensured that they indeed employed articulatory suppression as they were instructed to do. Participants completed two tasks, one consisting of six objects and one consisting of four objects (henceforth referred to as load 6 and load 4 respectively).

[Please insert Figure 1 approximately here]

Stimuli were presented on a black background using E-Prime 2.0 software (Psychological Software Tools, Inc). The memory array was generated randomly for each participant at the beginning of the task and the array objects were created as the random combination of distinct

features drawn from a list of 8 geometric shapes (arrow, circle, cross, diamond, heart, square, star, and triangle) and 8 colours (blue, cyan, green, grey, magenta, red, white, and yellow) without replacement. For the six item arrays, the items were symmetrically arranged in six locations around an imaginary circle, each at a  $5.63^\circ$  angular eccentricity from a central fixation point (that remained on the screen throughout the trial) from a viewing distance of about 50cm. In the four item arrays, objects were positioned one in each quadrant.

Participants completed 4 practice trials with different stimulus arrays from the main experimental trials to familiarize themselves with each task, followed by 6 test blocks of 20 trials each, totaling 120 experimental trials in each load task. From these, 60 (50%) were no-change trials and 60 (50%) were change trials (50% colour-change). Changes occurred with equal probability for all positions. With 120 trials, this resulted in the same stimulus array being repeated 180 times, with 120 times in the study phase and on 60 trials in the test phase when no change was presented. The proportion of same/different trials was the same for each of the six blocks.

### *Procedure*

Participants were comfortably seated in front of the computer screen. They were first given written and verbal instructions. For practice trials only, participants received visual feedback (correct, incorrect) on the screen after each trial. The memory array in practice trials was different from the memory array in test trials. Also, the memory array was different between the two memory load tasks. We considered that in the load 4 condition it was more likely than in the load 6 condition that participants might notice the repetition spontaneously. Therefore, participants completed the load 6 task first, followed by a short 5-minute break before carrying

out the load 4 task. Self-paced breaks were inserted between the blocks of each task. Each individual testing session lasted about one hour. At the end of the whole testing session, that is after completing both the load 6 and the load 4 tasks, participants were asked explicitly whether they noticed that the array was repeated on every trial in any of the two tasks. This information allowed us to examine whether reported awareness was associated with learning of repeated objects in the change-detection task that was employed.

### *Statistical design and analyses*

Two, 2 (load: 6 vs. 4) x 6 (blocks: 1 to 6) repeated-measures ANOVA were carried out<sup>3</sup> to examine the effects of load and array repetition on long-term learning. The first analysis considered the percentage correct scores. For the second analysis, because our primary focus was on whether or not learning occurred, we considered the number of trials taken by each participant to reach their maximum level of performance. Very few participants reached consistent 100% accuracy on the load 6 task, so for this measure we adopted the criterion of the number of trials required by each participant to achieve a correct response on nine out of ten consecutive trials, or 90% correct. Significant findings were subsequently followed by Bonferroni-corrected post-hoc comparisons. In addition, we divided participants into two “awareness” groups, specifically those who reported at the end of the test session that they had noticed the repetition of the memory array versus those who reported not noticing the repetition. Finally, we complemented our accuracy analyses with repeated-measures ANOVAs on mean reaction times (RT). The

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<sup>3</sup> We also carried out an analysis of  $d'$  scores. Results were essentially the same as for percentage correct scores, with participants showing increased sensitivity across trial blocks. However,  $d'$  could not be calculated for Experiment 2, and because we had a major interest in contrasting the effects of repetition across the two experiments, we report here the detailed results of the analysis of percentage correct and trials to criterion, both of which can be calculated for both experiments.  $d'$  scores are available on request from the first author.



Greenhouse-Geisser correction was employed to deal with violations of sphericity when necessary and the adjusted degrees of freedom are reported. Partial eta squared values obtained from the ANOVA are reported for effect sizes.

## Results

Two participants were excluded from analyses, one due to incomplete data resulting from an equipment failure and another due to below-chance performance in blocks 4-6 in the load 6 task. First, we report the analysis of percentage correct scores, and mean scores across blocks for load 6 and load 4, illustrated in Figure 2a.

[Please insert Figure 2a and 2b approximately here]

The analysis comparing change-detection performance between the two load tasks yielded significant main effects of block,  $F(5,140)=15.64$ ,  $p<.001$ ,  $\eta^2_p=.36$ , and of load,  $F(1,28)=57.73$ ,  $p<.001$ ,  $\eta^2_p=.67$ . The block x load interaction was significant,  $F(5,140)=5.45$ ,  $p<.001$ ,  $\eta^2_p=.16$ . Pair-wise comparisons revealed that the interaction was driven by the difference in performance across blocks in the load 6 task. More specifically, performance (percentage correct) in the load 6 task improved significantly in blocks 3 – 6 compared to block 1 (all  $p<.02$ ) and in block 6 compared to block 2 ( $p<.001$ ). In contrast, performance did not differ across blocks in the load 4 task (all  $p>.50$ ). This appears to be due to participants performing close to ceiling in block 1 of the load 4 task, leaving little room for further improvements as a result of learning (percentage correct: .90, .91, .92, .93, .93, .94 for blocks 1 – 6 respectively). A total of 20 out of 29 participants reached 100% performance within the first ten trials of block 1 for the load 4 task, with a small number of errors occurring on subsequent trials. On the load 6 task, only four out of 29 participants achieved 100% correct within the first ten trials of block 1.

We carried out further analyses after dividing participants into those who reported, after the completion of the whole test session (i.e., both load 6 and load 4 tasks), that they had become aware of the memory array repetition. In the load 6 task, 16 participants reported that they had become aware and 13 reported that they had not been aware. The analysis of percentage correct showed main effects of reported awareness,  $F(1,27)=5.75, p=.02, \eta^2_p=.18$ , and of block,  $F(5,135)=14.52, p<.001, \eta^2_p=.35$ , as well as a significant interaction of awareness x block,  $F(5,135)=2.83, p=.01, \eta^2_p=.10$ . These results are illustrated in Figure 2b. Notably, results from pairwise comparisons showed that performance for the “aware” group improved significantly in blocks 3 – 6 compared with block 1 and in blocks 3 – 6 compared with block 2 ( $ps<.05$ ). In contrast, there were no statistically significant differences across blocks in the “no-awareness” group except between blocks 1 and 6 ( $p<.001$ ), blocks 3 and 6, and blocks 4 and 6 ( $ps=.03$ ; Figure 2b). Also, the “awareness” group performed significantly better than the “non-awareness group” in block 3 ( $p=0.01$ ), block 4 ( $p=0.006$ ), and block 5 ( $p=0.03$ ).

