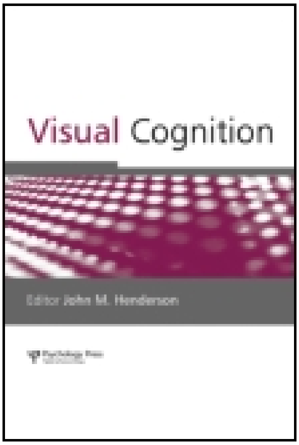

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Correspondence problems cause repositioning costs in visual working memory

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Visual working memory performance often declines when objects are tested in new positions from those they were observed. We report an asymmetry in repositioning costs for orientation compared to colour memory (Experiment 1). Follow-up experiments demonstrated a similar asymmetry for line length memory compared to shape memory (Experiment 2). When different shades of the same colour category were used, however, repositioning costs emerged for colour as well (Experiment 3). Finally, a direct comparison experiment demonstrated an asymmetry for orientation compared to categorical colours, but in a task with no explicit memory demands (Experiment 4). These results challenge previous accounts of repositioning costs, suggesting that they emerge not due to the contents of visual working memory, but naturally because of correspondence procedures that must be executed in order to use a memory to judge the present.

Keywords: Capacity limit; Change detection; Correspondence problem; Visual working memory.

Human visual working memory is critical for a variety of daily activities and it is known to predict myriad outcomes including intelligence and forms of mental impairment (Cowan, 2000; Jarrold & Towse, 2006; Kane & Engle, 2002). Commensurate with its importance, a great deal of research has explored the nature of human visual working memory. The lion's share of this work has focused on the contents of visual working memory, that is what gets stored in memory—bound objects, unbound features, or noisy distributions in feature space, for instance—and how much of it can get

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stored—a discrete number of items, a total amount of information, or an infinite set of items with declining precision, for instance. Vigorous debate surrounds these questions (Bays & Husain, 2008; Luck & Vogel, 1997; Zhang & Luck, 2008). As a result of this intense interest in the contents of visual working memory, another aspect of its mechanisms has been relatively neglected. Namely, we know surprisingly little about the procedures through which a memory is used in order to judge the world faced presently. Both in life and in experimental tasks we do not remember items for the pure sake of it; instead, we use visual working memory in order to eventually make judgements about new observations. Are they the same as those seen before? Is something missing? Has something been added? And so on. Making these judgements requires not only that a memory with some contents is stored, but also some mechanisms for comparing two representations, the one in memory and the one of the world observed. These mechanisms have been taken for granted and left unspecified. As a result, some observations about human performance in memory tasks have likely been attributed to the nature of the contents of visual working memory, when in fact they are due to the procedures involved in comparing memories and observations. In the current study we suggest that correspondence mechanisms are a crucial procedure supporting the use of visual working memory. Correspondence mechanisms support inferences about which objects in memory correspond to which observed objects.

In order to demonstrate the importance of correspondence mechanisms, we explored the repositioning of items between sample and test, a manipulation that is known to impair human change detection performance. In several studies, such repositioning has resulted in costs to performance, and these costs have been taken to reflect the contents of visual working memory and its spatial nature (Jiang & Kumar, 2004; Jiang, Olson, & Chun, 2000; Logie, Brockmole, & Jaswal, 2011). Contrary to these prevailing theories, we suggest that repositioning costs emerge naturally because knowing which items in memory correspond to which of the ones observed is more difficult when items do not occupy the same locations.

REPOSITIONING ITEMS IMPAIRS WORKING MEMORY

Consider the following typical working memory experiment. An observer needs to remember the colours of several observed squares. They all disappear briefly, and when they reappear the observer needs to judge whether one of them has undergone a colour change. It is well known that, as the number of memory items increases, participants become more likely to make mistakes. But now consider a variant of the same task: When the squares reappear they all occupy new and previously unoccupied locations.

What impact will this have on task performance? We will return to this specific question in Experiment 1 for both colour and orientation memory. But first, we consider prior evidence on the role of spatial position in working memory.

Unsurprisingly, the majority of work on the role of spatial position in working memory has considered effects on memory for position itself, in other words, effects on spatial working memory. Jiang and colleagues (2000) conducted a variety of experiments exploring how relocation of nontarget items may influence memory performance for the position of a target item. In their Experiment 2a, for instance, participants memorized the locations of up to 12 squares. After the squares disappeared for 900 ms, participants were required to assess if one of the previous items, a square enclosed by an outline box, had moved or not. This target square was presented under three conditions: (1) in isolation, (2) with all the previously presented items occupying their previously occupied positions, or (3) with all the previously presented items occupying new and randomly assigned locations. By far the worst performance obtained in this latter condition, and the best performance obtained when all the items appeared in the same positions as before. When the nontargets appeared in different positions than originally encountered, the ability to detect a location change was impaired considerably, even when as few as three items were memorized. Generally, Jiang and colleagues interpreted these and related results as evidence that participants automatically encode relative positions and configurations into working memory, leading to impairments when these relative features are disrupted. Thus, their interpretation focuses on the contents of visual working memory.

