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Asymmetrical Access to Color and Location in Visual Working Memory

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Abstract

Models of Visual Working Memory (VWM) have greatly benefitted from the use of the delayed-matching paradigm (Wilken & Ma, 2004). However, in this task, the ability to recall a probed feature is confounded with the ability to maintain the proper binding between the feature that is to be reported and the feature (typically location) that is used to cue a particular item for report. Given that location is typically used as a cue-feature, we used the delayed-estimation paradigm to compare memory for location to memory for color, rotating which feature was used as a cue and which was reported. Our results revealed several novel findings: (1) the likelihood of reporting a probed object's feature was superior when reporting location with a color cue than when reporting color with a location cue, (2) location report errors were composed entirely of swap errors, with little to no random location reports, and (3) both colour and location reports greatly benefitted from the presence of non-probed items at test. This last finding suggests that it is uncertainty over the bindings between locations and colors at memory retrieval that drive swap errors, not at encoding. We interpret our findings as consistent with a representational architecture that nests remembered object features within remembered locations.

Keywords: Visual Working Memory, Precision, Spatial Working Memory

Asymmetrical Access to Color and Location in Visual Working Memory

When processing sensory information, it is crucial to retain some data regarding what was recently seen in order to minimize the processing of redundant information over time and link visual representations across sudden changes in gaze that result from saccades. Visual working memory (VWM) is the memory system that supports the retention of visual information over time, allowing this visual information to be accessed by higher cognitive functions. A central issue that has received considerable attention in VWM research is the question of representation: what are the units of VWM? An active debate in VWM research is whether information is represented as discrete-units, or as a more graded representation, wherein a continuously variable amount of information may be stored per item. The former position conceptualizes VWM capacity as a limited number of slots available to hold information about remembered objects, whereas the latter considers VWM capacity to be continuously allocable across the objects that are to be remembered. According to slot-based theories (Zhang & Luck, 2008; Fukuda, Awh, & Vogel, 2010), VWM stores representations of individuated visual objects, and it is the number of to-be-remembered objects that limits memory capacity. In contrast, continuous-resource theories (Bays, Catalao, & Husain, 2009; van Den Berg et al., 2012) argue that VWM is limited by a continuous resource, and that additional items can be stored in memory at the cost of reduced representational precision. Most critically, continuous-resource theories argue that the number and precision of object representations are not separable: they are inversely related. However, framing the question of VWM representation in this way – as slots versus continuous resources – overlooks the potentially unique contribution of different visual features. In the present study, we compare the representation of a remembered color with a feature that has proven to be “special” in visual cognition: location (Nissen, 1985; Tsal & Lavie, 1988; van der Heijdan, 1993). First, we review research on the role of location in the traditional measure of VWM performance: the one-shot change detection task.

Location in Delayed-Estimation

In the past several years, a relatively new task has been used to explore the dynamics of VWM. As discussed earlier, the delayed-estimation task (Wilken & Ma, 2004; Zhang & Luck, 2008) has been critical in reorienting attention to the issue of whether the information per item in VWM is allocated in a discrete or continuous fashion, as it provides a finer measure of memory performance than the change detection task. Unlike the change detection task, which has been used in the bulk of VWM studies, the delayed estimation task is not a recognition task, but a cued-recall task. In this task, each object presented in the memory sample has two features (e.g., location and color). For the memory test, participants are cued with one feature (e.g., location) and are tasked with reporting the value of the second feature (i.e., color). Although often discussed as a direct measure of memory for the to-be-reported item, (Zhang & Luck, 2008), performance in such tasks also depends on untested aspects of item memory. This argument has been made by Bays, Catalao & Husain (2009), who were the first to emphasize the difference between responses constituting guesses, where the participant's report reflects complete ignorance, and responses swaps (i.e., binding errors), where the participant's report reflects confusion regarding which information is to be reported.

In the delayed-estimation task, because only one of several items is to be reported, the to-be-reported item must be identified based on partial information (usually location, for exceptions, see: Bays, Gorgoraptis, Wee, Marshall, & Husain, 2011, Gorgoraptis, Catalao, Bays, & Husain, 2011) provided by the cue. However, this means that a failure to accurately identify the reported feature of an item may stem from multiple sources. Even in the simple case of colored, homogenously-shaped objects, a successful report hinges on maintaining the memory of an object’s color, location, and the binding of these two features. Given recent work showing that memory for an object is not all-or-none, and that partial memory for an item may exist (Fougnie & Alvarez, 2011; Bays, Wu, & Husain, 2011), it seems reasonable then that report failure could actually reflect memory failure for either features or their bindings. Although memory for object locations is clearly a necessary component of successful performance, spatial memory has yet to be evaluated under the same conditions as other object features. Understanding how factors like set size affect VWM for locations is a necessary step in characterizing the sources of performance declines in the delayed-estimation task. In the following section, we review studies of VWM that specifically address the role of location and location-feature bindings in performance.

Location in Change Detection

The bulk of evidence that bears on the question of representation in VWM comes from the one-shot change detection task (Luck & Vogel, 1997). At its core, this is a recognition task, wherein participants are provided with a memory sample, followed by a memory probe. To successfully detect a difference between the memory sample and probe, the probe must be compared with a stored representation of the sample. The most robust finding across change detection studies is that increasing the number of items in a display leads to a reduction in correct recognition (Luck & Vogel, 1997; Vogel, Woodman, & Luck, 2001; Wheeler & Treisman, 2002). However, as noted by Lee and Chun (2001), change detection studies typically confound number of items and number of locations (i.e., each item has its own unique location). By overlaying objects onto the same display locations, Lee and Chun were able to demonstrate that the number of objects, and not the number of locations, primarily limits change detection performance. While the work of Lee and Chun provides support for the claim that information in VWM is stored as objects, other findings demonstrate that spatial information is an important aspect of VWM representation.

