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What does visual suffix interference tell us about spatial location in working memory?

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Abstract

A visual object can be conceived as comprising a number of features bound together by their joint spatial location. We investigate the question of whether the spatial location is automatically bound to the features or whether the two are separable using a previously developed paradigm whereby memory is disrupted by a visual suffix. Participants were shown a sample array of four colored shapes followed by a post-cue indicating the target for recall. On randomly intermixed trials, a to-be-ignored suffix array consisting of two different colored shapes was presented between the sample and the post-cue. In a random half of suffix trials one of the suffix items overlaid the location of the target. If location was automatically encoded, then one might expect the co-location of target and suffix to differentially impair performance. We carried out three experiments, cueing for recall by either spatial location (Experiment 1) color or shape (Experiment 2), or both randomly intermixed (Experiment 3). All three studies showed clear suffix effects but the co-location of target and suffix was differentially disruptive only when a spatial cue was used. The results suggest that purely visual shape-color binding can be retained and accessed without requiring information about spatial location, even when task demands encourage the encoding of location, consistent with the idea of an abstract and flexible visual working memory system.

Key words: working memory, binding, location, suffix, cued recall

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Studies of visual working memory typically involve presentation of an array or sequence of visual objects and their subsequent testing by recognition or cued recall. A good deal of research has focused on the process of binding features such as color and shape into perceived objects, a process that under typical conditions appears to be relatively automatic (e.g. Allen, Baddeley, & Hitch, 2006, 2014; Allen, Mate, Hitch, & Baddeley, 2012). Such objects are of course spatially located and the question arises as to whether location functions in the same way as other features such that objects are automatically bound to the location at which they are presented. In addressing this issue, it is important to distinguish two separate ways in which spatial location might prove important. First of all, one should bear in mind that by definition, a visual object requires that the relevant features be at the same location at the same time; a patch of red beside a square is not the same as a red square. In addition to this defining effect of co-location, there is another aspect of spatial location that is important, characterized either in absolute terms as the position of the object within a spatial field, or relatively, based on its spatial relationship to other objects, regardless of absolute location. In order to store this latter information it is not sufficient to note that the features of color and shape are co-located, but also where the resultant object is located either within the visual field or in relation to other objects. The question arises as to whether the spatial location of a stimulus is automatically encoded and maintained in the same way as the spatial co-location of color and shape that defines the object.

Woodman, Vogel and Luck (2012) studied this question in a series of change-detection experiments in which the test items were presented in the same or different locations from the initial stimuli (see also Jiang, Olson, & Chun, 2000; Logie, Brockmole, & Jaswal, 2011; Treisman & Zhang, 2006). They found little effect on change detection accuracy, concluding that spatial location was not a rigidly bound part of the memory representation. Changes in location only impacted on performance when the task implicitly encouraged spatial encoding (via use of a spatial cue at test). Woodman et al. (2012) suggested that an abstract representation of location was being stored, rather than a precise retinal copy of the original stimulus, and that "change detection tasks rely on a flexible, abstract and manipulable memory system; that is a *working* memory system" (p.21). They accept however that it is still unclear whether the abstractness occurs in the memory representations themselves, or in the processes used to compare such representations with incoming stimuli. Accurate performance might, for example, result from a flexible perceptual representation of the test stimulus that could be scaled and shifted before comparison. Yet another possibility is that "people simply have the ability to ignore spatial information and not encode it into memory when they know that it is irrelevant and potentially misleading" (p. 22).

We presently describe experimental work that resembles that of Woodman et al. (2012) in focusing on the role of spatial encoding in visual working memory, but instead uses an interference paradigm. Interposing a potentially disruptive event between the encoding of stimuli and retrieval allows the possibility of separating the retention of memory representations from the retrieval phase. Varying the nature of such an event can throw light on the characteristics of the encoded features. The intervening items may themselves require encoding for subsequent retrieval (Allen et al., 2006, 2014; Hu, Hitch, Baddeley, Zhang, & Allen, in press; Pertsov et al. 2013) or they might require an active response. Using such a paradigm Fiacconi and Milliken (2012; 2013) report the disruption of the binding between an object and its location when participants respond to other items presented subsequently in the same location as the target. They suggested that this might reflect updating and overwriting of object files (Kahneman et al., 1992) caused by interpolated stimuli sharing the same spatial coordinates. However, in line with the findings of Woodman et al. (2012), these effects could equally be attributed to the location-oriented nature of both the primary memory measure and the response task performed during retention.

This leaves the question of whether spatial location mediates interference effects in visual object maintenance when intervening stimuli do not have to be attended, and when the importance of location for the memory task varies. An interference paradigm involving presentation of a visual 'suffix' is particularly informative in this context. In this paradigm participants are instructed to ignore an irrelevant stimulus presented during the retention interval. Previous work has found that memory is disrupted by the presentation of a single suffix item immediately after the study display (Ueno, Allen, Baddeley, Hitch & Saito, 2011; Ueno, Mate, Allen, Hitch, & Baddeley, 2011). These interference effects were mediated by suffix identity; 'plausible' suffixes (with shape and color from the experimental set, though not from the study items presented on that trial) caused greater disruption than 'implausible' suffixes (with perceptually distinct features that were never part of the to-be-remembered set), with the presence of a single plausible feature in the suffix enough to cause this increased interference. Analysis of errors when memory was tested by cued recall indicated that plausible suffixes led to recall of suffix features (suggesting overwriting of targets by suffixes), rather than recall of features from other target objects (which would reflect more general 'misbindings'). These interference effects emerged even though the suffix always appeared in a neutral spatial location. An obvious question in the present context is whether the amount of interference will vary when the suffix is presented at the same location as an item in the memory task.