There is also evidence that spatial repositioning influences memory for object features (as opposed to object locations). Treisman and Zhang (2006, Exp. 3) asked participants to remember feature conjunctions (e.g., red triangle), detecting instances when remembered items swapped features. Performance declined considerably when display items appeared in new and previously unoccupied locations. In other words, memory for feature bindings eroded when object locations were altered between memory and test, which was taken as evidence that feature bindings depend on spatial information. Several studies, including this one, have also looked for effects of spatial position on memory for individual features (as opposed to conjunctions). But these results have been less conclusive, with several studies failing to find effects (Treisman & Zhang, 2006; Wheeler & Treisman, 2002), though at least one recent study did find an effect (Logie et al., 2011). A variety of other kinds of results also point to the importance of spatial features in perception and memory. For instance, we seem to have rapid and automatic access to the spatial layout of a visual scene (Biederman, 1981; Metzger & Antes, 1983; Sanocki & Epstein, 1997), and spatial changes are usually much more easily detected than changes to surface properties such as colours (Aginsky & Tarr, 2000; Simons, 1996). In visual working memory, changes to nonspatial properties usually have a modest or no impact on memory for other nonspatial properties (but see Logie et al., 2011; Vidal, Gauchou, Tallon-Baudry, & O'Regan, 2005). For instance, Jiang and colleagues (2000, Exp. 4) asked participants to judge whether the colour of a target item changed, and then found that turning the colour of all the context items grey (though they were colourful at test) produced only a 7% decrease in accuracy (compared to a condition in which the nontargets remained unchanged), whereas a difference of almost 20% was observed when context locations changed.

REPRESENTATIONS OF CONFIGURATION?

What might explain why changes in spatial context impair performance in memory tasks for target locations and possibly features? Jiang, among others, has proposed that locations and configurations are encoded in a mandatory way into the contents of working memory, accounting for the influence and importance of spatial position in terms of disruptions (or preservations) of these configurations (Jiang et al., 2000; Logie et al., 2011; Vidal et al., 2005). No specific model has detailed the exact nature of a configuration representation—and it is worth noting that configurations must be different for different numbers of items and, of course, depending on their exact spatial arrangement. The same shape cannot be used to remember three items as four, and four items can take on multiple shape configurations, including squares, diamonds, rectangles, trapezoids, and also irregular shapes. A complete theory would need to specify representational formats for different configurations and mechanisms for their acquisition. Thus, to some extent, a configurational hypothesis is fairly unspecific, at present, and able to account for nearly any results.

Moreover, the literature has not been specific with respect to how and why encoding configurations ends up impairing memory performance. In other words, just because a configuration is encoded, performance need not decline when spatial context is altered. Perhaps the operating hypothesis includes some assumptions about how configurational encodings might induce a conflict or compatibility effect when spatial context changes are noticed. But the literature is not clear. Overall, several studies simply argue (Jiang et al., 2000; Logie et al., 2011) that if changing a feature from sample to test has an impact on performance, it should be taken as evidence that the feature is encoded in a mandatory way into the contents of visual working memory.

But drawing such conclusions about the contents of memory is not warranted without first considering whether changing aspects of a test display will have an impact on unavoidable comparison procedures that are used when a memory is consulted to make a judgement. For example, consider again the experiment by Jiang and colleagues (2000) in which participants were asked to judge whether a cued item moved or not. Performance was impaired when the item appeared in a new spatial context than originally observed. In order to accomplish that task, a participant needed to compare a representation of the cued item's position with the position of the newly observed item. But how would a participant know which item in memory corresponded with the cued one? This correspondence was something that the participant had to infer using all the knowledge she stored about the memory display, and evaluating it in light of all the items redisplayed. Surely such inferences fail more frequently when many of the redisplayed items appear in new and random locations. In this experiment, and generally, repositioning may not exert its impact by impairing the ability to judge whether a particular item and a particular memory representation share some feature value (e.g., a position), but instead by impairing the ability to know which memory representation corresponds with a particular observed item. To be sure, human observers very likely describe scenes in terms of configurations and employ such representational formats to their advantage. But the question of interest in the present study is whether configurations are the reason for repositioning costs in change detection. We present a series of results that cannot be explained entirely on the basis of configurations, and which emphasize the neglected role of correspondence procedures in visual working memory.