Jiang, Olson, and Chun (2000) investigated the role of spatial and non-spatial feature context in successful recognition. Across a number of studies, participants viewed and encoded displays of colored boxes, or monochromatic shapes. Jiang et al. varied the characteristics of the probe display to determine what information was necessary for correct memory retrieval. The authors discovered that the original spatial configuration of the probe display is very important for correctly detecting the change in the position, color, or shape of an isolated item. Removing the non-tested items from the probe display (i.e., using a partial report display), or scrambling untested items' positions, led to a decrement in change detection performance. Performance on spatial change detection, however, did not suffer when the untested items' colors changed, suggesting that the contextual effect of locations noted previously does not extend to non-spatial features. These results provide compelling evidence that access to VWM for the purposes of recognition is not based on item-based indexing, but that indexing in VWM is at least partially location-based. Olson and Marshuetz (2005) provided further evidence for a location-dependent memory. Participants in this task were required to detect a change in object identity across sample and test arrays. The test arrays were either presented in the same configuration in the same quadrant of the computer monitor, the same configuration in a different quadrant, or in the same quadrant but with a different spatial configuration. Response latencies were consistently slower in the latter condition, showing that VWM for object identity is coded with positional information relative to other items in the array.

Treisman and Zhang (2006) further examined the role of location in detection of changes, finding that the appearance of a new feature value was most easily detected when feature-bindings and locations were preserved from sample to test. When objects were presented in new locations at test, binding changes produced a small reduction in performance. However, when the objects occupied the same location at test, a change in feature bindings was often missed, causing a substantial decline in performance. This pattern of findings was also limited to whole display test conditions; performance using a single item probe did not lead to an interaction between binding changes and location changes. Once again, the results implied a special role for location in VWM performance, leading to the suggestion that non-spatial information is bound across features using location as a common index.

The finding of location-mediated indexing fits well with the visual architecture postulated by Feature-Integration theory, wherein information regarding the presence of non-spatial features is stored in independent maps that are coordinated by a master-map of locations (Treisman, 1998; Quinlan, 2003). This architecture suggests a representational scheme for visual information that exhibits properties similar to those predicted by the object-based and feature-stores theories of VWM representation, with the additional claim that location is a special feature that is critical for indexing and organizing remembered information.

Characterizing Memory for Location in the Delayed-Estimation Paradigm

As is evident from research using change detection, location appears to have unique properties in VWM, and location-feature bindings are a limiting factor. The extent to which the uniqueness of location affects the precision and capacity of VWM is currently unknown. Specifically, the precision of memory for location changes with set size has yet to be quantified. A further unresolved issue is whether in cued-recall it is the loss of bindings, as opposed to lost memory for features or locations, that contributes most to changes in precision and successful retrieval of items . With this in mind, we used the delayed estimation task with a novel twist: at test, the feature used as the memory cue and the feature that is to be reported were changed from trial-to-trial. This allowed us to measure the precision and stability of memory for locations, and provided a means of observing VWM representations from both sides of the task-necessitated binding. On the basis of findings from the change detection literature, we predicted that memory for location would be superior to memory for color; that it would be more easily retrieved and stored. Over three experiments we uncovered three novel insights: (1) the likelihood of retrieving information about a cued object in memory is greater when retrieving location with color than retrieving color with location, (2) errors in cued-recall of location are qualitatively different from those in the cued-recall of color, (3) providing distractor context increased the ability to report a probed location or color, eliminating binding errors entirely.

Experiment 1

The goal of Experiment 1 was to assess the quality of VWM for all aspects of a remembered item by varying the item feature that served as a cue and the feature that was reported during the test portion of a trial. This provided two conditions: Color Report, where item location was used to cue report of a particular remembered item’s color; and Location Report, where item color was used to cue report of a particular item’s location. For one group of participants, trials for the two report conditions were randomly inter-mixed. As a consequence, participants could not anticipate whether they would be tested on their memory for location or color, and so any differences between these two report conditions cannot be attributed to differing encoding or rehearsal strategies. However, in order to assess the contributions of encoding or rehearsal strategies, we ran a second population of participants: one for whom the two report conditions were blocked.

Method

Participants.

Eighteen adults participated in this study; nine participated in the Mixed report condition and nine participated in the Blocked report condition. Our aim was to collect at least eight participants for both report conditions, following Zhang and Luck (2008), and we continued with the same number of participants in the following two experiments for consistency. Participants were compensated with course credit or $10 in cash. All participants reported normal vision and were recruited from a first-year Psychology course and from a list of university students and hospital staff who had expressed interest in Psychology study participation.

Apparatus.

All experiments were conducted on a personal computer in a dimly-lit, sound-attenuated room. Stimuli were presented on a 16” CRT monitor. Participants viewed stimuli from a distance of 50cm, and a chin rest was used to ensure constant viewing distance. Stimuli were created and presented using Matlab version 7.04 and the Psychophysics Toolbox version 3.0.8 (Brainard, 1997; Pelli, 1997; Kleiner, Brainard, & Pelli, 2007).

Design and Procedure.

Each trial began with the presentation of a memory sample consisting of a variable number of stimulus items (set sizes 1, 3, 5, or 7). To ensure that we could sample equally from all colors as well as locations while still providing discriminable stimuli, we chose colored rings as memory items. This allowed nearby items to overlap with minimal occlusion (our thanks to Daryl Fougnie, personal communication, for this suggestion). Each ring subtended 2° of visual angle. Radial positioning of the centre of each ring was fixed at approximately 6° from fixation and angular positioning was randomized between 0° and 358° in steps of 2° with the restriction that no two rings could be assigned the same angle. Ring colors were determined in a similar manner; a unique angle was chosen for each color between 0° and 358° in steps of 2°. This angle determined which position on an imaginary circle in L*A*B color space would be used to generate the item's color. The parameters of the imaginary circle were as follows: centre: [70, 0, 0], circle radius: 60, where the plane of the circle was orthogonal to the luminance axis of the color space.