For our second analysis, participants required a mean of 32.66 trials ( $SD=24.15$ ) to achieve the criterion 90% consistent level of performance. Participants who reported being aware of the repetition ( $N=16$ ) required a mean of 23.56 ( $SD=16.08$ ) trials and participants who reported not being aware ( $N=13$ ) required a mean of 43.85 ( $SD=29.69$ ) to reach 90% correct. This difference was significant,  $F(1,27)=5.51, p<0.05, \eta^2_p=0.17$ .

In the load 4 task, 21 participants reported noticing the repetition (Mean Trials to Criterion=11.1,  $SD=2.57$ ), and 8 reported not noticing the repetition (Mean Trials to Criterion=14.38,  $SD=4.56$ ). The latter were among the 13 who reported not being aware in the load 6 condition. The group comparison was significant,  $F(1,27)=6.06, p<0.05, \eta^2_p=0.18$ .

Finally, it is possible that participants who reported that they were not aware of the repetition were somehow more distracted or less focused on the task than were participants who reported noticing the repetition. If this were the case, then we might expect that participants who reported not being aware would have longer response times than those who reported being aware. We might also expect that response times would reduce across blocks, complementing the increase in percentage correct. Inspection of response times did not reveal any statistically significant differences across blocks for load 6 or load 4 or between aware and not aware participants for load 6. Specifically, the interaction of load x block was not significant,  $F(5,140)=.53, p=.75, \eta^2_p=.02$ , indicating that RTs did not differ significantly as blocks progressed in either load 6 or in load 4 (mean RTs for load 6: 1939.94, 1912.03, 1917.50, 2044.68, 2042.79, 1918.36 for blocks 1 – 6 respectively; mean RTs for load 4: 1586.81, 1466.36, 1479.66, 1461.92, 1491.90, 1441.93 for blocks 1 – 6 respectively). Similarly, the interaction of awareness x block failed to reach significance,  $F(2.46,66.38)=2.62, p=.07, \eta^2_p=.09$ , in load 6 (mean RTs for ‘aware’ group: 1937.46, 2009.28, 2171.42, 2302.81, 2347.12, 2257.99 for blocks 1 – 6 respectively; mean RTs for ‘not aware’ group 1942.99, 1792.33, 1603.75, 1726.98, 1668.22, 1500.34 for blocks 1 – 6 respectively).

## Discussion

Performance on four item arrays was around 90% in block one, and remained at around this level throughout the 120 trials. The majority of participants achieved 100% correct within the first 10 trials, with errors on less than 10% of the remaining 110 trials. As noted earlier, previous studies have suggested that the capacity of VSTM is around 3-4 items (Cowan, 2001; Luck & Vogel, 1997), so the near ceiling performance throughout suggests that participants

could achieve accurate recall of 3 or 4 items on each trial without any need for learning the repeated array. Another possibility is that participants learned the four item arrays across the first 20 trials of the experiment. However, an examination of performance within the first block revealed that participants achieved 90% accuracy on the first 5 trials, and 92% accuracy on trials 16-20. These numbers were not significantly different. So, there is no evidence of learning even across the first few trials of the experiment, with performance close to ceiling from the start. These data are consistent with the interpretation that participants could perform at high levels without learning because a four-item array is close to their VSTM capacity on each individual trial. It would be interesting in future studies to explore whether performance is any different when the array of four objects changes from trial to trial compared, in the same experiment, with when the same four item array is repeated.

Experiment 1 did provide evidence of learning of six item arrays presented 180 times. The post-hoc pairwise analyses across blocks indicated that most of the learning occurred over the first 40 trials, and an examination at the trial level showed that participants required a mean of around 33 trials to reach 90% accuracy. Thereafter performance did not significantly improve further across the remaining 80 trials. This is a contrast with the lack of learning observed over 60 repetition trials (90 presentations) for change detection with a load of six items in the Logie et al. (2009) study. Some insight into the observation that the mean performance of the group on load 6 fell short of 100% after 120 trials comes from Figure 2b from which it is clear that participants who reported becoming aware of the repetition learned much more quickly than those who did not report awareness. However, even participants in the 'aware' group did not exceed 90% accuracy after 120 trials. Because participants were not asked about awareness until after completing both tasks in the experiment, we do not know how many trials the participants

had completed before they became aware of the repetition, and it is not clear how reliable participant responses would have been if we had asked them to estimate, retrospectively, when their awareness began. However, it is clear that those who reported becoming aware at some stage generated faster learning than those who reported not being aware, with evidence of a significant improvement in block 3 compared with block 1. Those who reported not being aware did not show a significant improvement in performance until block 6 (120 trials). Logie et al. (2009) did not ask participants about awareness of the repetition, but showed no learning over 60 trials, which is consistent with the performance of the ‘not aware’ group in our current experiment. One possible caveat is that participants who reported not being aware of the repetition were more distracted or were less focused on the task than those who reported becoming aware. If this were the case, we might have expected to see slower response times for the participants reporting no awareness. However, response times did not differ between groups, suggesting that differences in attention to the task are unlikely to account for the different rates of learning.

One possible account is that a residual trace for representations of features from trial to trial in long-term episodic memory would be required for a participant to detect that an array that is currently in view is the same as the array they saw on the previous trial. If there is no such residual trace from trial to trial, or a very weak trace, then there would be no basis on which to detect that a repetition had occurred. There would then also be no or a very weak basis for the accumulation of residual traces across multiple trials to support learning. This supports the conclusion from the Logie et al. (2009) study and our expectations for Experiment 1, that in visual change detection tasks, participants rely on visual cache that retains information only for the few seconds needed for the current trial, after which its contents are replaced by the visual

information presented on the next trial, even if the stimulus array is identical across trials. This visual cache is thought to be separate from episodic long-term memory, and to have a primary role in supporting temporary retention of novel or rapidly changing visual input. However, if episodic long-term memory holds a weak, residual trace of a given stimulus array from trial to trial, and then the same stimulus array is repeated, this trace may support a modest degree of learning, but that during the first block of trials, the amount of learning is too small to provide additional support for change detection performance that would supplement the use of the visual cache. This interpretation is consistent with the conclusion by Colzato et al., (2006) and by Treisman (2006) that there may be some learning of the stimulus material in visual feature change detection paradigms, but this learning process and change detection of visual arrays rely on separate mechanisms. However, with enough repetitions of the same stimulus array (total 180 in Experiment 1), some evidence of the influence of learning may be observed in change detection. Any such learning initially may be implicit and not influence performance, but with an increasing number of repetitions, slow and gradual learning may lead, in some participants, to a sense of familiarity for parts, and then for all of the repeated array. Familiarity may then underpin awareness of the repetition, so learning gradually makes a more substantial contribution to change detection performance and participants who become aware are those whose learning has reached a level at which they rely progressively less on a limited capacity visual cache for detecting changes in the repeated array, and more on a learned array. This process appears to require, on average, around 23 trials (more than 30 repetitions to include the no-change trials) to achieve, even for participants who show the earliest signs of learning. This contrasts sharply with the speed of learning in a typical Hebb learning paradigm. For example, in the original Hebb (1961) studies, substantial learning of random digit sequences was achieved with just eight

repetitions of the target sequence. So, even for the participants who state, after completing the experiment, that they had become aware of the repetition, learning still appears to have been remarkably slow compared with previous research on Hebb repetition paradigms. For other participants, evidence of learning required 40 or more trials (60 repetitions), and very few participants reached ceiling. We return to this issue in the general discussion after reporting the results of Experiment 2.