INFERENCES ABOUT CORRESPONDENCE

The current set of experiments was designed to test a specific hypothesis about the causes of repositioning costs in visual working memory. We suggest that whenever working memory is used to make a judgement about the present, correspondences must be inferred between remembered objects and observed ones. When items are repositioned, these inferences become considerably more challenging since position no longer supplies a source of evidence over which to make the inferences. Thus, when observed items are in the same positions as their stored representations, solving correspondence problems should be relatively easier. In contrast, when items are repositioned from the time they were remembered, the challenge may be severe, potentially accounting for the consequences of spatial rearrangement on memory performance.

One prediction that follows from the theory that correspondence challenges account for effects of spatial position is that spatial repositioning should have a more severe effect in situations where correspondences are especially hard to infer on the basis of properties other than position. But when other properties readily facilitate correspondences, then spatial position should play a less critical role. For instance, in a standard change detection experiment with highly distinct colours, one may detect a change simply by noting that a feature present in memory is absent at test, or vice versa. Thus, one could infer a mismatch in featural correspondences between memory and test without recourse to spatial position. In contrast, if items in memory and at test are relatively similar to one another on a featural basis, then one would not be able to merely note the presence or absence of a feature in order to detect a change. A good spatial basis for knowing which items in memory to compare with which observations could greatly ease this challenge. Consider an analogy. If you need to pick up someone at the airport, and you know only what they look like, finding them in the crowd will depend greatly on how similar they look to individuals in the crowd. In contrast, if you set a definite meeting place, finding your target should be independent of her similarity in appearance to other individuals. In Experiment 1, we explored the effects of spatial position on working memory for two different surface features, one for which we expected easy feature-based correspondences—and thus little or no effect of spatial repositioning—and one for which we expected feature-based correspondences to be very challenging—and thus a substantial impairment caused by repositioning.

EXPERIMENT 1: A COST FOR REPOSITIONING

We contrasted working memory for colour and orientation. In the case of colour, we used a handful of highly discriminable colours and expected that, in a change detection paradigm, participants would not be affected by spatial repositioning since colour categories should not be very confusable. In contrast, precision for orientation is known to be quite low (especially when participants need to remember several items; Bays & Husain, 2008), and so we expected that items with different orientations would be relatively confusable with one another, and, as a result, that working memory performance should decline considerably when items were repositioned.

In every trial, participants observed three coloured boxes, or three oriented black bars. At test, the coloured boxes or the oriented bars reappeared, either in the same exact locations they occupied previously, or in new, previously unoccupied locations. The participants' task was to report whether one of the previously seen objects had failed to reappear and had been instead replaced by a new object (which happened in half of the trials) or not. Figure 1 supplies a schematic depiction of "change" trials. Inspecting the first two rows—the ones depicting colour changes—it becomes