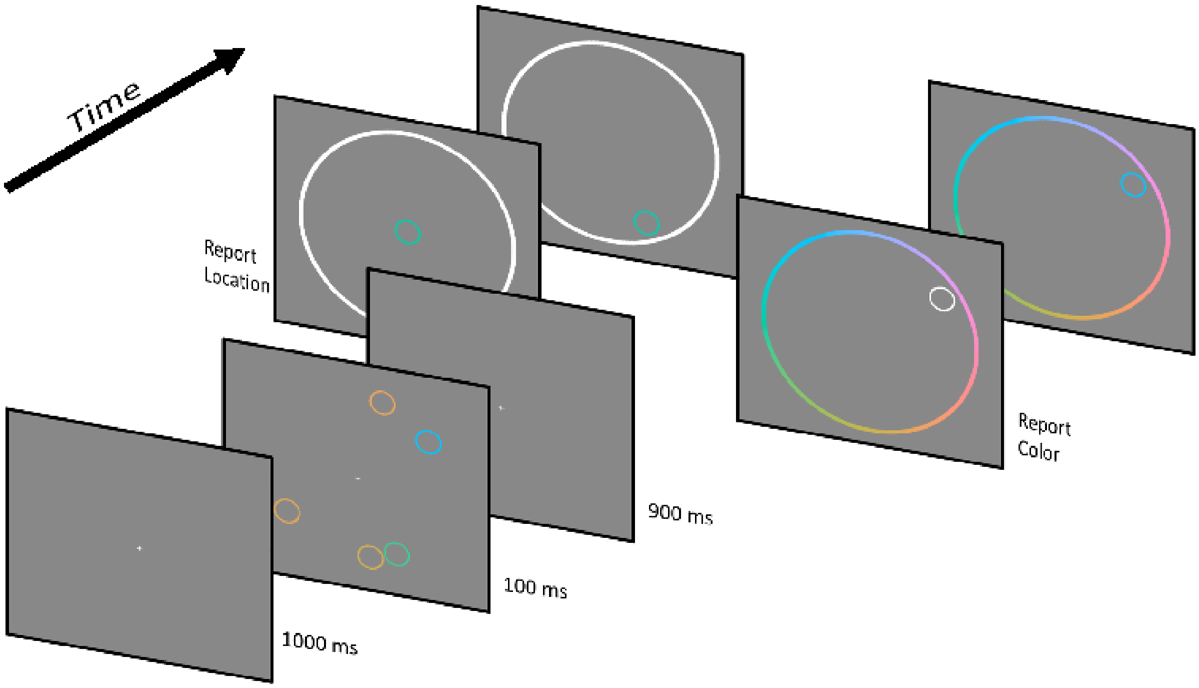
After the memory sample had been presented for 100 ms, there was a 900 ms retention interval consisting of a blank screen. Following the retention interval, the memory test was displayed. For Color Report, a location cue (a single ring whose spatial position matched one of the rings presented in the memory sample) was presented, and a 0.5º wide color ring appeared centred at fixation with a radius of 8°. The location ring cue was colored in white at the onset of the test display. The task for participants was to use a computer mouse to adjust the color of this ring by moving the cursor towards the desired color on the color wheel so that the ring matched the color of the memory item that appeared in the cued location earlier in the trial. When the participant clicked the mouse, the response was submitted, and 1000ms of feedback was provided in the form of a small black dot outside the location of the correct color on the color wheel.

For Location Report, the memory test display instead included a blank wheel of identical size and position to the color wheel, but with no color (filled in white). A single colored ring, whose color matched the color of one of the items from the memory sample display (the color cue), was presented in the centre of the screen at the outset of the memory test. The task for participants was to use the mouse to adjust the position of the ring so that it matched the position of the memory item that was cued by color. To equate the Report Location condition with the Report Color condition, the allowable response positions were constrained to possible locations; more specifically, the position of the response ring was always drawn with its distance to fixation fixed at the actual presentation distance. This allowed responses in both report conditions to be measured in angular values only, which were used to compute memory error. Again, after a response was chosen, 1000 ms of feedback was provided in the form of a small black dot appearing adjacent to the cued item's correct location on the empty color wheel before the next trial automatically began. A graphical depiction of our procedure is shown in Figure 1. Participants completed 512 trials in total, spread over eight blocks.