## Experiment 2

In Experiment 2 we explored whether using a reconstruction method to test memory, rather than recognition of a change, might lead to learning from repeated presentation of visual arrays of objects. Because performance on the first few trials with four item arrays was around 90% accuracy in Experiment 1, we used only six item arrays in Experiment 2 to maximise the opportunity to observe any learning that occurred. Logie et al. (2009, Experiment 3) used a verbal recall procedure for the names of the visual features cued by location, in contrast with a change detection task that was used in Experiments 1 and 2 in that earlier study. The authors argued that, in their Experiment 3, it was the requirement to recall the names of the features repeatedly across trials that led to the residual memory trace in episodic memory from trial to trial, and thereby to the learning that was observed. The first two experiments in that study suggested that it was not the repeated presentation of the array that was the basis for learning. However, it was unclear whether it was the requirement specifically to recall and generate verbal labels repeatedly that led to the learning of a visual array, or if it was the requirement for participants to recall feature combinations and reconstruct a part of the stimulus array for verbal responses on each trial that was crucial for learning. In our new Experiment 2 we tested the

hypothesis that reconstruction of stimulus features makes a major contribution to learning, and that this does not depend specifically on recall of verbal labels for the features. Therefore, we adopted a visual reconstruction procedure that should be unlikely to rely on the names of the features.

## Methods

### *Participants*

Thirty new healthy adults (10 males and 20 females), aged 18 to 33 years old ( $M = 23.4$  years old,  $SD = 3.70$ ), participated in Experiment 2. Recruitment procedures were similar to those reported in Experiment 1. Ethical approval and informed consent were obtained as for Experiment 1.

### *Materials and Procedure*

The procedure for presentation was identical to that employed for six item arrays in Experiment 1, including articulatory suppression at a rate of two per second throughout the trial until the test array onset. The major change for this experiment was that participants were told that their memory would be tested by asking them to reconstruct each object on every trial. This followed a test procedure used by Johnson, Logie, and Brockmole (2010; Brockmole & Logie, 2013), and by Hoefelijzers, Gonzalez, Magnolia & Parra (2017). As shown in Figure 3, in the test array eight colour patches and eight shape outlines appeared along the top and left edges of the screen respectively. Each of the six previously occupied locations was marked with an “x”. Participants recalled each object by using the mouse to click on a location, click on a shape, and click on a colour patch using the mouse. At the beginning of the task, participants completed 2 practice trials to familiarize themselves with the task, followed by 6 test blocks of 20 trials each,



totaling 120 experimental trials with six item arrays. Each individual testing session lasted about 1 hour and fifteen minutes. At the end of the testing session participants were explicitly asked whether they noticed the array repetition. In contrast to Experiment 1, all participants reported that they had noticed the repetition.

[Please insert Figure 3 approximately here]

### *Statistical design and analyses*

Two repeated-measures ANOVAs across trial blocks were performed on proportion correct. We scored performance in two different ways in order to investigate a) feature binding abilities for correctly bound objects (*full binding score*), that is, the number of objects for which shape, colour, and location combinations were reported accurately within a trial; b) feature binding abilities for unbound objects, specifically colour-location combinations regardless of shape (*colour binding score*), shape-location combinations regardless of colour (*shape binding score*), and colour-shape combinations regardless of location (*colour-shape binding score*). The two different scoring methods, i.e., feature binding abilities for bound vs. unbound objects, allowed us to examine the respective relative proportion of bound and unbound features in VSTM as a function of block and hence of long-term learning. The Greenhouse-Geisser correction was employed to deal with violations of sphericity when necessary and the adjusted degrees of freedom are reported.

### Results

One participant was excluded from the analyses due to performance dropping dramatically in all binding conditions pertaining to location after the first 2 blocks.

The results of the one-way ANOVA for the full binding score yielded a main effect of block,  $F(1.84,51.50)=72.75$ ,  $p<.001$ ,  $\eta^2_p=.72$ . Post hoc tests using the Bonferroni correction revealed that performance improved significantly in blocks 2 – 6 compared with block 1 ( $ps<.001$ ) and in blocks 4 – 6 compared with block 2 ( $p=.05$  for the comparison between blocks 2 and 4;  $p=.036$  for the comparison between blocks 2 and 5;  $p=.037$  for the comparison between blocks 2 and 6). Performance did not differ significantly between blocks 2 and 3 and across blocks 3 – 6 (all  $p>.1$ ; Figure 4). The results for the colour binding score yielded a main effect of block,  $F(1.71,47.99)=51.56$ ,  $p<.001$ ,  $\eta^2_p=.65$ , with performance improving significantly in blocks 2 – 6 compared with block 1 ( $ps<.001$ ). The results for the shape binding score were similar to those of the colour binding score,  $F(1.61,44.95)=82.59$ ,  $p<.001$ ,  $\eta^2_p=.75$ . Finally, results for the colour-shape binding score yielded a main effect of block,  $F(1.88,52.51)=71.56$ ,  $p<.001$ ,  $\eta^2_p=.72$ , with performance improving significantly in blocks 2 – 6 compared with block 1 (all  $p<.001$ ), and in blocks 5 and 6 compared with block 2 (both  $p\leq.04$ ); also, there was a marginal difference between blocks 2 and 4, and between blocks 3 and 5 (both  $p=.057$ ).

### *Analyses across experiments*

In Logie et al. (2009), there was only very weak evidence of learning with a change detection task and very strong evidence of learning with a cued verbal recall task. Extrapolating from those results, we expected to observe faster learning with visual reconstruction than we found in Experiment 1 with change detection. To test this prediction, we compared the rates of learning across the two experiments (considering only the awareness group of Experiment 1 so that learning is contrasted only for aware participants across retrieval modes), by investigating the number of trials completed until there was clear evidence of learning in each case. Using the

number of trials to criterion as our measure avoids difficulties of comparing experiments that start with different baseline levels of performance.