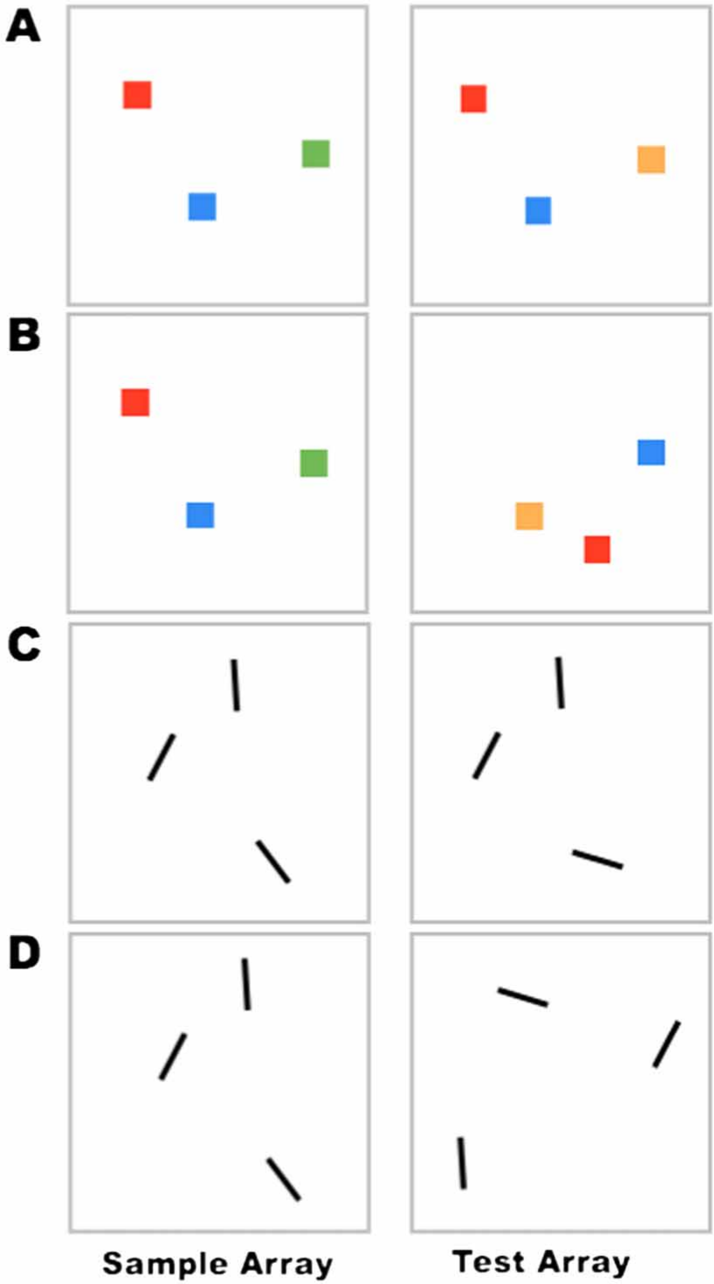

Figure 1. Examples of sample and test conditions in Experiment 1a: (A) Colour/same location, (B) colour/new location, (C) orientation/same location, (D) orientation/new location. To view this figure in colour, please see the online issue of the Journal.

immediately apparent that a yellow item has appeared in the test display, whereas no such item was present in the memory display. This seems to be true even when the test items occupy new locations (Figure 1B). In contrast, inspecting the orientation panels (C and D), it seems far more difficult to find changes when the objects occupy new locations (D). We suggest that this difficulty arises because drawing correspondences between the items in each of the panels is difficult. That is, deciding which item on the left to compare with which item on the right is challenging. As far as such correspondences, a memory task is really not so different from the comparison task the reader just engaged in. One of the panels is simply in memory instead of on the left (indeed, Experiment 4 will make this point directly). Therefore, we predicted that correspondence uncertainty should cause location changes to have a large impact on memory performance for orientation, whereas a relative lack of such uncertainty for colour would result in no impact of location changes in the current experiment.

Method

Participants. Twelve Johns Hopkins University undergraduates participated in this experiment, receiving either course credit or a small monetary compensation. All participants had normal or corrected-to-normal visual acuity. The protocol for this experiment was approved by the Johns Hopkins University Homewood IRB.

Stimuli and procedure. Visual stimuli were displayed on a 21.5-inch iMac running MATLAB 7.6.0 with Psychophysics toolbox (Brainard, 1997; Pelli, 1997). Participants were seated at a viewing distance of 60 cm such that the display subtended approximately $39.56^\circ \times 25.35^\circ$ of visual angle.

On each trial, two arrays were presented, separated by a blank screen (Figure 1). The memory array was presented for 1 s, followed by a retention interval of 900 ms and then the test array, which remained on screen until a participant gave a response. A new trial started as soon as the response was registered. The items were randomly scattered on a grey background, across a $20.4^\circ \times 20.4^\circ$ region, with the constraint that no two items were within 4.8° of each other.

The memory array consisted of either three coloured squares ($0.8^\circ \times 0.8^\circ$) or three oriented black bars ($0.1^\circ \times 1.7^\circ$). The coloured squares were selected at random without replacement from a set of eight different hues (blue, yellow, green, cyan, brown, orange, purple, and red). In the same way, the oriented bars were selected at random without replacement from a set of eight orientations (20°, 40°, 60°, 80°, 100°, 120°, 140°, 160°).

The test array was identical ("no change") to the memory array on 50% of trials, and the colour or the orientation of one item changed on the remaining 50% ("change"). When coloured squares were displayed, the new colour was randomly selected from the remaining hues in the colour set. Likewise, a new oriented bar was randomly selected from the remaining orientations in the orientation set. In 50% of trials, all items maintained their locations between sample and test ("same location trials"). In the other 50% of trials, all items occupied new and randomly assigned locations at test ("new location trials").

We instructed participants to report (by keypress) whether the test array contained a new item. We told them explicitly that the location changes would take place, but that these were irrelevant to the task.

Each participant completed 20 trials for each change condition (change/no change) by location condition (same/new) by feature (colour/orientation), totalling 160 trials.

Analysis. In all experiments we measured performance in terms of A'. We favoured A' over d' since A' is considered a more accurate measure of sensitivity when yes/no paradigms are considered (Donaldson, 1993), and because A' can be applied when false alarm rates are equal to 0, which they were for some of our subjects in some conditions. A' was calculated for each participant in each condition, following the formula by Grier (1971):

$$A' = .5 + (\mathrm{H} - \mathrm{F})^{*}(1 + \mathrm{H} - \mathrm{F})/[4^{*}\mathrm{H}^{*}(1 - \mathrm{F})],$$

In this formula H is the hit rate and F is the false alarm rate. When the false alarm rate was greater than the hit rate, we used the following formula instead:

$$A' = .5 + (\mathrm{F} - \mathrm{H})^{*}(1 + \mathrm{F} - \mathrm{H})/[4^{*}\mathrm{F}^{*}(1 - \mathrm{H})].$$

To compare performance in same versus new location trials as a function of feature, we conducted a two-way repeated measures ANOVA on A' individual means, and all post hoc tests were alpha adjusted with Bonferroni correction.