Results

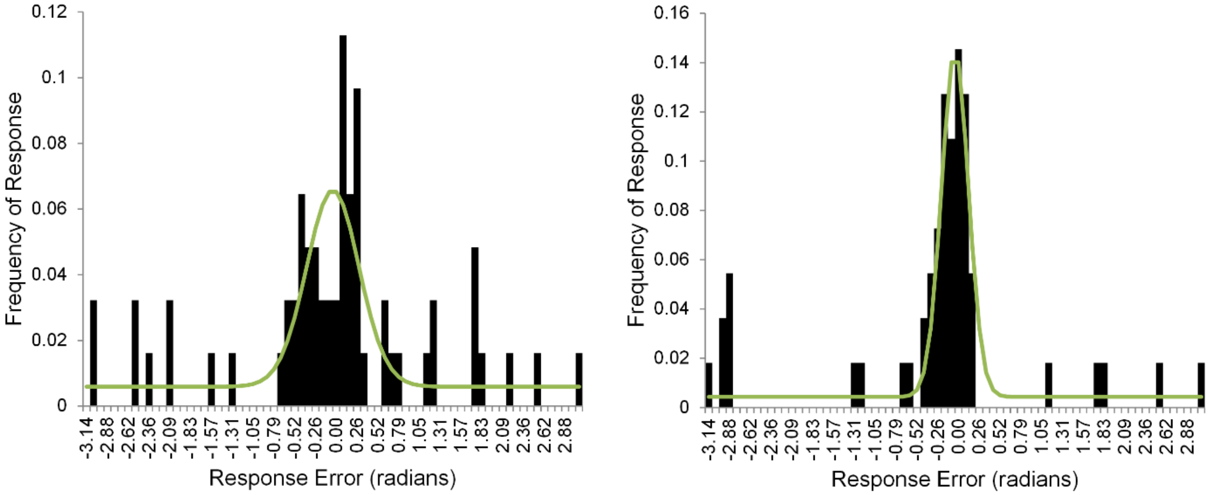
A representative histogram depicting memory performance (response angle – actual angle) for one participant at Set Size 5 is plotted in Figure 2. To determine how memory for each Report condition was affected by set size, we fitted performance for each subject in each condition (eight in total: four set sizes X two report conditions) with the 3-component mixture model developed by Bays, Catalao, & Husain (2009). Briefly, this model uses maximum likelihood estimation to determine the combination of four parameters that maximizes the likelihood of the observed responses. The four parameters returned by the fitting procedure are memory precision (which we express in its inverse: angular standard deviation of the circular normal distribution component of the fitted response distribution, in radians), p(Target), p(Swap), and p(Guess). The latter three parameters refer to the weightings of the three possible distributions, or sources, of responses: a circular normal distribution centered on the cued item's report value, the sum of circular distributions centred on the non-cued items' report values, and a

Figure 1.



A partial depiction of the trial procedure for Experiment 1. Report Condition varied between trials, with either Location (left) or Color (right). The initial display at test is depicted in front; behind the initial test display is a depiction of the displays’ appearance after a participant had provided a response. After providing a response, participants received feedback in the form of a small black dot appearing outside the color wheel at the angular value of the correct response (not depicted).

Figure 2.

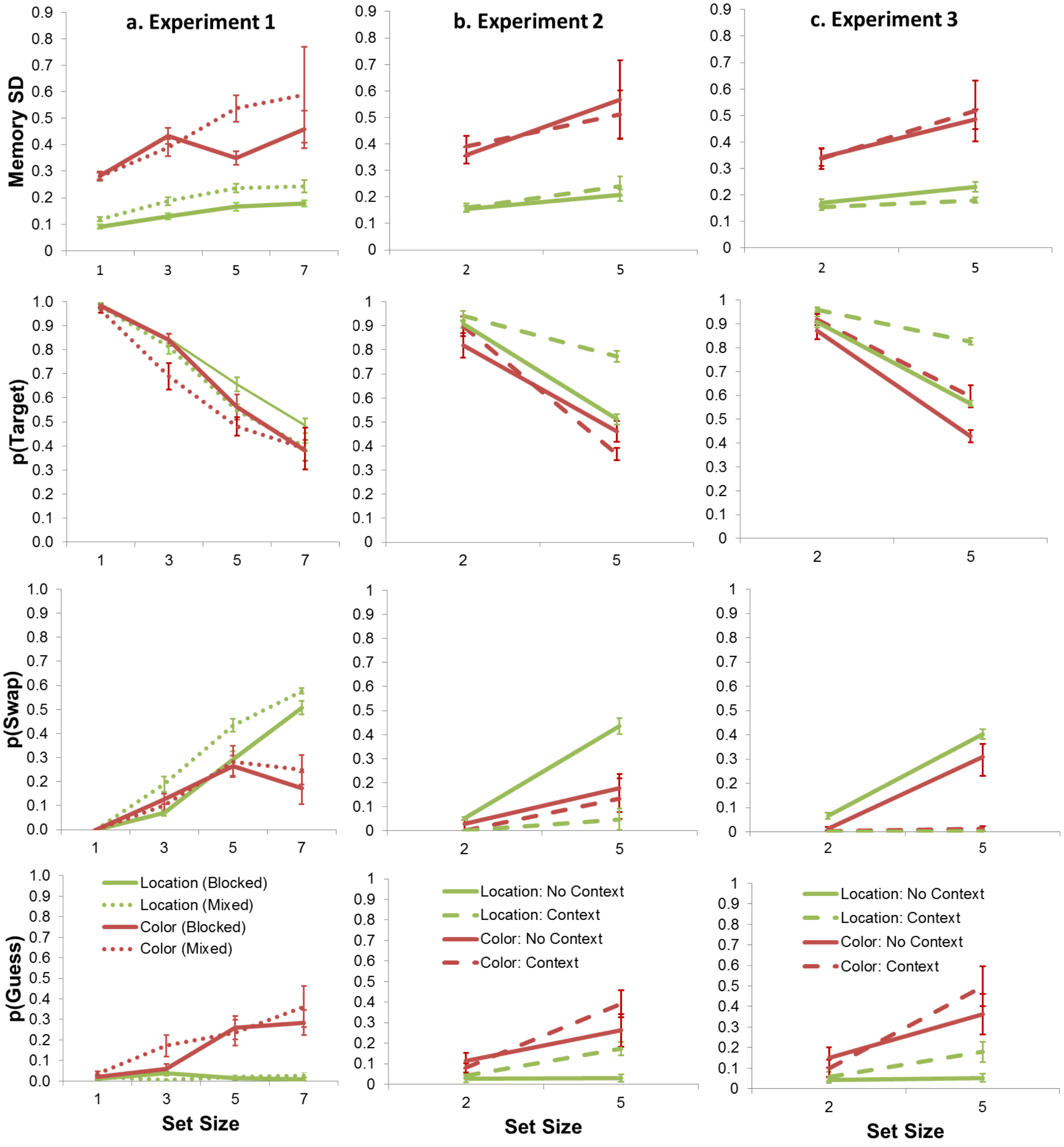


Histograms of response error for a sample participant at Set Size five. On the left is performance when color was reported and on the right is performance when location was reported.

uniform distribution. The values of these three parameters reflect the likelihood of each type of response in a particular condition, and since the three sources are mutually exclusive, the values of these three parameters must sum to one for a particular fit. For a more detailed explanation of the model, see Bays, Catalao, & Husain, 2009. Our analyses were concerned with determining which, if any, of these markers of memory performance differed between report conditions.