Because we were expecting learning to be faster with reconstruction than with change detection, for Experiment 2, we chose a more conservative criterion of the number of trials for each participant to achieve their first perfect score of 6 (100%) as an assessment of learning of the repeated array, compared with a score of 90% used for this same purpose in Experiment 1. On this basis, participants required a mean of 18.93 trials ( $SD=10.44$ ) to reach our (100%) criterion for learning in Experiment 2, compared with a mean of 32.23 trials ( $SD=24.15$ ) to reach the 90% criterion in Experiment 1. These means were significantly different,  $t(56)=2.73$ ,  $p<0.01$ . If we use a more stringent criterion of number of trials to achieve 100% correct on both experiments, the mean number of trials for change detection was 47.21 ( $SD=30.09$ ), and comparison across experiments yielded  $t(56)=4.78$ ,  $p<0.0001$ .

## Discussion

Using a visual reconstruction procedure, the results of Experiment 2 revealed a clear effect of learning across trial blocks one and two, and less improvement thereafter as performance came close to ceiling. These results are consistent with those reported by Logie et al. (2009) in showing clear learning with a reconstruction task in the current experiment but without the requirement to recall by means of verbal labels for the visual features as was the case for Logie et al. (2009, Experiment 3). Contrasting these results with those in Experiment 1, the results of Experiment 2 are consistent with our assumption that reconstruction of the stimuli generates a residual trace in episodic long-term memory from trial to trial that accumulates with repeated reconstruction of the same material to support faster learning than for change detection.

However, participants could perform well above chance in both experiments before any learning occurred, so learning was not crucial for task performance in either experiment, consistent with our assumption that a temporary visual cache memory supports performance in the absence of learning.

### General Discussion

In Experiment 1, which involved 180 presentations of the same stimulus array across 120 trials, very little learning of the repeated array occurred when memory was tested by a recognition procedure involving detection of whether or not a change occurred between the study and test array in the bindings between visual features in the array. When learning did occur, this was most evident among 16 participants (out of 29) who reported that they had become aware of the repetition. At first glance it seems remarkable that learning was so slow over such a large number of repeated presentations of the same stimulus array. Contemporary studies using the Hebb repetition paradigm have shown substantial learning with as few as 12 repetitions, with those repetitions occurring only on every third trial or fourth trial (e.g., Couture & Tremblay, 2006; Szmalec et al., 2009), rather than on every trial as in Experiment 1. However, typically those experiments have used a recall procedure. It also seems remarkable that 13 (out of 29) participants reported that they did not notice the repetition. Just over half (22) of Hebb's (1961) 40 participants reported noticing the repetition of his digit series, and 26 of the participants could successfully recall all nine of the digits in the repeated list whether they had noticed the repetition or not. However, in the original Hebb (1961) experiment, the learning outcome was obtained after just eight repetitions of a target supra-span digit list with a repetition every third

trial. This is in contrast with 24 trials (36 repetitions including no-change trials) for ‘aware’ participants and 44 trials (66 repetitions) for ‘not aware’ participants to first achieve 90% correct.

Our results extend those reported by Logie et al. (2009, Experiments 1 and 2), indicating that some learning of temporary feature bindings can be observed with a change detection paradigm if there are enough trials and enough participants. However, this suggests that the effect is rather weak and the observed learning was slow, even for participants who reported noticing the repetition. For participants who reported not becoming aware of the repetition in Experiment 1, they could nevertheless perform well above chance, even in the first two blocks of trials when there was no evidence of learning, so the task can be performed on a trial by trial basis without evidence of improvement as a result of the repetition. These results are consistent with the interpretation that in change detection tasks, the visual information in a single visual array is retained in a visual cache only for the duration of a single trial, and it is displaced by the subsequent study array, even if that array is identical to the one previously retained. There does appear to be some form of residual trace generated from trial to trial that can support learning in some participants, but the learning is very slow relative to previous studies using Hebb-type repetition. We have suggested one possible account, that any residual trace from trial to trial is generated within episodic long-term memory, not within a visual temporary memory system that we refer to as the visual cache, but this trace is weak and it takes many trials to lead to learning that results in familiarity and performance improvements. In both experiments, awareness of the repetition is associated with fewer trials to reach criterion levels of performance. But awareness of the repetition and learning of the array were not required to perform the task above chance levels in the early trials. This kind of account is consistent with the Colzato et al. (2006) proposal that temporary memory for feature bindings and learning of feature combinations involve

different mechanisms. We extend this argument by suggesting that as learning occurs, the familiarity associated with learning helps improve performance above what is possible when relying on a temporary, limited capacity visual cache alone, and that both systems contribute to performance as learning progresses.

It is possible that the memory for the study array was disrupted by the presentation of the changed test array on 50% of trials, and that this contributed to the slow learning that was observed. There is some evidence that testing memory for feature bindings with a whole array at test distracts visual attention and interferes with memory for the study array relative to testing memory using a single probe (e.g., Wheeler & Treisman, 2002; Rhodes, Cowan, Hardman, & Logie, in press). However, subsequent studies have shown that attentional distractors do not appear to have a specific impact on memory for visual feature bindings (Allen et al., 2006; Gajewski & Brockmole, 2006), and that whole display interference may occur only for study-test intervals of less than 1000 ms when participants might be relying on a retinotopic representation in iconic memory rather than in the visual cache (Logie et al., 2011). We avoided the latter by using a study-test interval of 2000 ms to ensure that an iconic trace was no longer available at the time of test. It has also been suggested that using a single probe might overestimate the capacity for temporary retention of visual arrays because of the increased possibilities for guessing, and that having a whole array at test may provide a more accurate estimate of capacity (e.g., Cowan et al., 2013; Cowan, Saults, & Blume, 2014; Rhodes et al., in press; Zhang, Xuan, Fu, & Pylyshyn, 2010). Moreover, on 50% of test trials the test array was identical to the study array. So, disruption of the study array by the test array remains a possibility, but seems unlikely.

The relative lack of learning might seem less surprising when set in the context of previous studies of memory for common everyday objects that are viewed many thousands of

times across a lifetime. For example, Nickerson and Adams (1979) demonstrated that few of their US-based participants could accurately recall the details on each side of a one cent coin. Rubin and Kontis (1983) reported a similar lack of learning with the full range of US coins. Jones (1990) and Richardson (1992) reported similar results with British participants who were asked to remember details of UK coins and postage stamps. Often the error in recall was for large and obvious features such as which way the Queen faces on a UK coin (to the right) and on a stamp (to the left). However, presumably participants had no difficulty recognising each coin or postage stamp when they saw it, and typically successful recognition based on size, shape, and key visual details (e.g., value) is all that is required for everyday use. Returning to one of the examples given in the introduction, it is sufficient to recognize a traffic light and to retain only briefly that it is showing green when driving through, with contents of the visual cache soon replaced by the temporary visual details of the traffic lights at the next crossroads.