We report three experiments using the suffix paradigm to investigate the role of spatial location in the representation of objects in visual working memory. Firstly, we examined whether the location of a suffix determines the extent of disruption to memory for shape-color binding. If spatial location is necessary for retaining feature binding and determining what constitutes an object over time, a suffix encountered in the same location as a previously presented to-be-remembered target item should impact on memory for this item, leading to increased interference effects. Given that participants are instructed to ignore the suffix, observing such an effect would suggest a relatively automatized source of location-based interference that does not depend on active encoding. In contrast, if, as Woodman et al. (2012) claim, the representation of location in visual working memory is flexible and abstract in nature, and not critically tied to spatial location at encoding, then suffix location should only reliably impact on performance when location is an important part of the task. We therefore explored suffix location effects under different task conditions in which memory for spatial location either was or was not explicitly required.

A secondary aim of the study was to find whether suffix plausibility effects found previously (Hu et al., in press; Ueno, Mate, et al., 2011) generalize to the use of dual suffixes and location-cued recall. Connected to this, we examined whether any effects of suffix identity and location are interactive or additive in nature. If plausible suffixes are more likely to be encoded into working memory (Ueno, Allen et al., 2011; Ueno, Mate, et al. 2011), a suffix containing plausible features might be expected to cause greater disruption when in the same location as the to-be-recalled target. However, if spatial location is registered separately in the processing stream (e.g. Huang, 2010; Treisman & Gelade, 1980), before encoding of features, its effects may be independent of and additive to those of identity.

Experiment 1

This first experiment examined whether the spatial location and identity of a to-be-ignored stimulus suffix mediates its interfering effect in visual working memory. Participants were shown an array of 4 colored shapes followed by a cue pointing to one of the 4 locations. They were required to recall the shape and color of the item that had been presented in the location indicated by the cue. We were particularly interested in whether a suffix presented in the same location as the target item would cause greater interference. We also manipulated the identity of the suffix to see whether the previously observed effect of suffix plausibility (Ueno, Allen et al., 2011; Ueno, Mate, et al. 2011) would extend to this new methodology, and whether any effects of suffix location would be greater for plausible suffixes.

Method

Participants

There were 22 participants (mean age 19.05 years) in this experiment, all students at the Universitat Autònoma de Barcelona, Spain.

Materials

All stimuli were drawn from Ueno, Mate, et al. (2011, Experiment 3). Target items and plausible suffixes were colored shapes drawn from a set of eight colors (black, green, gray, blue, red, yellow, turquoise, and violet) and eight shapes (circle, chevron, triangle, diamond, star, cross, arch, flag). Implausible suffixes consisted of pale colored shapes based on Japanese prefectures (See Ueno, Mate, et al., 2011, for further details).

Design, and Procedure

The experiment followed a within-subjects design, with 5 conditions. We manipulated location (overlaid target item vs. non-overlaid target item) and suffix type (plausible vs. implausible). We also included control trials in which no suffixes were presented.

There were 96 test trials within the single experimental block. These consisted of 32 no suffix control trials, 32 implausible suffix trials, and 32 plausible trials. Within each set of suffix trials, 16 trials involved the cued testing of an item that had been subsequently overlaid by a suffix in the same location, and 16 involved recall of a non-overlaid target (see Figure 1 for illustration of method). All trials were randomly intermixed within the experimental block.

The experimental session began with a brief phase in which participants were presented with the target shapes and colors that they would encounter along with their verbal labels, so that they would be clear how to respond. Each individual trial started with the presentation of a fixation cross for 500ms, followed by the to-be-remembered array (for 2000ms), which consisted of 4 colored shapes located at the corners of an invisible square (2.25° in size). This was followed by a 1000ms delay, and then the recall cue. This consisted of a black arrow presented in the centre of the screen, pointing towards one of the 4 target locations (see Figure 1). Participants were required to verbally recall the shape and color of the object that had been presented in the cued location, before moving on to the next trial, with verbal cued recall responses being recorded by the experimenter. Cueing was controlled so that half of the trials in each suffix type condition cued a target item that had not been subsequently overlaid by a suffix, while half had. This method meant that participants did not know which two (if any) of the four targets would be overlaid until suffix presentation, and that suffix location was not predictive of which target would be cued.

Conditions differed in terms of what was presented during the 1000ms retention interval. No-suffix trials simply involved a blank screen delay for the duration of retention. In all suffix trials, a 250ms blank screen delay following presentation offset was followed by two suffix items appearing simultaneously on screen, for 250ms, with a further 500ms blank screen delay before the recall cue. This timing of the suffix presentation (250ms after target presentation offset, in all experiments) places this source of possible interference within the temporal period in which location is maximally important for feature binding, as indicated by previous studies (Logie et al., 2011; Treisman & Zhang, 2006). The two suffixes could appear in any of the four locations previously occupied by to-be-remembered targets, in any configuration. Plausible suffixes consisted of shapes and colors drawn from the experimental set, but not any appearing in the sample array in the same trial whereas the shapes and colors of implausible suffixes formed distinctive sets that never appeared in the sample array.

Participants performed articulatory suppression (repeatedly articulating the sequence "1-2-3-4") during presentation and retention in each trial, in order to minimize verbal recoding.

Results

Object recall was scored as correct if participants successfully recalled both the color and shape of the target item. Mean proportions correct are displayed in Figure 2. Bonferroni-Holm adjusted comparisons (Holm, 1979) of each suffix condition with the no-suffix control revealed significant interference in each case (implausible non-overlaid, t (21) = 3.40, p < .01; implausible overlaid, t (21) = 5.69, p < .001; plausible non-overlaid, t (21) = 8.48, p < .001; plausible overlaid, t (21) = 7.81, p < .001). Proportion correct rates in the suffix conditions were subjected to a 2 (overlay) x2 (identity) repeated measures ANOVA. This revealed a significant effect of suffix location, F (1,21) = 8.84, MSE = .01, p < .01, *np2* = .30, reflecting poorer recall when the suffix overlaid the location of the target item. There was also a significant effect of suffix identity, F (1,21) = 18.05, MSE = .02, p < .001, *np2* = .46, replicating our previous finding that suffixes containing plausible features cause more interference. However, the suffix type by location interaction was not significant, F (1,21) = .01, MSE = .01, p = .94, *np2* < .01. As the primary focus of the present work concerned effects of suffix spatial overlay, planned contrasts examining this factor for each suffix type were carried out; these revealed significant effects of location on both implausible, t (21) = 2.26, p < .05, and plausible suffixes, t (21) = 2.36, p < .05.