As can be seen in Figure 3a, performance differed in two notable ways: when reporting location with color, the probability of a target response was overall greater, and only swap errors were made, with no random guessing. To assess the reliability of differences in performance for the two Report conditions, we performed a three-way, mixed model ANOVA for each parameter value returned by the fitting procedure detailed above. The ANOVA's factors were Randomization Condition (Mixed or Blocked: Between-Subjects), Report Condition (Color Report or Location Report: Within-Subjects), and Set Size (1, 3, 5, or 7: Within-Subjects). The ANOVA showed a main effect of Randomization Condition for p(Target), *F*(1, 16) = 4.61, *p* = .048, *MSE* = 0.004, such that the likelihood of correctly reporting the tested item's feature value was slightly higher in the blocked condition (see Figure 3a). This increase in p(Target) was accompanied by a marginal increase in memory precision, *F*(1, 16) = 3.71, *p* = .07, *MSE* = 0.005, suggesting that p(Target) performance in the blocked condition did not increase because of a trade-off between quantity and quality of item representations in VWM. In addition, a marginal interaction was found between Set Size and Randomization condition on p(Swap), *F*(3, 48) = 2.47, *p* = .07, such that swaps were more likely in the Mixed condition, with this trend being most prominent at higher set sizes. In summary, advance knowledge of the reported feature (Blocked condition) did lead to a slight increase in performance. We suggest that this may reflect preferential VWM resource allocation to the feature to be reported.

Figure 3.



Estimated memory parameters in Experiment 1 (a), Experiment 2 (b), and Experiment 3 (c) as a function of Memory Set Size (x-axis), Report Condition (location, color), and Randomization Condition (blocked, mixed). The first row depicts the mean estimated circular standard deviation of the fitted target distributions, the second depicts mean estimated p(Target), the third depicts mean estimated p(Swap), and the fourth mean estimated p(Guess). Error bars reflect one within-subjects standard error of the mean.

Set Size exhibited an expected main effect for all memory parameters, all *F*s(3, 45) > 8.78, *p*s < .001. For both Report conditions, increasing the number of to-be-remembered items led to a decrease in precision, as well as a decrease in p(Target) and an increase in the p(Swap) and p(Guess). There was also a main effect of Report condition on all memory parameters, *F*s(1, 16) > 7.58, *p*s ≤ .01. Precision differed considerably between location reports and color reports, although given that these are different features, comparison of absolute angular precision is uninformative. When expressed as percent changes in precision between set sizes, Report condition no longer reached significance, *F*(1, 16) = 0.82, *p* = .38, suggesting that increasing set size modulated precision similarly regardless of the reported feature. When it came to p(Target), however, the main effect of Report condition demonstrated that participants were more likely to correctly report an object's location given its color than they were to report an object's color given its location. The p(Swap) was overall higher when locations were reported, likely as a consequence of the striking absence of guesses at all set sizes when location was reported (see Figure 3a).

Set Size and Report condition interacted as well, but only for p(Swap) and p(Guess), *F*s(3, 48) > 10.92, *p* < .001. For p(Guess), this interaction shows that for reporting color, guesses increased with set size, but for location report, there were few guesses regardless of set size. In contrast, for p(Swap), the interaction shows that swaps increase with set size more for location reports than for color reports.

Discussion

Experiment 1 revealed two interesting findings. First, the likelihood of a correct response, p(Target), was overall higher when locations were reported given color than when colors were reported given a location. Intuitively, the p(Target) should be identical if item memory is a simple bundle of features (location and color) that has a probabilistic failure rate, determined in part by set size, as a correct response requires the maintenance of both features as well as their binding. It is unclear whether this difference should be attributed to color's superiority as a cue or locations superiority as a reported feature. A full assessment of this issue is beyond the intended scope of this paper; our goal is to stress that VWM performance departs from what would be expected if the representation of an item in VWM consisted of two components: feature values, and a uniform "binding" (or "bindings") between them. Rather, our results suggest that alternatives must be considered (see General Discussion).

The second finding of interest was a substantial difference in the types of incorrect responses observed between Report conditions. When participants were reporting color, errors were best modelled as a mixture of swaps and guesses. However, when reporting location, participants never guessed a random location – errors were always swap errors. We have reported this finding earlier (Rajsic & Wilson, 2012, see also: Pertzov, Dong, Peich, & Husain, 2012), and believe it to be a robust effect reflecting fundamental differences in memory for location and color. The difference in these two conditions cannot be attributed to an effect of location clustering, as our previous work showed the same distinct difference in types of errors while imposing a 30º buffer between the color and location values selected for memory displays. The results of this experiment, however, leave unclear whether participants have a higher capacity for locations, and their performance was limited by their ability to use color to report the correct location, or if participants simply guess locations that they remember instead of choosing random locations when they do not know which to report. To resolve this ambiguity, we designed a second experiment which included a new condition; a distractor-context condition. In this condition, participants were again cued to recall a location given a color, or a color given a location, but the test display included the non-tested, or distractor, items from the memory sample display. We reasoned that these displays would provide participants additional cues as to the tested information, providing a superior index of the amount of information stored regarding the tested item.