Results

Mean A' as a function of memory feature and location condition is displayed in Figure 2. Inspection of the data suggests that location changes impaired performance for orientation memory, but not for colour memory. Statistics confirmed these intuitions. We found a main effect of feature type, $F(1, 11) = 207.05$, $p < .0001$, $\eta^2 = .4$, and location, $F(1, 11) = 91.86$, $p < .0001$, $\eta^2 = .25$.

Crucially, the interaction between the two factors was significant, $F(1, 11) = 12.12$, $p < .01$, $\eta^2 = .08$. Regarding the difference between same location and new location trials, we found a significant difference in

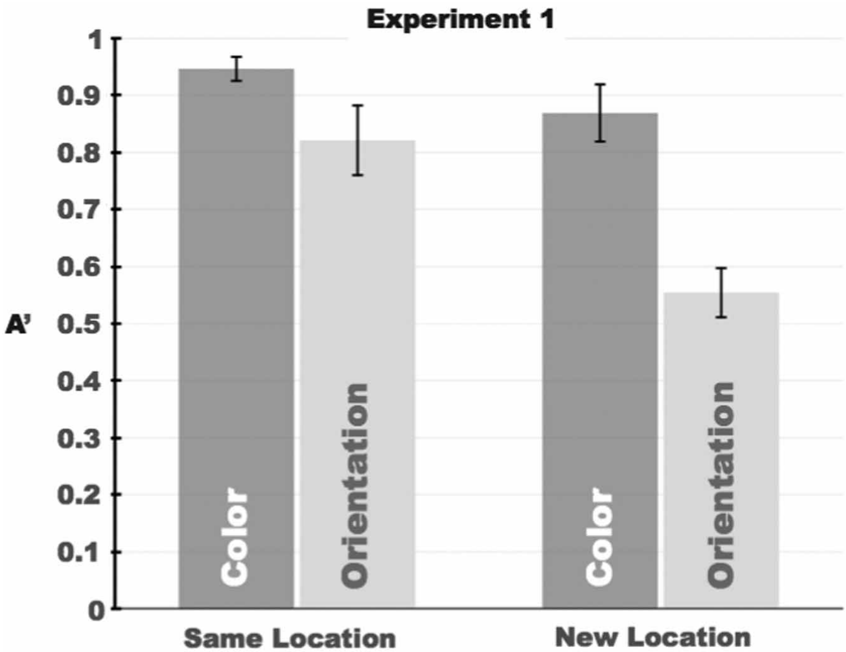

Figure 2. Experiment 1: Mean A' as a function of the type of feature to remember and the location of the items in the test array. Error bars show the standard deviation.

performance when oriented bars were remembered, post hoc test, $t(11) = 6.85$, $p < .001$, $d = 2.52$, but not when coloured squares were remembered, post hoc test, $t(11) = 1.92$, $p = .39$, $d = 0.97$. Testing the items at new locations only made an impact when participants had to remember orientations.

Discussion

In a change detection task, repositioning items after the retention interval frequently impairs working memory performance (Jiang et al., 2000; Logie et al., 2011; Treisman & Zhang, 2006). Indeed, we found that in a very simple memory task, in which only three items had to be retained, identifying memorized orientations became more difficult when the bars reappeared at different locations. However, when coloured boxes were tested, no impairment was observed.

Prevailing theories argue that the effects of spatial relocation on memory performance are due to the storage and use of spatial configurations. But these theories should not predict the observed asymmetry between colour and orientation, at least not without a post hoc accommodation (i.e., that orientation is more "configurational"). We argue instead that the asymmetry arises because location changes preclude the ability to make correspondence inferences on the basis of location, and correspondence inferences are much more challenging when made on the basis of orientation than colour. Simply imagine knowing that a red item was present in one display, and then seeing a red item present in another display, but in a new location; you would know with certainty—at least in the current experiment—that these two are the same item. Now imagine that you saw a 20° bar in a memory display and, moreover, that your representation of that bar includes imprecision with a standard deviation of as much as 10° (a conservative estimate; Bays & Husain, 2008). In the test display there may be several bars that appear to be reasonable candidates for "the same" bar as the one you saw before. We argue that the very large error rate for orientation trials with location changes reveals the impact of such correspondence challenges.