Table 1 displays the rates of within-display confusion errors (recall of a feature from a different object in the presented set, along with a correct target feature, i.e. a 'binding' error) and external intrusions (recall of 1 or 2 features from the wider experimental set, including suffix intrusions, i.e. an 'overwriting' error). Other error types occurred at a proportion of less than .03 of all responses and are not reported in this or the following experiments. A 2x2 ANOVA on within-display confusions revealed no effects of location, $F\ (1,21) = .42$, $MSE = .01$, $p = .53$, $np2 = .02$, suffix type, $F\ (1,21) = .61$, $MSE = .01$, $p = .44$, $np2 = .03$, or the interaction, $F\ (1,21) = .06$, $MSE = .01$, $p = .81$, $np2 = .01$. In contrast, analysis of external intrusions revealed there were significantly more intrusions when the suffix overlaid the target, $F\ (1,21) = 9.36$, $MSE = .01$, $p < .01$, $np2 = .31$, and when the suffix contained plausible features, $F\ (1,21) = 36.81$, $MSE = .01$, $p < .001$, $np2 = .64$. However there was no interaction between type of suffix and suffix location, $F\ (1,21) = 1.48$, $MSE = .01$, $p = .24$, $np2 = .07$.

Discussion

The results show that previous evidence for suffix effects (Ueno, Allen, et al., 2011; Ueno, Mate, et al., 2011) extends to dual-suffix presentation and a different method of cueing recall. Thus a post-stimulus suffix impaired memory, the effect was greater when the color and shape of the suffix were plausible, and features of plausible suffixes tended to be recalled as intrusion errors. In line with previous claims, these effects can be interpreted as reflecting occasional failures of a feature-based perceptual filter set up to exclude the suffix from further processing. Suffixes with plausible features are more likely to pass this filter and subsequently disrupt and overwrite object representation in visual working memory.

As regards spatial location effects, recall of target shape and color combination was less accurate when the target was overlaid by one of the suffix items. This observation fits with the idea that spatial location is necessary for retaining conjunctions of features such as shape and color in visual working memory (e.g. Kahneman et al., 1992). However, it is also consistent with Woodman et al.'s (2012) suggestion that location is not crucial for retaining information about object identity, but can play a role depending on task demands. On this account one could argue that the use of a spatial cue for recall fostered a strategy of encoding information about the spatial locations of items.

We note that suffix location appears to influence performance in a similar manner to plausibility, increasing intrusion errors while having no effect on within-display confusions, suggesting a similar process of overwriting. However, suffix location and identity effects were statistically additive rather than interactive, suggesting that the two effects are independent. Further consideration of this outcome is reserved for the final discussion.

Experiment 2

The first experiment found that interference effects in visual working memory are mediated by suffix location when recall is cued by location. Experiment 2 examined whether this finding extends to a cueing method that does not require explicit memory for spatial location for an accurate response. In this method the target is cued by its shape (or color) and participants must recall its color (or shape). It has previously been shown to be sensitive to suffix effects (Hu et al., in press; Ueno, Mate, et al., 2011). At issue here was whether there would be an effect of whether the suffix overlaid the location of the target item. If memory for location is crucial for maintaining feature bindings, following Kahneman et al. (1992), results should follow the same pattern as in Experiment 1, with poorer recall when the target is overlaid by the suffix. If on the other hand memory for location is not crucial (Woodward et al., 2012), use of a task that does not encourage spatial encoding should follow a different pattern, with little or no effect of spatial overlay of the suffix.

Method

Participants

There were 23 participants (mean age 18.92 years) in this experiment, all students at the University of York, UK and Universitat Autònoma de Barcelona, Spain.

Materials, Design, & Procedure

We used the same design, stimuli, and trial procedure as in Experiment 1, with the exception of a different recall cue and task. Non-canonical color blobs and unfilled black shape outlines were used as cues on the respective color and shape cue trials. Specifically, this cue involved either a color or shape that had been present in the original array, with participants required to verbally recall the corresponding other feature that had been part of the same object. As in Experiment 1, the four locations were cued for recall an equal number of times across each condition.

Results

Mean proportions of correct responses, within-display confusions and external intrusions are displayed in Table 1. The proportion correct data are illustrated in Figure 3. Bonferroni-Holm adjusted comparisons of each suffix condition with the no-suffix control revealed significant interference in each case (implausible non-overlaid, t (22) = 2.35, $p < .05$; implausible overlaid, t (22) = 3.90, $p < .01$; plausible non-overlaid, t (22) = 4.16, $p < .001$; plausible overlaid, t (22) = 4.46, $p < .001$). Data from the suffix conditions were subjected to a 2x2 repeated measures ANOVA. The effect of suffix location did not approach significance, though there was a small numerical trend towards greater interference when the location of the suffix overlapped with the location of the target item, F (1,22) = 1.51, MSE = .02, p = .23, *np2* = .06. There was a significant effect of suffix type, F (1,22) = 4.60, MSE = .02, $p < .05$, *np2* = .17, replicating Experiment 1 and previous findings regarding suffix plausibility. As before, the location by suffix type interaction was not significant, F (1,22) = .58, *MSE* = .03, p = .45, *np2* = .03. Planned contrasts for each suffix type revealed no significant effect of spatial overlay on either implausible, t (22) = 1.35, p = .19, or plausible suffixes, t (21) = .25, p = .81.