Experiment 2

Methods

Stimulus presentation was identical to the Mixed condition of Experiment 1 with two differences. First, only two set sizes were used to allow a sufficient number of observations per condition to be collected: set sizes two and five. Second, one additional type of memory test display was added; the distractors-present display. The distractors-present displays were identical to the stimulus displays used in the previous experiment, except that the un-tested items were drawn in their original positions and colors, while the tested item was either drawn as a white ring in its original location (to be filled in with its remembered color) for the Color Report condition, or drawn as a colored-in ring in the centre of the screen (to be positioned in its remembered location) for the Location Report condition. Participants (*n* = 9) again completed 512 trials over eight blocks.

Results

The results, plotted in Figure 3b, show a strong effect of context on location reports, greatly increasing p(Target), and eliminating swap errors in favor of guessing, but no such change occurred for color. Participant responses were again fit to the 3-component mixture model developed by Bays et al. (2009). These estimated parameter values were each submitted to a 3-way repeated measures ANOVA with the following factors: Context (No Context or Distractors-Present), Set Size (2 or 5), and Report Condition (Color Report or Location Report).

Three-way interactions between Context, Set Size, and Report Condition on p(Target) and p(Swap), *F*s > 10.32, *p*s < .02, demonstrated that the Context and Set Size conditions had different effects on memory performance for the two Report conditions. As such, we examined the effects of Context and Set Size for the two Report Conditions separately (see Figure 3b).

When color was reported, Set Size did not modulate precision, *F*(1, 8) = 2.73, *p* = .14, but affected all other memory parameters, *F*s(1, 8) = 7.77, *p* < .03, reducing p(Target) and increasing both types of errors. Context showed no main effects, *F*s(1, 8) < 1.82, *p*s > .22. However, Context interacted with Set Size for p(Target) and p(Guess), *F*s(1, 8) > 7.01, *p*s < .03, suggesting that the presence of distractors affected the success of item retrieval. At Set Size 2, the presence of distractors led to an increase in p(Target) of 8%, but at Set Size 5, distractors caused a decrease in p(Target) of 9%. It appears that providing distractor context was helpful in providing access to additional information when only two items were remembered, but at larger set sizes, the additional information impaired performance.

When location was reported, qualitatively different results were obtained again. Set Size showed a main effect on all memory parameters, *F*s(1, 8) > 11.64, *p*s < .01, as expected. In contrast to when color was reported, there was a main effect of Context for p(Target), p(Swap), and p(Guess), *F*s(1, 8) > 8.63, *p*s < .02, and Context interacted with Set Size on the same three memory parameters, *F*s(1, 8) > 9.98, *p*s < .02. As can be seen in Figure 3b, these interactions came in the form of difference amplification; the impact of Distractor Context was greater in all cases as Set Size increased. Overall, the presence of Distractor Context led to an increase in p(Target), a decrease in p(Swap), and an increase in p(Guess). Especially noteworthy was the near elimination of swap errors when Distractor Context was presented ($M_{\text{Set = 2}}$ = 0.0002, $SE_{\text{Set = 2}}$ = 0.0002; $M_{\text{Set = 5}}$ = 0.05, $SE_{\text{Set = 5}}$ = 0.04) compared to when it was not ($M_{\text{Set = 2}}$ = 0.04, $SE_{\text{Set = 2}}$

= 0.007; $M_{\text{Set = 5}}$ = 0.43, $SE_{\text{Set = 5}}$ = 0.03), and the emergence of random guesses when location was reported.

To determine if the asymmetry in navigating color-location bindings at retrieval found in Experiment 1 was replicated, we compared the p(Target) between Report Conditions by conducting a repeated Measures ANOVA on Set Size and Report Condition only for trials in which context was not provided at test. A main effect of Set Size was present, $F(1, 24) = 47.41$, $p < .01$, as well as a marginal main effect of Report Condition, $F(1, 24) = 3.20$, $p = .09$, both of which were qualified by an interaction, $F(1, 24) = 47.64$, $p < .01$. Follow up *t*-tests revealed that at Set Size 2, Reporting Location given color was superior to Reporting Color given Location, $F(1,24) = 5.15$, $p = .03$, but at Set Size 5, the difference was not reliable, $F(1, 24) = 1.72$, $p = .20$. Experiment 2, therefore, provided a partial replication of the retrieval asymmetry uncovered in Experiment 1.

Discussion

Experiment 2 demonstrated an additional way in which memory for location differed from memory for color. When reporting location, Distractor Context had no impact on memory for Set Size 2 but substantially improved memory for Set Size 5. In contrast, when reporting color, Distractor Context produced a small memory improvement only for Set Size 2 and seemed to actually impair memory performance for Set Size 5. It is possible that, instead of reflecting differences in the ability to use location and color information to access VWM, the effect of context at retrieval was constrained by our brief sample presentation (100ms). Specifically, participants may have encoded and maintained too few colors for context to have improved color recall. With this in mind, we ran a third experiment where the sample presentation was extended to 600ms.

Experiment 3

Methods

An additional nine adults participated in an experiment that was identical to Experiment 2, with the sole adjustment of an increase in the sample duration from 100ms to 600ms.

Results

The results of Experiment 3, shown in Figure 3c, demonstrate that a longer encoding time led to an effect of context for color reports as well as location report. Data from Experiment 3 was analysed in the same fashion as in Experiment 2; fitted parameters were submitted to a 2 (Context) x 2 (Set Size) x 2 (Report Condition) repeated-measures ANOVA. Figure 3c depicts the fitted parameters for each of the Report Conditions, Set Sizes, and Contexts. For memory precision, a main effect of Report Condition, $F(1, 56) = 65.38$, $p < .01$, and of Set Size, $F(1, 56) = 12.37$, $p < .01$, were present, indicating that precision was overall higher for location than color, and that increasing Set Size overall decreased precision. Report Condition and Set Size also interacted, $F(1, 56) = 4.06$, $p = .049$, such that the slopes relating Set Size to precision were not equal across the Report Conditions. This finding is not terribly consequential, however, given that increasing Set Size would not add a constant decrement in precision, but produce a multiplicative change. When expressed as percent changes in precision across set size, Report Condition did not significantly affect the reduction in precision caused by Set Size, $F(1, 8) = 3.21$, $p = .11$.