Clearer evidence of learning was obtained in Experiment 2 (Figure 4), using a reconstruction method to test memory. This evidence for substantial learning using a visual reconstruction procedure is consistent with the rapid learning using a cued verbal recall procedure for visual arrays reported by Logie et al. (2009). The result is also consistent with the Brady et al. (2009) observation of learning of colour combinations using a reconstruction procedure. Although in their case, learning was somewhat slower than shown here, possibly because only part of an array was repeated and only on 22% of 600 trials.

The evidence from Experiments 1 and 2 suggests that it is repeated recall of the specific combinations of the visual features (verbal or via reconstruction) from memory for the study array, and not repeated presentation and recognition, that generates strong residual traces in episodic long-term memory from trial to trial to support learning. When the number of trials to

asymptote levels of performance were compared, it was clear that the overall rate of learning was faster for reconstruction in Experiment 2 than it was for change detection in Experiment 1. However, participants could perform the task, even if at a relatively low level, even on the early trials, before learning occurred. Therefore, learning improved task performance, but learning was not essential to allow above chance reconstruction. Moreover, if initial performance before learning had been based solely on a memory trace in episodic long-term memory, then it seems very surprising indeed that learning took such a large number of repetitions of the same stimulus array to benefit performance. It seems much more plausible to account for these findings by assuming that two different types of memory system can contribute to performance, and when no learning has occurred, only a limited capacity temporary visual memory system, the visual cache, does so. So, learning does not increase the capacity of the visual cache. Rather, learning allows for the use of an additional cognitive system, namely episodic long-term memory and both the visual cache and the effects of learning in a long-term memory system then together support higher levels of performance.

Presumably if the early studies on remembering coins and stamps had required repeated recall of the visual details (e.g., for numismatists or philatelists) and not just repeated presentation of the objects in everyday life, then the participants would have generated residual traces from trial to trial, and would have shown substantial learning leading to more accurate recall.

Evidence supporting the idea that learning in long-term memory and temporary memory for feature bindings rely on separate cognitive systems was reported from an fMRI study of healthy young adults by Parra, Della Sala, Logie, and Morcom (2014) who asked participants to perform a change detection task similar to that used for Experiment 1, but with a different array



shown on every trial. There was clear activation in regions within the parietal, temporal, and occipital cortex when detecting changes in feature bindings, but not within the prefrontal cortex or the medial temporal lobe, and specifically not in the hippocampus which is well established as being essential for efficient learning and for retrieval from episodic long-term memory. Other evidence comes from a neuropsychological case study (Baddeley, Allen, & Vargha-Khadem, 2010) who, as a result of complications from premature birth, had around 50% lower hippocampal volume than normal. When tested as a young adult, he showed the expected impairments in episodic memory that are typical of hippocampal damage. However, he was completely normal on tests involving temporary feature binding.

The findings described above are consistent with the observation in Experiment 1 that learning was not necessary for participants to perform well above chance on change detection. Indeed, performance above chance is virtually universal in temporary binding experiments that typically involve a different array on every trial, thereby preventing learning of any one specific array. As suggested in the introduction, in the case of repeating the same array across trials, and testing with a reconstruction task as in Experiment 2, the acts of selecting a colour, a shape and a location in the correct combination for each item in the array across trials could strengthen an otherwise weak episodic memory trace that resulted from presentation of the array on a given trial. Therefore, the repeated reconstruction of the same feature combinations across trials would lead to a rapid increase in the episodic trace, and therefore rapid learning and rapid increases in performance. Further evidence that a reconstruction procedure may result in a stable representation in episodic memory was reported by Hoefeijzers et al. (2017) who demonstrated that it benefitted the retention of bindings for novel and unusual associations between features of everyday objects.

In Experiment 1, there is only a weak episodic memory trace generated from presentation of the same array on each trial, so any learning is slow, and change detection requires many more trials to result in learning than does a reconstruction paradigm. As argued above, performance in this case is based on a temporary representation in a domain-specific visual cache. The latter can support above chance performance for arrays of six items, but arrays of this size may be beyond the capacity of the visual cache, so performance is below ceiling, at least for six item arrays. If we accept from previous studies, the estimate of the capacity for temporary visual retention as sufficient to store details of three or four items, each comprising three features (colour, shape location), then an array of four items could be retained within such a system to generate near ceiling performance, without assuming any involvement of learning across trials, as was found for the load 4 task. For the purposes of the present paper, we are remaining neutral as to whether this capacity is based on number of items and features, or the level of precision with which those details may be retained. Moreover, our data do not speak to that distinction directly. The visual cache is viewed as being a specific, temporary, limited capacity visual memory system that is distinct from visual attention, and from episodic long-term memory (Allen et al., 2006; Gajewski & Brockmole, 2006; Logie et al., 2011), as well as from verbal short-term memory (Logie, 1995; Todd & Marois, 2004). The results are not inconsistent with the concept of an episodic buffer (Baddeley, 2000), but we would argue that the concept of a domain-specific visual cache, together with a contribution from episodic long-term memory to support learning is sufficient to account for our results, based on the idea that cognitive performance reflects the operation of multiple cognitive systems acting in concert (Logie, 1995; 2003; 2011; 2016). This is wholly compatible with the idea that the hippocampus supports learning and recall for representations in episodic long-term memory, but that a different network, referred to here as a visual cache,

supports rapid updating of temporary visual representations to allow successful interaction with rapid changes in our visual environment.