Turning to the main error types (Table 1), analysis of within-display confusions revealed no effects of location, F (1,22) = .01, *MSE* = .02, p = .93, *np2* < .01, suffix type, F (1,22) = .46, *MSE* = .01, p = .51, *np2* = .02, or the suffix by location interaction, F (1,22) = 2.43, *MSE* = .02, p = .13, *np2* = .10. In contrast, analysis of external intrusions revealed a significant effect of type of suffix, reflecting more intrusions when the suffix was compatible, F (1,22) = 12.99, *MSE* = .01, p < .01, *np2* = .37, but no effect of location, F (1,22) = 2.61, *MSE* = .01, p = .12, *np2* = .11, or the interaction, F (1,22) = .59, *MSE* = .01, p = .45, *np2* = .03.

Discussion

As in Experiment 1, presentation of a suffix interfered with recall, and feature plausibility effects were observed in both accuracy and intrusion errors, providing further confirmation of the robustness of these effects. However, in contrast to Experiment 1, there was no significant effect of spatial location on proportion correct or error rates (though a small numerical trend can be observed). This runs counter to the general idea that spatial location information plays an important role in visual feature binding, as in the notion of object files (Kahneman et al., 1992), and a more specific suggestion that this is the case early after item offset (Logie et al., 2011; Treisman & Zhang, 2006). Instead, the absence of a significant effect of spatial overlay suggests that retaining information about spatial location is not critical for maintaining visual object representations. This fits with Woodman et al.'s (2012) observation that location shifts at recall do not disrupt recognition accuracy unless the memory task emphasizes the importance of retaining spatial location, and their conclusion that visual working memory uses an abstract and flexible representational system in which feature bindings can be stored independently of their location.

Experiment 3

Our final experiment explored Woodman et al.'s (2012) suggestion that participants may simply choose to ignore spatial location during encoding unless they know it to be useful for the task. On this account, the more reliable location effects observed in Experiment 1 reflect a strategic focus on encoding the location of each object as participants know they will be cued by location. Participants would not have the same strategic focus on location in the feature-cued task used in Experiment 2 in which location is not explicitly relevant. To evaluate this possibility, Experiment 3 examined whether the patterns of findings observed in Experiments 1 and 2 would replicate when trial types were randomly intermixed. Under these conditions, spatial location is potentially relevant on every trial and we would expect participants to adopt a strategy of encoding spatial location information. If such a strategy was responsible for the spatial interference effects observed in Experiment 1, we would now expect to see spatial interference effects when recall is cued by shape or color as well as location. The alternative possibility is that the different spatial interference effects observed in Experiments 1 and 2 reflect differences intrinsic to the methods of cueing recall. If so, we would expect the same overall pattern of results when randomly intermixing trial types: larger suffix location effects on location-cued than feature-cued trials.

Method

Participants

There were 50 participants in this experiment (mean age 22.49 years), all students at the University of York, UK and Universitat Autònoma de Barcelona, Spain.

Materials, Design, and Procedure

This experiment manipulated suffix type (plausible vs. implausible), location (overlaid target item vs. non-overlaid target item), and cue-type (location-cued vs. feature-cued) in a within-subjects design. Control trials in which no suffixes were presented were again included, for both cue types. The experiment essentially involved a combination of procedures from Experiments 1 and 2. There were therefore 192 trials in total, constituting 96 using the feature-cue, and 96 using a location-cue, randomly intermixed. The breakdown of trials for each cue-type was the same as in the previous experiments.

Results

The main aim of Experiment 3 was to establish whether the previously observed patterns of suffix location and identity effects would replicate when trials using the two cueing methods were randomly intermixed. Table 1 summarizes the results in terms of proportion correct, within-display confusions and intrusion errors. We first conducted an omnibus analysis, implementing a 2 (cue type: location vs. feature) x 5 (suffix condition) repeated measures ANOVA on proportion correct rates. This revealed significant effects of cue type, F (1,49) = 8.19, $MSE = .01$, $p < .01$, $np2 = .14$, reflecting slightly better performance in feature-cued recall, and suffix condition, F (4,196) = 43.48, $MSE = .01$, $p < .001$, $np2 = .47$, most evidently reflecting better performance in the absence of a suffix. There was also a significant interaction between cue type and suffix condition, F (4,196) = 2.50, $MSE = .01$, $p < .05$, $np2 = .05$, indicating that the pattern of suffix effects was different for the spatial and feature cue conditions. To explore these patterns, we conducted separate analyses of performance for each cue type, focusing on suffix-present trials.

Location-cue trials

Proportion correct rates in the suffix conditions are displayed in Figure 4 (upper panel). Bonferroni-Holm adjusted comparisons of each suffix condition with the no-suffix control revealed significant interference in each case (implausible non-overlaid, t (49) = 3.40, p < .01; implausible overlaid, t (49) = 5.69, p < .001; plausible non-overlaid, t (49) = 8.48, p < .001; plausible overlaid, t (49) = 7.81, p < .001). Data from the suffix conditions were subjected to a 2 (spatial overlay) x2 (plausibility) repeated measures ANOVA. This revealed significant effects of suffix location, F (1,49) = 10.49, *MSE* = .01, p = .002, *np2* = .18, and suffix type, F (1,49) = 48.00, *MSE* = .01, p < .001, *np2* = .49, similar to those observed in Experiment 1. Once again, the suffix type by location interaction was not significant, F (1,49) = 0.05, *MSE* = .01, p = .82, *np2* < .01. Planned contrasts for each suffix type revealed significant effects of spatial overlay on both implausible, t (49) = 2.14, p < .05, and plausible suffixes, t (49) = 2.21, p < .05.