When it came to p(Target), the critical three-way interaction from Experiment 2 no longer held, $F(1, 56) = 0.54$, $p = .47$. As is visible in Figure 3c, both Color and Location benefitted from the presence of Context when a longer sample duration was provided. Main effects of Set Size, Report Condition, and Context, were found, $F(1, 64)$s > 14.28, ps < .01. In addition, 2 two-way interactions were present – between Report Condition and Set Size, *F*(1, 64) = 6.22, *p* = 0.02, and between Set Size and Context, *F*(1, 64) = 7.97, *p* < .01. The former indicated that Set Size reduced p(Target) when reporting color more than when reporting location, *t*(8) = 2.75, *p* = 0.03. The latter indicated that the effect of Context was far greater at Set Size 5 than at Set Size 2, *t*(8) = 6.26, *p* < .01.

The most dramatic change occurred for p(Swap). There was a main effect of Set Size, *F*(1, 56) = 30.31, *p* < .01, demonstrating that swaps increased when more items were present in the memory sample display, and a main effect of Context, *F*(1, 56) = 43.80, *p* < .01, such that swaps decreased when context was provided at retrieval. Inspecting Figure 3c, it appears that swaps never occurred at all when context was provided. One-tailed, one-sample *t*-tests confirmed that, for location and color both, p(Swap) was statistically indistinguishable from zero when context was provided, *t*(8)s < 1.00, *p*s > .17. A two-way interaction was also present, *F*(1, 56) = 28.20, *p* < .01, between Set Size and Context, such that the reduction in swaps was larger at Set Size 5, *t*(8) = 11.57, *p* < .01. Finally, p(Guess) showed the same main effects and interactions as p(Target), consistent with the conclusion that Context, by eliminating swap errors, led to memory reports being either correct reports or guesses.

As in Experiment 2, we endeavoured to determine whether the retrieval asymmetry found in Experiment 1 would replicate. To do this, we again ran a 2-way repeated measures ANOVA using only No Context trials. The resulting main effects of Set Size and Report Condition were both significant, *F*(1, 24)s > 12.96, *p*s < .01, but were qualified by an interaction, *F*(1, 24) = 138.67, *p* < .01. To determine the nature of this interaction, we compared p(Target) between Report Color and Report Location separately for both set sizes. At Set Size 2, the p(Target) did not differ between the two, *F*(1, 24) = 2.10, *p* = 0.16, but at Set Size 5, p(Target) was significantly greater for Report Location, *F*(1, 24) = 33.06, *p* < .01. These results demonstrate that the retrieval asymmetry again appeared, even when the sample duration was increased.

Discussion

When given sufficient time to encode color information, Context was also able to improve color memory performance. For both features, p(Target) increased substantially when context was provided, and p(Swap) was eliminated. Providing context at retrieval increased p(Target) for colors from 0.43 (+/- 0.06, 95% WS CI) to 0.60 (+/- 0.11, 95% WS CI), and p(Target) for locations from 0.57 (+/- 0.03, 95% WS CI) to 0.83 (+/- 0.03, 95% WS CI). These results strongly suggest that swap responses in the delayed estimation task are largely due to uncertainty regarding feature bindings at memory retrieval, not illusory conjunctions at encoding. In other words, swap errors could be considered "educated guesses" as opposed to mistaken beliefs. It is also noteworthy that, even with the longer sample duration – a duration long enough to eliminate all swap errors for both features – capacity for locations still exceed that of colors. In addition, the p(Target) for location reports was overall higher than that of color reports even when context was not provided, replicating the retrieval asymmetry from Experiment 1.

General Discussion

Summary of results

Across three experiments we demonstrated notable differences in memory performance depending on whether the color or locations of items was reported. When color was reported, a mixture of guessing and swapping errors emerged as set size increased, replicating previous findings (Bays, Catalao, & Husain, 2009). However, when locations were retrieved with color, virtually no guess errors were present and only swap errors were made. Experiment 2 compared distractor context with no context at test. When location was reported, context had no impact on memory for set size 2 but greatly improved memory for set size 5. When color was reported, context improved memory at set size 2, but actually hurt memory at set size 5. After increasing the sample duration to 600ms in Experiment 3, context at retrieval benefitted memory not just for location but also for color report, and led to an elimination of swap responses. Again, it should be stressed that during encoding the participant did not know which feature would be tested so that both color and location needed to be encoded regardless of which was to be reported.

Our results suggest that memory for an item's location is encoded more quickly than an item's color. This can be most simply seen by comparing the data of Experiment 2 and 3. In Experiment 2, for Location report, multiplying p(Target) from the Distractor Context condition by the number of items at set size five provides an average capacity estimate of k = 3.87 (+/- 0.0.25: 95% WS CI), notably larger than the estimate provided by the No Context condition (k = 2.56, +/- 0.0.25: 95% WS CI) or for the average capacity for color report in either the Context (k = 1.84, +/- 0.30: 95% WS CI) or No Context (k = 2.31, +/- 0.50: 95% WS CI) conditions. In Experiment 3, this was still true – the k estimate for color when context was present (2.98 +/- 0.53, 95% WS CI) was lower than for location (4.13 +/- 0.17, 95% WS CI).