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## References

- Allen, R. J., Baddeley, A. D., & Hitch, G. J. (2006). Is the binding of visual features in working memory resource-demanding? *Journal of Experimental Psychology: General*, *135*(2), 298–313. <http://doi.org/10.1037/0096-3445.135.2.298>
- Baddeley, A. (2000). The episodic buffer: a new component of working memory? *Trends in Cognitive Sciences*, *4*(11), 417–423. [http://doi.org/10.1016/S1364-6613\(00\)01538-2](http://doi.org/10.1016/S1364-6613(00)01538-2)
- Baddeley, A. D. (1986). *Working Memory*. Oxford: Clarendon Press.
- Baddeley, A., Allen, R., & Vargha-Khadem, F. (2010). Is the hippocampus necessary for visual and verbal binding in working memory. *Neuropsychologia*, *48*, 1089-1095.
- Borst, G., Niven, E., & Logie, R. H. (2012). Visual mental image generation does not overlap with visual short-term memory: A dual-task interference study. *Memory & Cognition*, *40*(3), 360–372. <http://doi.org/10.3758/s13421-011-0151-7>
- Brady, T.F., Konkle, T., & Alvarez, G.A. (2009). Compression in visual working memory: Using statistical regularities to form more efficient memory representations. *Journal of Experimental Psychology: General*, *138*, 487-502.
- Broadbent, D. E., & Broadbent, M. H. P. (1981). Recency effects in visual memory. *Quarterly Journal of Experimental Psychology*, *33A*, 1-15.
- Brockmole, J. R., & Logie, R. H. (2013). Age-related change in visual working memory: A study of 55,753 participants aged 8-75. *Frontiers in Psychology*, *4*(JAN), 1–5. <http://doi.org/10.3389/fpsyg.2013.00012>
- Brown, M. W., & Aggleton, J. P. (2001). Recognition memory: What are the roles of the perirhinal cortex and hippocampus? *Nature Reviews Neuroscience*, *2*(1), 51–61. <http://doi.org/10.1038/35049064>
- Colzato, L. S., Raffone, A., & Hommel, B. (2006). What do we learn from binding features? Evidence for multilevel feature integration. *Journal of Experimental Psychology: Human Perception and Performance*, *32*(3), 705–716. <http://doi.org/10.1037/0096-1523.32.3.705>
- Cowan, N. (2001). The magical number 4 in short-term memory: a reconsideration of mental storage capacity. *The Behavioral and Brain Sciences*, *24*, 87–185.
- Cowan, N., Blume, C. L., & Saults, J. S. (2013). Attention to attributes and objects in working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *39*(3), 731–747. <http://doi.org/10.1037/a0029687>
- Cowan, N., Naveh-Benjamin, M., Kilb, A., & Saults, J. S. (2006). Life-span development of visual working memory: when is feature binding difficult? *Developmental Psychology*, *42*(6), 1089–1102. <http://doi.org/2006-20488-009> [pii]n10.1037/0012-1649.42.6.1089
- Cowan, N., Saults, J. S., & Blume, C. L. (2014). Central and Peripheral Components of Working Memory Storage. *Journal of Experimental Psychology: General*, *143*(5), 1806–1836. <http://doi.org/10.1037/a0036814>
- Couture, M., & Tremblay, S. (2006). Exploring the characteristics of the visuospatial Hebb repetition effect. *Memory and Cognition*, *34*, 1720\_1729.

- Della Sala, S. (2010). *Forgetting*. Hove, UK: Psychology Press.
- Faul, F., Erdfelder, E., Lang, A., & Buchner, A. (2007). G\*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, *39*(2), 175–191.
- Gajewski, D. A., & Brockmole, J. R. (2006). Feature bindings endure without attention: Evidence from an explicit recall task. *Psychonomic Bulletin & Review*, *13*(4), 581–587. <http://doi.org/10.3758/BF03193966>
- Hebb, D. O. (1961). Distinctive features of learning in the higher animal. In J. . Delafresnaye (Ed.), *Brain mechanisms and learning* (pp. 37–51). Oxford, U.K.: Blackwell Scientific Press.
- Hoefjeijzers, S., Gonzalez, H. A., Magnolia, R. A., & Parra, M. A. (2017). Feature Binding of Common Everyday Items Is Not Affected by Age. *Frontiers in Aging Neuroscience*, *9*, 122.
- Johnson, W., Logie, R. H., & Brockmole, J. R. (2010). Working memory tasks differ in factor structure across age cohorts: Implications for dedifferentiation. *Intelligence*, *38*(5), 513–528. <http://doi.org/10.1016/j.intell.2010.06.005>
- Jones, G. . (1990). Misremembering a common object: When left is not right. *Memory & Cognition*, *18*, 174–182.
- Lee, C. L. (1976). Short-term recall of repeated items and detection of repetitions in letter sequences. *Journal of Experimental Psychology: Human Learning & Memory*, *2*(2), 120–127. <http://doi.org/10.1037/0278-7393.2.2.120>
- Logie, R. H. (1995). *Visuo-spatial Working Memory*. Hove, UK: Lawrence Erlbaum Associates.
- Logie, R. H. (2003). Spatial and visual working memory: A mental workspace. In D. E. Irwin & B. H. Rossion (Eds.), *Cognitive Vision: The Psychology of Learning and Motivation* (pp. 37–38). San Diego: Academic Press.
- Logie, R. H. (2011). The Functional Organization and Capacity Limits of Working Memory. *Current Directions in Psychological Science*, *20*(4), 240–245. <http://doi.org/10.1177/0963721411415340>
- Logie, R. H. (2016). Retiring the central executive. *The Quarterly Journal of Experimental Psychology*, *69*(10), 2093–2109. <http://doi.org/10.1080/17470218.2015.1136657>
- Logie, R. H., Brockmole, J. R., & Jaswal, S. (2011). Feature binding in visual short-term memory is unaffected by task-irrelevant changes of location, shape, and colour. *Memory & Cognition*, *39*(1), 24–36. <http://doi.org/10.3758/s13421-010-0001-z>
- Logie, R. H., Brockmole, J. R., & Vandembroucke, A. R. E. (2009). Bound feature combinations in visual short-term memory are fragile but influence long-term learning. *Visual Cognition*, *17*(1–2), 160–179. <http://doi.org/10.1080/13506280802228411>
- Logie, R. H., Della Sala, S., Beschin, N., & Denis, M. (2005). Dissociating mental transformations and visuo-spatial storage in working memory: Evidence from representational neglect. *Memory*, *13*(3–4), 430–434. <http://doi.org/10.1080/09658210344000431>
- Logie, R. H., & van der Meulen, M. (2009). Fragmenting and integrating visuospatial working memory. In J. R. Brockmole (Ed.), *The visual world in memory* (pp. 1–32). Psychology

Press.