Error patterns (see Table 1) closely replicated those observed in Experiment 1. A 2x2 ANOVA on within-display confusions revealed an effect of suffix type, F (1,49) = 4.15, *MSE* = .01, p = .04, *np2* = .08, with a slightly higher rate emerging for implausible suffixes, and non-significant effects of location, F (1,49) = 0.91, *MSE* = .01, p = .34, *np2* < .01, and the interaction, F (1,49) = 0.33, *MSE* = .01, p = .56, *np2* < .01. In contrast, analysis of external intrusions revealed significant effects of suffix location, F (1,49) = 18.40, *MSE* = .01, p < .001, *np2* = .29, suffix type, F (1,49) = 61.10, *MSE* = .01, p < .001, *np2* = .55, but not the interaction, F (1,49) = 2.22, *MSE* = .01, p = .14, *np2* = .04.

Feature-cue trials

Proportion correct rates in the suffix conditions are displayed in Figure 4 (lower panel). Bonferroni-Holm adjusted comparisons of each suffix condition with the no-suffix control revealed significant interference in each case (implausible non-overlaid, t (49) = 4.85, $p <$ .001; implausible overlaid, t (49) = 6.73, $p < .001$; plausible non-overlaid, t (49) = 6.85, $p <$ .001; plausible overlaid, t (49) = 6.90, $p < .001$). Data from the suffix conditions were subjected to a 2 (spatial overlay) x2 (plausibility) repeated measures ANOVA. The effect of suffix location was not significant, F (1,49) = 0.46, $MSE = .02$, $p = .22$, $np2 = .009$, nor was the suffix type by location interaction, F (1,49) = 2.31, $MSE = .01$, $p = .13$, $np2 = .03$. There was however a significant effect of plausibility, F (1,49) = 15.95, $MSE = .01$, $p < .001$, $np2 =$ .24, with plausible suffixes again leading to lower accuracy. Planned contrasts for each suffix type revealed no significant effect of spatial overlay on either implausible, t (49) = 1.71, $p =$ .10, or plausible suffixes, t (49) = .52, $p = .61$.

For the error types (Table 1), the overall patterns closely replicated the error patterns observed in Experiment 2. Analysis of within-display confusions revealed no effect of location, F (1,49) = 1.08, $MSE = .031$ $p = .30$, $np2 = .01$, a small effect of plausibility, F (1,49) = 5.19, $MSE = .01$, $p = .02$, $np2 = .09$, with a slight reduction in this error type for plausible relative to implausible suffixes, and no suffix x location interaction, F (1,49) = 0.54, $MSE = .01$, $p = .46$, $np2 = .01$. Corresponding analysis of external intrusions revealed no effect of location, F (1,49) = .1, $MSE = .01$, $p = .74$, $np2 < .01$, a significant effect of plausibility, F (1,49) = 42.04, $MSE = .01$, $p < .001$, $np2 = .46$, and no interaction, F (1,49) = 1.59, $MSE = .008$, $p = .21$, $np2 = .02$.

Discussion

This experiment examined whether the outcomes from different cueing methods in Experiments 1 and 2 would change when they were randomly intermixed, and participants were not aware during the encoding phase how they would be tested. An overall interaction between cue type and suffix condition was observed, indicating that the impacts of the different forms of suffix varied depending on how recall was cued. Further analysis revealed a close replication of the findings from the first two experiments. Thus, suffix plausibility significantly and negatively impacted on both cue types, with error analysis showing an increase in intrusion errors and not recall of false bindings. Suffix location, in contrast, was only reliably influential on trials cued via location. It did not significantly affect performance on trials cued via shape or color; a small numerical trend was observed on implausible suffix trials (as in Experiment 2), but there was no effect at all when using plausible suffixes. Given that cue types were randomly intermixed, this pattern of effects is not attributable to differences in encoding strategies. It seems instead to be non-strategic, indicating a reliable role for location information only when it is explicitly required at the retrieval stage. Finally, we note that, as before, effects of spatial overlay of the suffix were associated with increased intrusion errors, and effects of suffix identity and location did not interact.

General Discussion

This study explored whether location-based interference from to-be-ignored stimuli can be observed in visual working memory for shape-color combinations. Comparison of effects across the three experiments indicates that the spatial location of a to-be-ignored stimulus does mediate interference with representations in memory, but this is only reliably the case when location is a central element of the retrieval task. Thus, effects of suffix location emerged when target recall was cued via spatial location (Experiment 1), but not when recall was cued via shape or color (Experiment 2), and the differential patterns of location-based interference between cueing methods remained when these methods were randomly intermixed within a trial block (Experiment 3).

The observation of significant suffix location effects only on trials that cue via location suggests that the maintenance of color-shape binding over short delays does not always critically require associated spatial information to be intact and accessible. In Experiment 3 in particular, it is clear that suffix location is encoded, as accuracy declines for overlaid targets on location-cued trials. The absence of spatial interference when recall is cued by color or shape undermines the view that any presented item encountered in the same location as a previous stimulus will update (and thus overwrite) the featural and conjunctive information associated with that representation (Kahneman et al., 1992). Rather, it supports and extends the argument proposed by Woodman et al. (2012) that representations in visual working memory are more abstract with memory for the relationship between features such as color and shape not necessarily hinging on spatial location beyond initial encoding.

That memory for spatially overlaid targets only showed reliably greater disruption when recall was cued via location suggests explanations in terms of either the disruption and overwriting of associations between visual features and their locations or an increase in cue overload as a result of stimuli sharing location. Previous observations of location-mediated interference in visual memory may also reflect an emphasis on location placed by the nature of the task, which variously involved judgments concerning the location of intervening items (Fiacconi & Milliken, 2013) or spatially oriented recognition cues (Woodman et al., 2012). It is also likely that the requirement to actively encode stimuli (e.g. Pertsov & Husain, 2013) influences any impacts that are observed. The suffix paradigm is a useful complementary approach that avoids such influences.