We suggest that the Distractor Context conditions reflect the capacity for unbound features (i.e., color and location), whereas the No Context conditions reflect the capacity for color-location bindings, which are necessary for successful performance when no distractors are present. When distractors are present, participants are able to adopt the strategy of simply reporting the feature that is missing from their memory of the sample display, and do not need to rely on the cue feature at all. That this additional strategic possibility led to improved performance suggests that the features of remembered items are represented in a common space that allows for the comparison of the remembered features of multiple items to improve performance. In the multiple-object tracking literature, a higher capacity for locations than for feature-location bindings has also been reported (Pylyshyn, 2004), lending support to the conclusion the capacity for bindings is poorer than the capacity for maintaining unbound features.

Representation

One can interpret these findings in terms of the representational architecture of spatial and non-spatial visual (or object) working memory. Fractionation of the visual buffer in Baddeley's (1992) model of working memory has been suggested (Logie & Pearson, 1997), and the present data may be used to inform differences between these two postulated stores. Our results would imply that the capacity of spatial working memory exceeds that of visual working memory (at least in so far as our context manipulation can successfully isolate the ability to report unbound features). Furthermore, the cued-recall task places an additional burden of having to maintain temporary cooperation between the stores, binding object representations to their location for report, and that this is also a capacity-limited ability.

However, we suggest that considering these two types of memory as completely separate is not necessary. Instead, spatial memory may benefit from a greater capacity if the architecture of VWM is like that described by an alternate version of FIT in which each feature map also codes the locations of its coded features (Johnston & Pashler, 1990). This conceptualization of VWM suggests that instead of storing free-floating item representations, VWM codes information in a map-like format, where location is coded across multiple maps, unlike many other non-spatial features (see Franconeri, Alvarez, and Cavanagh, 2013, for a discussion of map-based representations in cognition). This representational format is inspired by the coding properties of the visual cortex, where receptive fields represent various non-spatial properties, but include some degree of spatial tuning (Van Essen & Maunsell, 1983). If visual working memory representations are grounded in the cortical machinery that codes the remembered information in perception, as suggested by Postle (2006, see also: Fuster, 1997), then a location-based representational format is a natural by-product of the visual system's coding scheme. A number of studies have provided support for this hypothesis using human fMRI, showing that information about remembered items is present in early visual areas during the retention interval of a visual memory test (Harrison & Tong, 2009; Ester, Anderson, Serences, & Awh, 2013; Emrich, Riggall, LaRocque, & Postle, 2013).

Our asymmetrical retrieval results may be accounted for by such an architecture, as binding in this format would not be a simple connection between two features. If memories in VWM exist in visual maps, there are numerous spatial codes available, and so retrieval of location could be augmented by tuning a retrieved memory trace from one map with the memory traces for location available on other maps. The same advantage could not be extended to features like color if fewer redundant codes are available, or if co-registration across maps must be mediated by location.

This architecture is also compatible with findings from change detection. As noted earlier, Jiang et al. (2000) showed that change detection is considerably poorer when spatial context is scrambled than when color context is scrambled. A map-based architecture easily accommodates this result, as this representational format requires that comparing remembered colors to the colors presented in a probe display must be mediated by location. While a dual-stores account could account for our data by suggesting that object-location bindings are required by the task, and so produce localized object representations held in VWM as a consequence, the data of Jiang et al. suggest otherwise. In their task, location was unnecessary for change detection, yet it still appeared to be intimately bound to the object representations that supported performance.

In addition, this architecture provides a mechanism for the now well-established retro-cue effect (Makowski, Sussman, & Jiang, 2008; Sligte, Scholte, & Lamme, 2008; Murray, Nobre, Clark, Cravo, & Stokes, 2013). The location signalled by the retro cue can be used to attend to the cued-location, allowing resources to be devoted to the item information specified by the cued location. Pertzov et al. have argued that the ability to focus attention within VWM using a retro cue may rely on spatial memory, in which case a spatial code is necessary for VWM to be attentively accessed (2013). Indeed, a recent study by Lara and Wallis (2014) showed that neurons in the prefrontal cortex show spatial selectivity when multiple items are being remembered, even when non-spatial information is being maintained in working memory. Finally, this representational format aligns nicely with the recent findings of Pertzov and Husain, (2013) who showed that colors and orientations are mis-bound more often when items are presented in the same location than when they are presented in different locations. In the former, a particular location must coordinate feature-bindings for multiple items, leading to increased interference.

Finally, an attractive feature of this representational format is that it provides a basis for retrieval mechanisms within VWM. As noted earlier, the map architecture suggested for VWM storage bears a strong resemblance to certain versions of FIT, which were designed to account for visual search performance. What emerges, then, is the possibility that VWM retrieval operates by analogy to visual search; representations are accessed in a similar fashion to how search may be guided to items in a visual search display. Indeed, Hyun et al. (2009) have shown that comparison of test displays with remembered displays operates similarly to the inspection of a display during visual search: detection of differences is more efficient than the detection of similarity, attention is oriented quickly to the location of a difference, and differences can be detected in a pop-out like fashion.

Conclusion

By varying the reported feature in a delayed-estimation memory paradigm, and by varying the presence of non-tested items at test, we have shown that the ability to report remembered features is improved when non-tested items are presented. In addition, for the no context conditions, when participants reported a location that did not correspond to the tested item's location, they consistently erred by reporting another item's location, never guessing at random, unlike when color memory was tested. Finally, we reliably found an asymmetry in cued-retrieval such that retrieving location with a color cue tended to be more effective that retrieving color with a location cue. We suggest that our results are best accommodated by a map-like representational format wherein non-spatial features are coded with some degree of spatial information, much like what is suggested by Feature-Integration Theory. This format would allow for the binding of non-spatial features, mediated by a common location index, and provide a mechanism for retrieving information.

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