- Luck, S. J., & Vogel, E. K. (1997). The capacity of visual working memory for features and conjunctions. *Nature*, *390*, 279–281. <http://doi.org/10.1038/36846>
- Morey, C. C., Morey, R. D., Van Der Reijden, M. & Holweg, M. (2013) Asymmetric cross-domain interference between two working memory tasks: Implications for models of working memory. *Journal of Memory and Language*, *69*, 324-348.
- Nickerson, R. S., & Adams, M. J. (1979). Long-term memory for a common object. *Cognitive Psychology*, *11*(3), 287–307. [http://doi.org/10.1016/0010-0285\(79\)90013-6](http://doi.org/10.1016/0010-0285(79)90013-6)
- Page, M. P. A., Cumming, N., Norris, D., Hitch, G. J., & McNeil, A. M. (2006). Repetition learning in the immediate serial recall of visual and auditory materials. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *32*(4), 716–733. <http://doi.org/10.1037/0278-7393.32.4.716>
- Parra, M. A., Della Sala, S., Logie, R. H., & Morcom, A. M. (2014). Neural correlates of shape–colour binding in visual working memory. *Neuropsychologia*, *52*, 27–36. <http://doi.org/10.1016/j.neuropsychologia.2013.09.036>
- Phillips, W. A. (1983). Short-term visual memory. *Philosophical Transactions of the Royal Society of London*, *B302*, 295-309., *B302*, 295–309.
- Phillips, W. A., & Christie, D. F. M. (1977). Components of visual memory. *Quarterly Journal of Experimental Psychology*, *29*(1), 117–133. <http://doi.org/10.1080/00335557743000080>
- Poppenk, J., & Moscovitch, M. (2011). A hippocampal marker of recollection memory ability among healthy young adults: Contributions of posterior and anterior segments. *Neuron*, *72*(6), 931–937. <http://doi.org/10.1016/j.neuron.2011.10.014>
- Rhodes, S., Cowan, N., Hardman, K.O. & Logie, R.H. (in press). Informed guessing in change detection. *Journal of Experimental Psychology: Learning, Memory, and Cognition*.
- Rhodes, S., Parra, M. A., & Logie, R. H. (2016). Ageing and feature binding in visual working memory: The role of presentation time. *The Quarterly Journal of Experimental Psychology*, *69*(4), 654–668. <http://doi.org/10.1080/17470218.2015.1038571>
- Richardson, J. T. E. (1992). Remembering the appearance of familiar objects: A study of monarchic memory. *Bulletin of the Psychonomic Society*, *30*(5), 389–392.
- Rubin, D. C., & Kontis, T. C. (1983). A schema for common cents. *Memory & Cognition*, *11*(4), 335–341. <http://doi.org/10.3758/BF03202446>
- Sadeh, T., Ozubko, J. D., Winocur, G., & Moscovitch, M. (2014). How we forget may depend on how we remember. *Trends in Cognitive Sciences*, *18*(1), 26–36. <http://doi.org/10.1016/j.tics.2013.10.008>
- Scoville, W. B., & Milner, B. (1957). Loss of recent memory after bilateral hippocampal lesions. *Journal of Neurology, Neurosurgery, & Psychiatry*, *12*(1), 11–21. <http://doi.org/10.1136/jnnp.20.1.11>
- Szmaliec, A., Duyck, W., Vandierendonck, A., Mata, A. B., & Page, M. P. A. (2009). The Hebb repetition effect as a laboratory analogue of novel word learning. *The Quarterly Journal of Experimental Psychology*, *62*(3), 435–443. <http://doi.org/10.1080/17470210802386375>
- Todd, J. J., & Marois, R. (2004). Capacity limit of visual short-term memory in human posterior

- parietal cortex. *Nature*, 428, 751–754. <http://doi.org/10.1038/nature02466>
- Treisman, A. M. (2006). Object tokens, binding, and visual memory. In H. . Zimmer, A. Mecklinger, & U. Lindenberger (Eds.), *Handbook of binding and memory: Perspectives from cognitive neuroscience* (pp. 315–338). Oxford, U.K.: Oxford University Press.
- van der Meulen, M., Logie, R. H., & Della Sala, S. (2009). Selective interference with image retention and generation: evidence for the workspace model. *The Quarterly Journal of Experimental Psychology*, 62(8), 1568–15680. <http://doi.org/10.1080/17470210802483800>
- Wheeler, M. E., & Treisman, A. M. (2002). Binding in short-term visual memory. *Journal of Experimental Psychology: General*, 131(1), 48–64. <http://doi.org/10.1037//0096-3445.131.1.48>
- Wixted, J. T., & Squire, L. R. (2010). The role of the human hippocampus in familiarity-based and recollection-based recognition memory. *Behavioural Brain Research*, 215(2), 197–208. <http://doi.org/10.1016/j.bbr.2010.04.020>
- Zhang, H., Xuan, Y., Fu, X., & Pylyshyn, Z. W. (2010). Do objects in working memory compete with objects in perception? *Visual Cognition*, 18(4), 617–640. <http://doi.org/10.1080/13506280903211142>
- Zokaei, N., Heider, M., & Husain, M. (2014). Attention is required for maintenance of feature binding in visual working memory. *Quarterly Journal of Experimental Psychology*, 67(6), 1191–1213. <http://doi.org/10.1080/17470218.2013.852232>



### Figure Captions

*Figure 1.* Schematic illustration of a trial sequence in the change-detection task, consisting of 6 objects, in Experiment 1. Each trial began with the presentation of two digits. After 1500ms, the memory array was presented briefly (200ms), followed by an interstimulus fixation interval (2000ms). Finally, the test array was presented and remained on the screen until a response was made. The top panel at the test array position depicts an example of a no-change trial, whereas the bottom panel depicts an example of a change trial; in this example a colour change.

*Figure 2.* Percentage correct scores comparing overall performance across blocks a) between load 6 and load 4 items and b) between awareness groups. Error bars represent standard errors of the mean.

*Figure 3.* An example of the “reconstruction” response in the test array period in Experiment 2. Participants reconstructed each object by first selecting a location, then selecting a shape, and finally selecting a colour. For each trial, participants were asked to reconstruct all six objects.

*Figure 4.* Mean number of objects remembered across blocks for the three different binding conditions. Error bars represent standard errors of the mean.

Figure 1.