One possible alternative to this account may appeal to a role of verbal encoding in these experiments, perhaps arguing that verbal encoding is more available for colours than orientations. To control for this possibility, we conducted Experiment 1b ($N = 9$, results in Figure 3), which included a verbal shadowing task. At the start of each trial, participants saw a random

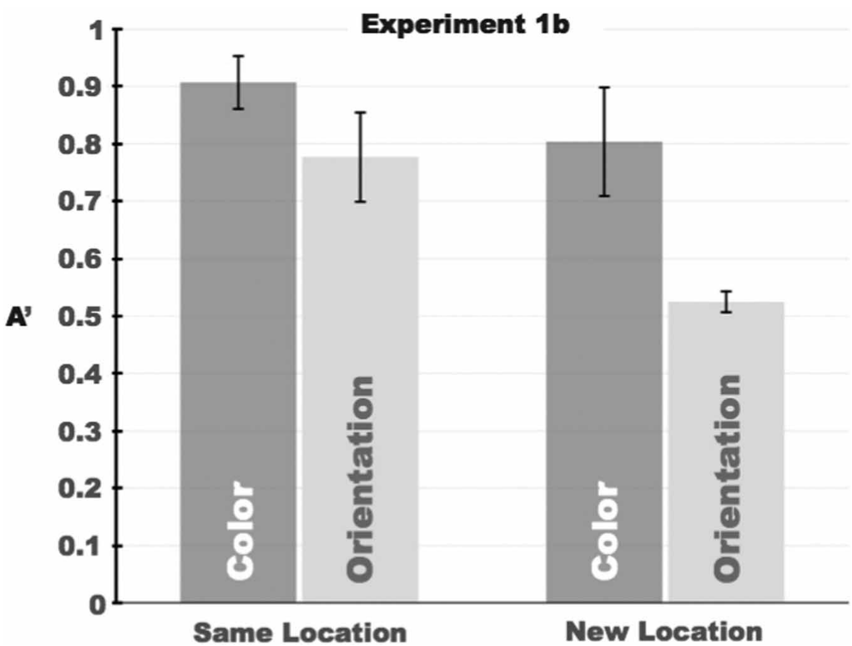

Figure 3. Experiment 1b: Mean A' as a function of the type of feature to remember and the location of the items in the test array. Error bars show the standard deviation.

number between 1 and 90. They then proceeded to count out loud from that number, incrementally, for the duration of the trial until test. After the test display, a second random number was shown, and participants reported whether this number was larger than or greater than the cardinal value at which their counting had ended. The results of this experiment were identical to the results of Experiment 1. We found a main effect of both feature type, $F(1, 8) = 26.12$, $p < .001$, $\eta^2 = .3$, and location, $F(1, 8) = 28.53$, $p < .001$, $\eta^2 = .22$, and a marginal interaction between the two, $F(1, 8) = 4.97$, $p = .06$, $\eta^2 = .04$. There was a significant difference between same location and new location when oriented bars were remembered, post hoc test, $t(8) = 5.34$, $p < .01$, $d = 2.22$, but not when coloured squares were remembered, post hoc test, $t(8) = 2.19$, $p = .31$, $d = 0.7$.

EXPERIMENT 2: SHAPE AND LENGTH

We have so far presented a repositioning cost for orientation memory, but not for colour memory. We have argued that this cost arises from the challenges of making correspondence inferences about test items and memory representations. Having evidenced the finding that motivates the next three experiments, we take a moment, here, to more explicitly explain the logic of our analysis. In any change detection trial, for a judgement to be made, an observer must decide which memory item corresponds with which observed item. In a standard experiment, for instance with identically shaped but differently coloured items (e.g., Luck & Vogel, 1997), optimal logic should lead observers to rely entirely on location to make correspondences, since they know that colour is the feature that may change (and there are no other features that distinguish items). But when locations change, and especially when they change randomly—as they have here—location can no longer supply a basis for correspondences. Now, the changing feature dimension (in this case colour) must be used to make correspondence inferences, and also, of course, to determine if any individual item has changed its feature value. Change detection and correspondence inferences become folded into one especially difficult problem. As a result, repositioning costs may emerge.

Whether they emerge depends on the difficulty of making correspondence inferences on the basis of the available feature dimension. Given noisy representations of orientation (Anderson, Vogel, & Awh, 2011; Bays & Husain, 2008), for example, correspondence inferences should be error prone, leading to repositioning costs. In colour trials, in contrast, repositioning costs did not emerge simply because the colours that we used in Experiments 1—which were always easily distinguishable and selected from a small palette of easily nameable colours—supplied a firm basis for correspondence inferences, even in the face of location changes. A red item in memory, in these experiments, could easily be inferred to correspond with a red observed item, whatever locations each of them occupied. In summary, then, repositioning leads to costs by aggravating correspondence challenges. A perfect storm arises when repositioning takes place and items are easily confusable with one another on the basis of the feature values they occupy. But if they can be readily distinguished on a feature basis, performance may withstand the effects of repositioning.