Across all three experiments, we replicated the finding that suffixes consisting of features from the experimental set (that are seen as ‘plausible’) are more likely than implausible suffixes to disrupt memory (Ueno, Allen et al., 2011; Ueno, Mate et al, 2011), extending this to the use of dual suffixes and to both feature-cued and location-cued recall tests. Plausibility effects appear to be based on an increase in the recall of features (including those from the suffix) that were not part of the presented set, rather than in confusion between target features. This error analysis also closely replicates previous findings, and fits with an interference account based on automatic overwriting and representational loss (as indicated by outside-list intrusions), rather than non-specific binding errors (within-list confusions).

As previously argued, the reduced effect of 'implausible' suffixes may reflect a feature-based filtering process that helps determine entry into or exclusion from working memory. If the plausibility of a stimulus suffix influences its likelihood of passing a feature-based attentional 'gate' and entering into working memory, then plausible suffixes should be more likely to be represented at location, feature, and object levels, assuming these levels of representation are separate (e.g. Baddeley et al., 2011; Wheeler & Treisman, 2002). If so, suffix effects might be expected to show an identity by location interaction, through either disruption of location coding, or disruption of object representations themselves (if the object level was organized on the basis of spatial location). However, no such interactions were observed across the three experiments, suggesting instead that location and identity are to some extent separate in working memory. One possibility is that location information is processed pre-filter. Thus when suffix items are encountered, their locations may be automatically activated before identity-based filtering is applied. This would be a simple way of capturing the absence of interactive effects, and fits with accounts that assume initial processing of an item's spatial location before its identity (e.g. Huang, 2010; Kahneman, Treisman, & Gibbs, 1992; Shomstein & Behrmann, 2008; Treisman & Gelade, 1980; Treisman & Sato, 1990).

Other types of evidence are broadly consistent with our suggestion that spatial co-location across time is not a critical determinant of what constitutes an object in working memory. For example, it has been suggested that item identity and location may be processed and retained in working memory at least somewhat independently (e.g. Darling, Della Sala, & Logie, 2009; Logie, 1995), and the current findings are in line with this possibility.

Furthermore, Karlsen, Allen, Baddeley, and Hitch (2010) examined memory for shape-color conjunctions when these elements were separated at encoding by a small difference in spatial location or a short temporal delay. Participants made only slightly less accurate recognition judgments than when remembering visually unitized objects and were no more influenced by a concurrent attentional load. These findings suggest that spatial co-location within the environment, while clearly useful, is not a necessary requirement in the encoding and storage of object representations. They point to a more abstract form of *mental co-location,* perhaps represented within the episodic buffer (Baddeley, 2000; Baddeley et al., 2011).

As in our previous work (e.g. Allen et al., 2006, 2014; Hu et al., in press; Ueno, Allen, et al., 2011; Ueno, Mate, et al., 2011), and in line with other research in this area (e.g. Brown & Brockmole, 2010; Logie et al., 2011), articulatory suppression was applied during encoding and retention in order to disrupt and minimize verbal recoding of target stimuli. Effective use of verbal coding in supporting task performance was therefore highly unlikely. Nevertheless, occasional verbal recoding, or activation of lexico-semantic representations associated with targets, may have mediated performance. However, this possibility does not provide an adequate explanation for the outcomes presently observed. Regarding suffix plausibility, this basic effect has been observed with shorter target presentation times (250ms per item; Hu et al., in press) and nameable implausible suffixes (Ueno, Allen, et al., 2011), and the very brief suffix exposure time in the present series of experiments (250ms for two suffix stimuli) makes it unlikely that the observed effects reflect their active verbal recoding, or activation of lexico-semantic representations. Furthermore, it is unlikely that these accounts could provide an explanation for the patterns of spatial overlay effects that were the primary focus of the current study.

In conclusion, the present findings suggest that the spatial location of a new item in the environment is registered in visual working memory, but the extent to which this disrupts existing representations depends on the information requirements of the recall task. This in turn suggests that while the co-location of features such as shape and color are important for defining an object at encoding, these features can nevertheless be maintained independently of the location of the object within the visual field. These findings fit broadly with the notion of visual working memory as a set of abstract and manipulable representations (Woodman et al., 2012), and can be interpreted in terms of a separation between spatial and mental co-location.

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Table 1. Mean accuracy and main error rates for the different suffix conditions in each experiment (with standard error). W-D = within-display.

	No suffix	Implausible Non-overlaid	Implausible Overlaid	Plausible Non-overlaid	Plausible Overlaid
Experiment 1					
Correct	.64 *(.04)*	.55 *(.04)*	.48 *(.03)*	.44 *(.03)*	.37 *(.03)*
W-D Confusions	.20 *(.02)*	.21 *(.02)*	.20 *(.03)*	.20 *(.03)*	.18 *(.02)*
Intrusions	.15 *(.01)*	.22 *(.03)*	.26 *(.03)*	.32 *(.03)*	.41 *(.04)*
Experiment 2					
Correct	.60 *(.04)*	.51 *(.04)*	.45 *(.03)*	.42 *(.04)*	.41 *(.03)*
W-D Confusions	.28 *(.03)*	.33 *(.03)*	.37 *(.03)*	.36 *(.04)*	.31 *(.03)*
Intrusions	.12 *(.02)*	.16 *(.02)*	.18 *(.03)*	.22 *(.03)*	.28 *(.03)*
Experiment 3					
Location-cue					
Correct	.62 *(.02)*	.53 *(.02)*	.48 *(.02)*	.44 *(.02)*	.38 *(.02)*
W-D Confusions	.18 *(.01)*	.19 *(.01)*	.19 *(.01)*	.17 *(.01)*	.15 *(.01)*
Intrusions	.16 *(.01)*	.23 *(.01)*	.26 *(.01)*	.34 *(.02)*	.42 *(.02)*
Feature-cue					
Correct	.62 *(.02)*	.54 *(.02)*	.50 *(.02)*	.46 *(.02)*	.47 *(.02)*
W-D Confusions	.26 *(.01)*	.31 *(.02)*	.34 *(.02)*	.29 *(.01)*	.29 *(.02)*
Intrusions	.11 *(.01)*	.13 *(.01)*	.14 *(.01)*	.24 *(.02)*	.22 *(.01)*

Figure captions

Figure 1. Illustration of methodology, displaying a) presentation procedure, including no suffix, plausible suffix, and implausible suffix conditions, b) location-cueing method (Experiments 1 and 3), and c) color- and shape-cueing method (Experiments 2 and 3). Colors are shown as grayscale, and stimuli are not to scale.