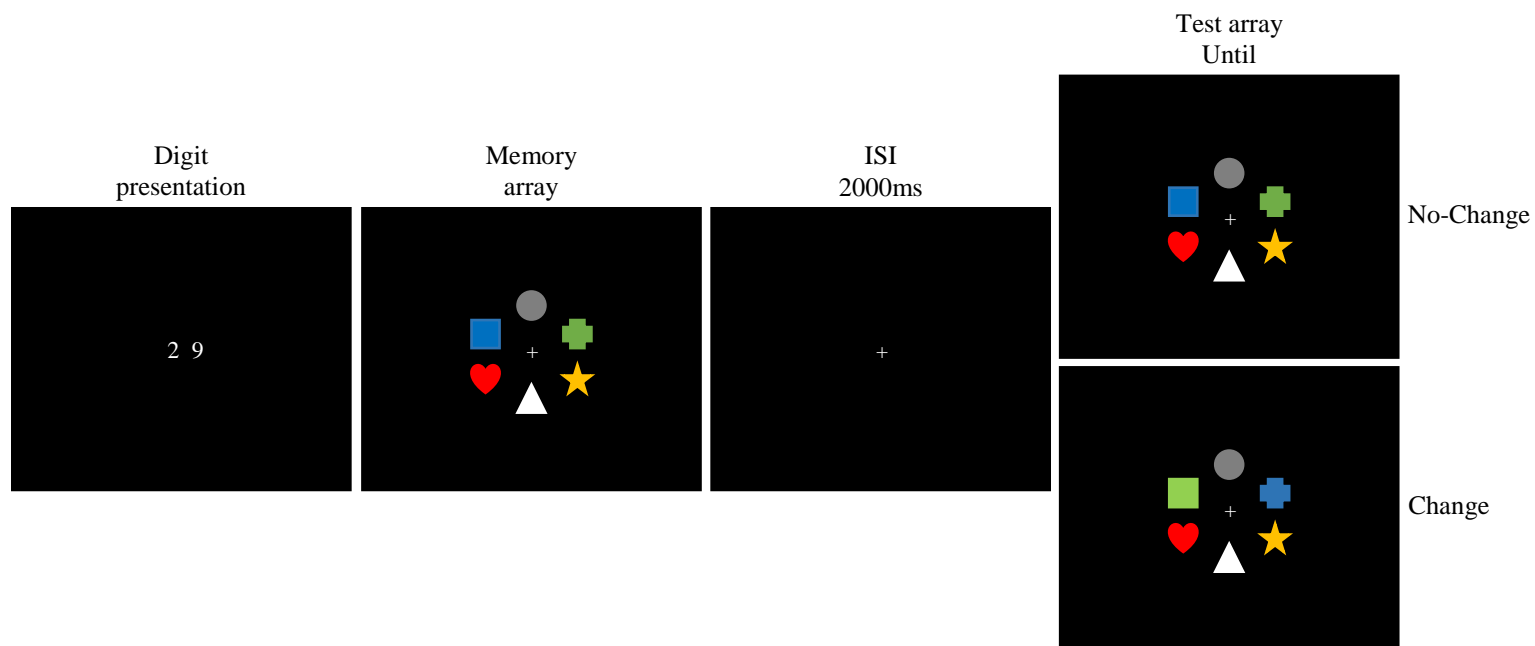
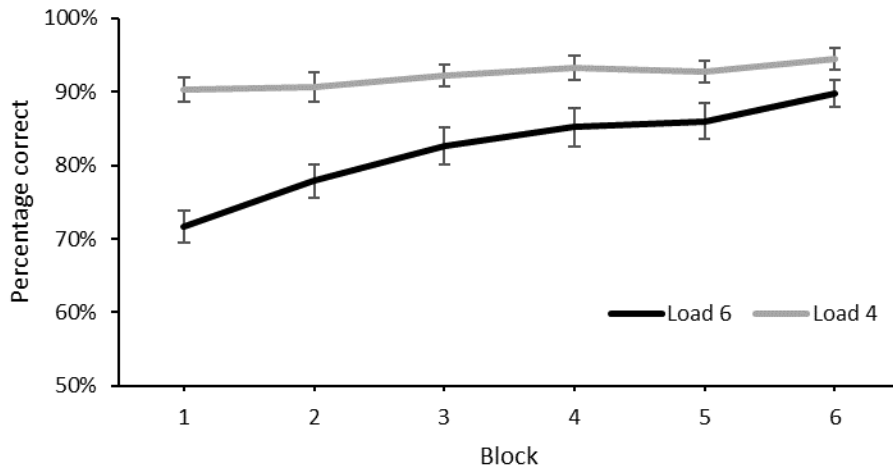


Figure 2.

a)



b)

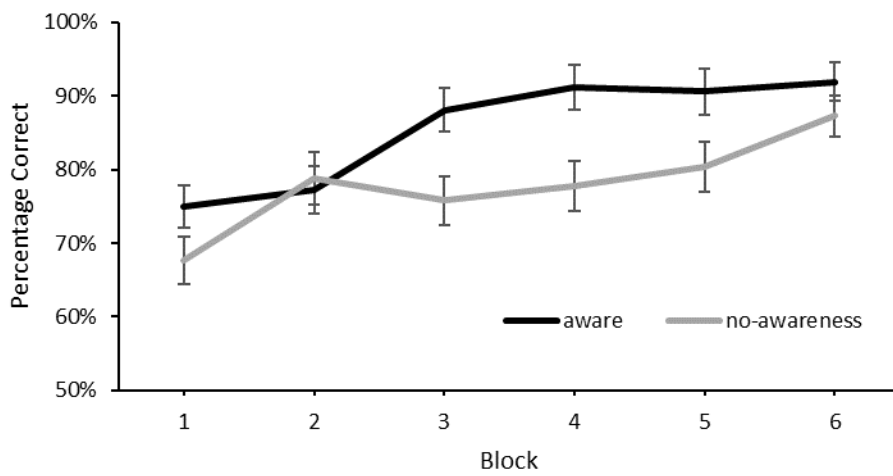


Figure 3.

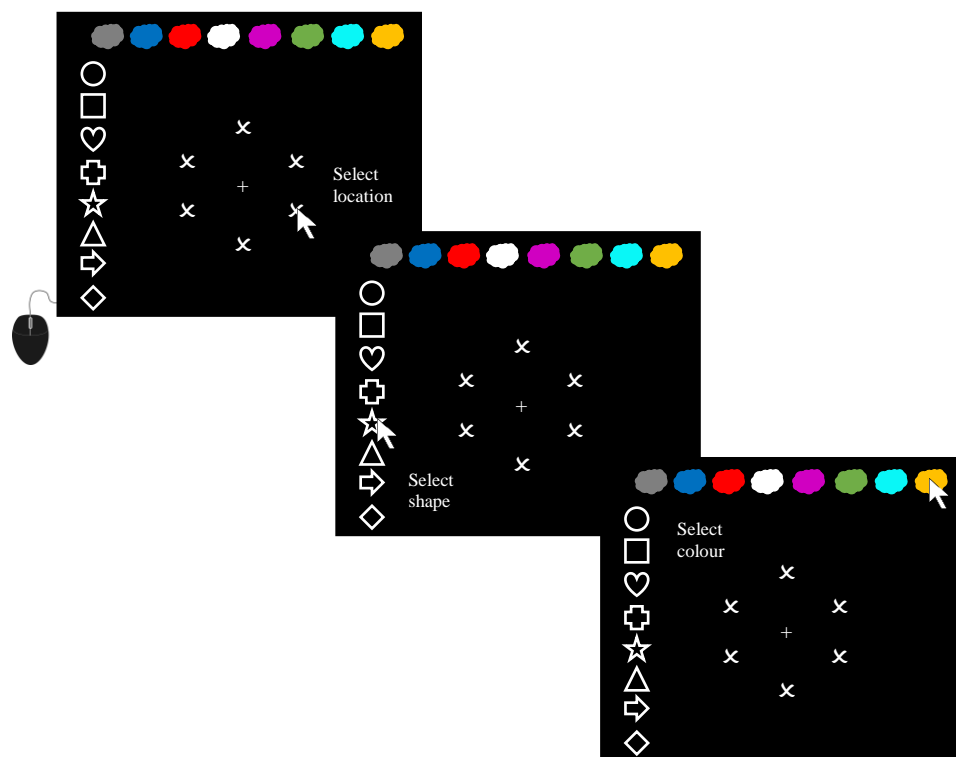


Figure 4.