As further evidence of this perspective, in the current experiment we explored two new object properties for which we expected an asymmetry in repositioning costs. Specifically, in one third of trials we asked participants to detect shape changes. By selecting stimuli from a set of easily distinguishable shapes (squares, circles, etc.), we expected that shape would behave like colour, revealing immunity to repositioning costs. In contrast we expected that line length should behave like orientation, evidencing repositioning costs, because we chose individual line lengths from within a relatively narrow range and with differences between exemplars as small as 20 pixels. As a baseline for comparison we also included colour trials in this experiment.

Method

Participants. Ten new participants were tested.

Stimuli, procedure, and analysis. We used similar methods to those of Experiment 1. Participants had to remember either three coloured squares, three shapes, or three vertical bars. The vertical bars were selected at random without replacement from a set of eight bars with different lengths (0.69°, 0.97°, 1.26°, 1.43°, 1,72°, 2°, 2.29°, 2.58°) (Figure 4a). The shapes were selected randomly without replacement from a set of eight different shapes (Figure 4b).

Each participant completed 20 trials for each change condition (change/no change) by location condition (same/new) by feature (colour/shape/length), totalling 240 trials.

Results

Mean A' as a function of memory feature and location condition is displayed in Figure 5. Inspection of the data suggests that location changes impaired performance for length, but not for colour or shape. Statistics confirmed these intuitions. We found a main effect of both feature type, $F(2, 9) = 31.44$, $p < .0001$, $\eta^2 = .41$, and location, $F(1, 9) = 8.31$, $p = .018$, $\eta^2 = .06$, and a marginal interaction between the two factors, $F(1, 9) = 3.16$, $p = .06$,

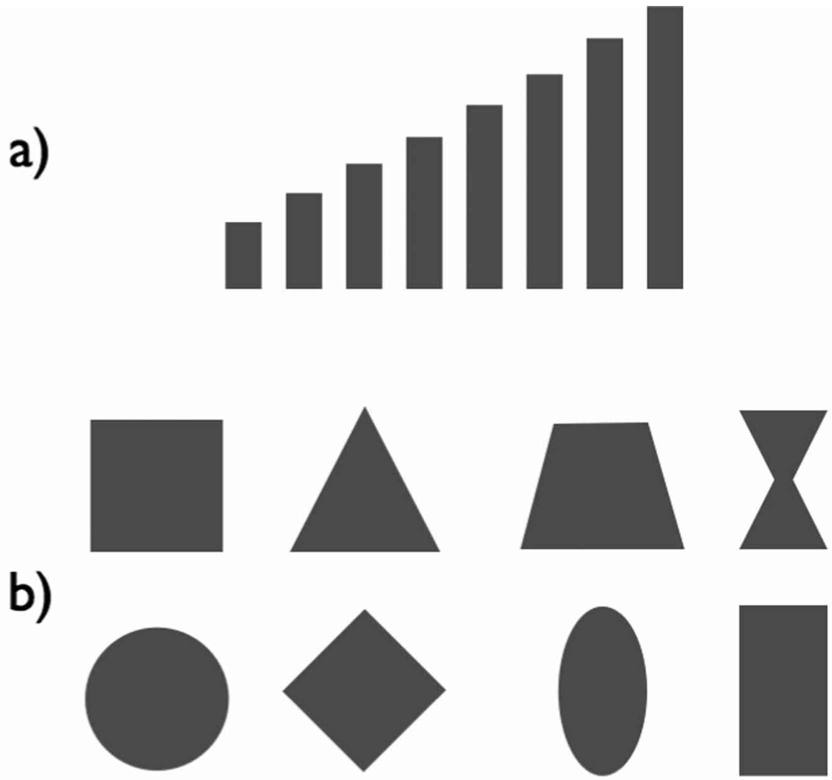

Figure 4. Schematic depiction of stimuli used in Experiment 2 for (a) length (vertical bars) trials and (b) shape (geometric shapes) trials. Stimuli drawn to scale.

$\eta^2 = .04$. Post hoc tests revealed a significant difference in performance between same location and new location trials when lengths were remembered, $t(18) = 3.78$, $p < .05$, $d = 1.2$, but not when the other features were remembered: Colour, $t(18) = 0.6$, $p = .99$, $d = 0.29$; shape, $t(18) = 0.82$, $p = .99$, $d = 0.31$.

Discussion

As in Experiment 1, colour was immune to any repositioning costs in this experiment. As predicted, memory for shape behaved similarly. However, memory for line length evidenced a significant cost, just as memory for orientation did in Experiment 1. We suggest that this was caused by the relative confusability of specific values within the dimensions of length and orientation, contrasted with the ease of discriminating specific exemplars from the shape and colour sets.