Figure 2. Mean proportion correct (and standard error) in location-cued recall in Experiment 1

Figure 3. Mean proportion correct (and standard error) in feature-cued recall in Experiment 2

Figure 4. Mean proportion correct (and standard error) in location-cued recall (upper panel) and feature-cued recall (lower panel) in Experiment 3

Figure 1

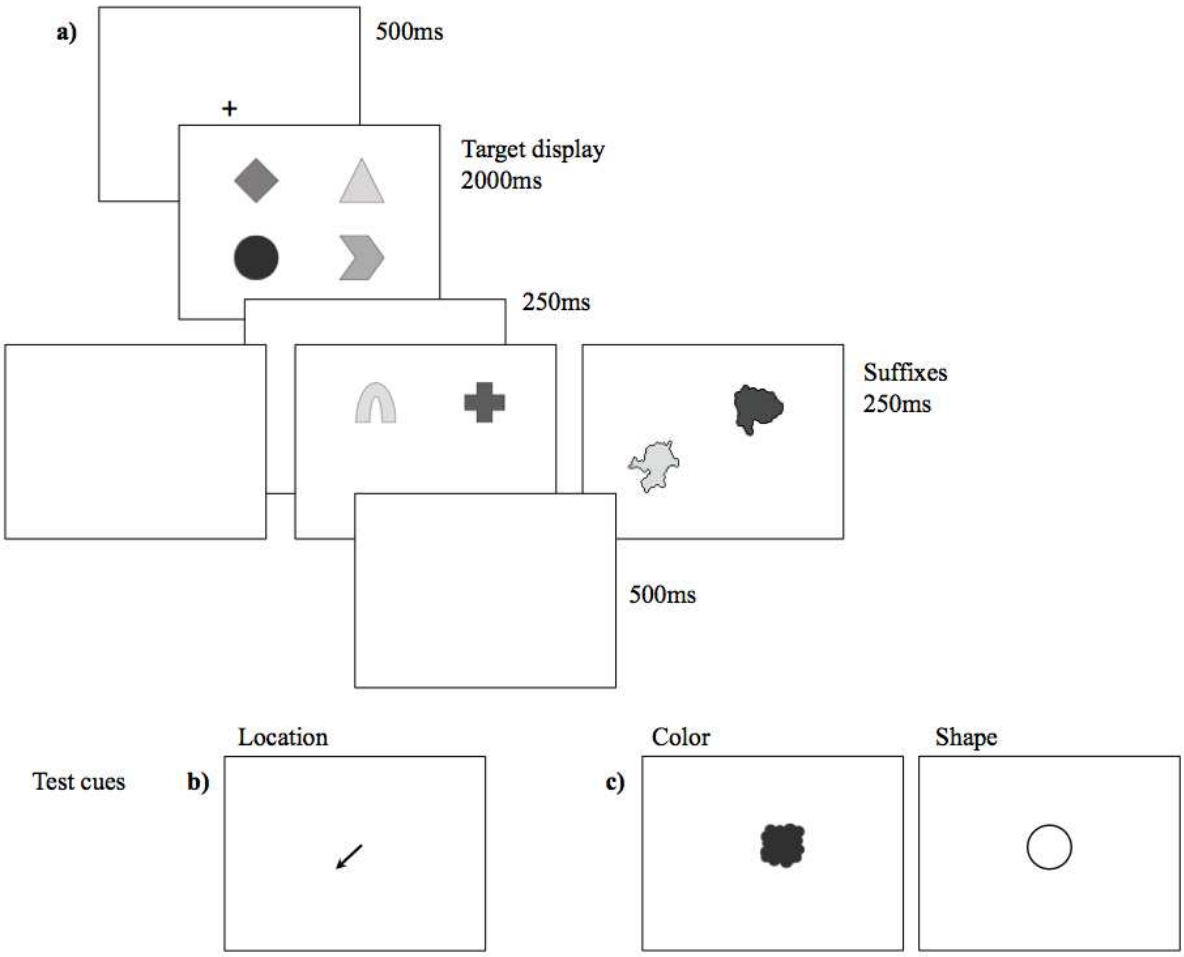
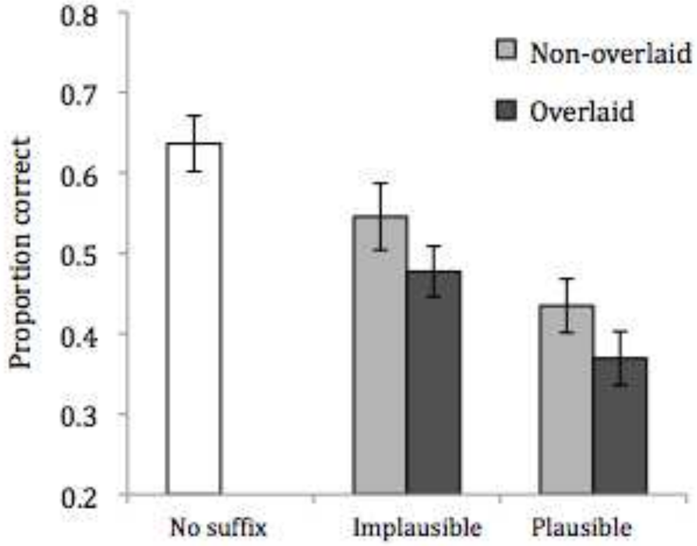
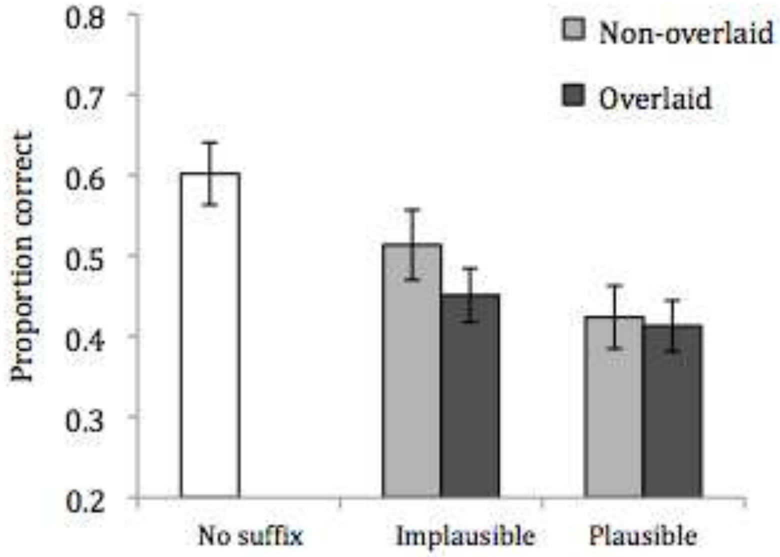

a)
500ms
+
Target display
2000ms
250ms
Suffixes
250ms
500ms
Test cues
b)
Location
c)
Color
Shape

Figure 2



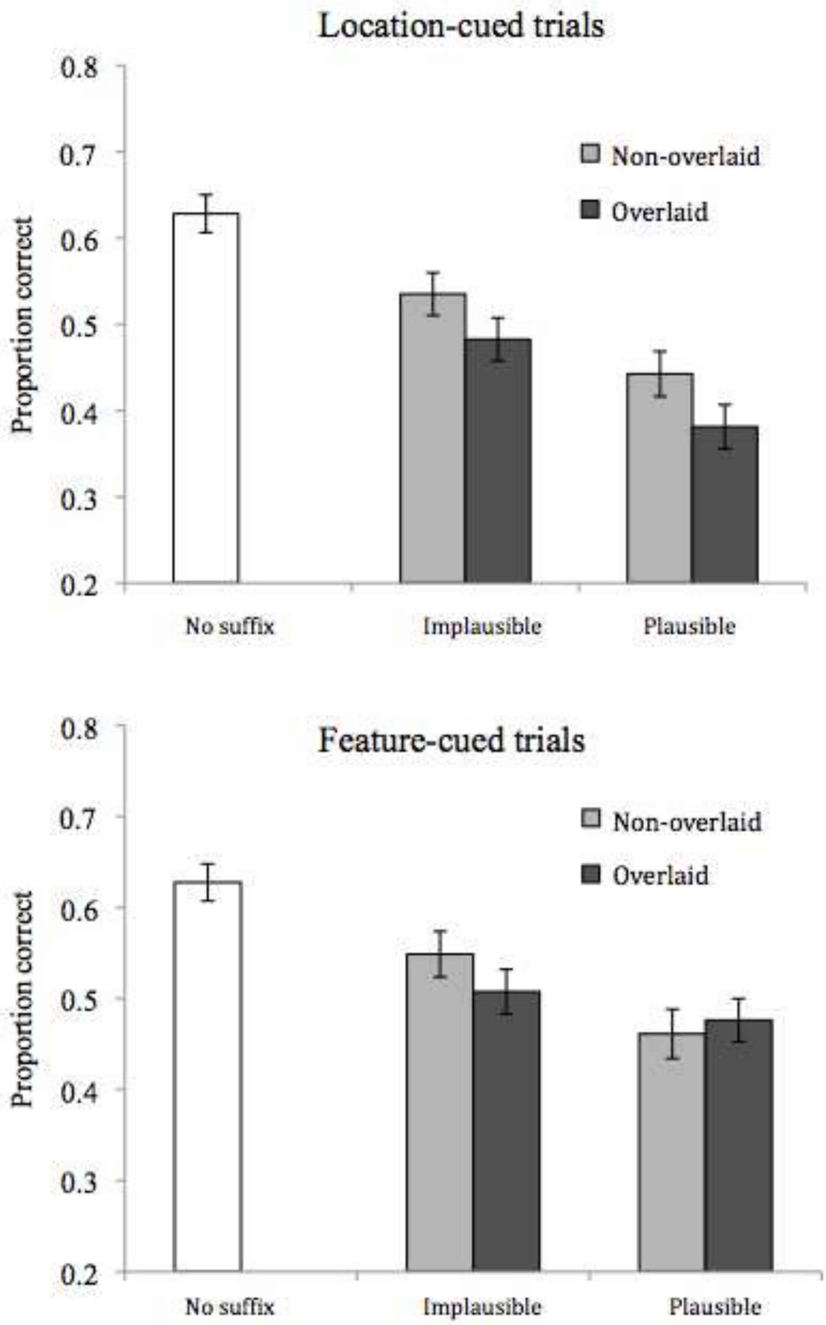
0.8
0.7
0.6
0.5
0.4
0.3
0.2
Proportion correct
Non-overlaid
Overlaid
No suffix
Implausible
Plausible

Figure 3



0.8
0.7
0.6
0.5
0.4
0.3
0.2
Proportion correct
Non-overlaid
Overlaid
No suffix
Implausible
Plausible

Figure 4


Location-cued trials
0.8
0.7
0.6
0.5
0.4
0.3
0.2
Proportion correct
Non-overlaid
Overlaid
No suffix
Implausible
Plausible
Feature-cued trials
0.8
0.7
0.6
0.5
0.4
0.3
0.2
Proportion correct
Non-overlaid
Overlaid
No suffix
Implausible
Plausible