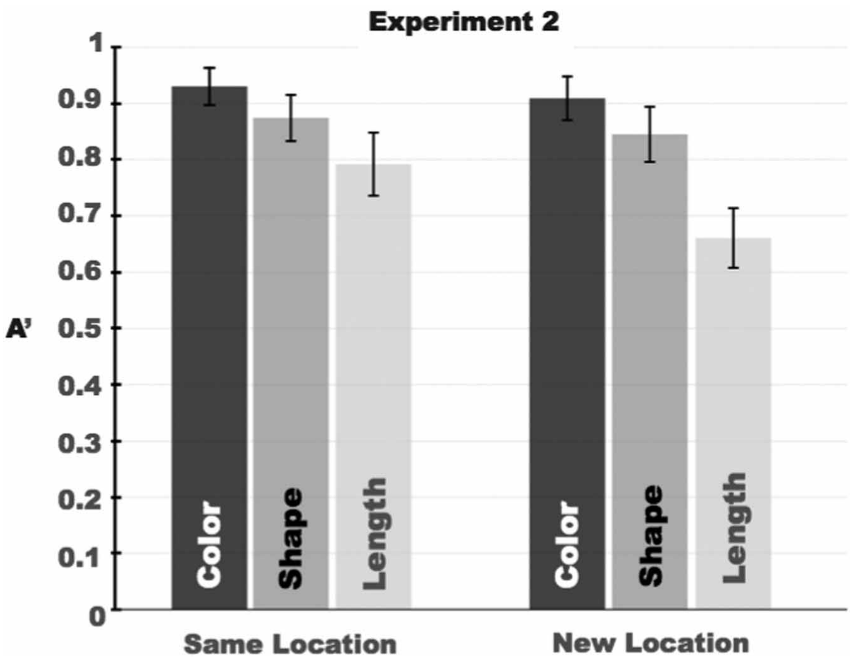

Figure 5. Experiment 2: Mean *A′* as a function of the type of feature to remember and the location of the items in the test array. Error bars show the standard deviation.

We add that this experiment can also be taken as additional evidence against a configurational or relational account of repositioning costs. There are clear differences between feature dimensions, where some evidence costs and some do not. An account of the causes of these costs should make a principled distinction between the features that do and do not incur costs. We have supplied one such principled distinction—namely, is the feature readily used as a basis for correspondence matching? It is not obvious what kind of principled distinction would be pointed to by a configurational account of these asymmetries.

EXPERIMENT 3: A CONFUSABLE COLOUR SPACE

We have argued so far that repositioning costs arise because of errors that emerge when location is rendered unusable as a basis for correspondence inferences. We have also claimed that this perspective helps to explain observed asymmetries in repositioning costs. Costs should only arise when objects' feature values are relatively confusable, making correspondence matching error prone. We have shown this to be the case, for instance, in

Figure 6. Shades of blue (with RGB values) used in Experiment 3. To view this figure in colour, please see the online issue of the Journal.

memory for orientation and line length, but not for easily distinguishable colours and shapes. Crucially, our theory predicts that asymmetries do not reveal inherent properties of feature spaces and their representation, but instead, they arise when the individual feature values used are relatively confusable. Thus, any feature space should evidence repositioning costs if the right feature values from within that space are assigned to sample items. Experiment 3 sought to provide direct evidence of this prediction by demonstrating a repositioning cost for colour memory. In each trial, all the items were blue, but different shades of blue were selected from a set of eight possibilities[1] (Figure 6). We expected to find repositioning costs for colour memory in this experiment since we expected that individual shades of blue provide a less firm basis for correspondence matching than colours from distinctly nameable categories (as in Experiments 1 and 2). As a baseline for comparison, we included trials with the same orientation stimuli used in Experiment 1.

Method

Participants. Nine new participants were tested.

Stimuli, procedure, and analysis. This experiment was identical to Experiment 1, except that in colour trials a new colour set composed of

[1] We thank James Brockmole for suggesting this experiment.

different shades of blue (Figure 6) replaced the previous colour set. (RGB values for each shade of blue are included in Figure 6.)

Each participant completed 20 trials for each change condition (change/no change) by location condition (same/new) by feature (colour/orientation), totalling 160 trials.

Results

Mean A' as a function of feature type and location condition is displayed in Figure 7. Inspection of the data suggests that location changes impaired performance for orientation memory, but, contrary to Experiment 1, also for colour memory. Statistics confirmed these intuitions. We found a main effect of location, $F(1, 8) = 57.41$, $p < .0001$, $\eta^2 = .55$, whereas feature type revealed no significant effect, $F(1, 8) = 0.88$, $p = .38$, $\eta^2 = .01$. The interaction between the two factors was significant, $F(1, 8) = 84.18$, $p < .0001$, $\eta^2 = .08$. Regarding the difference between same location and new location trials, we found a significant difference in performance both when oriented bars were remembered, post hoc test, $t(8) = 18.18$, $p < .0001$, $d = 5.86$, and when coloured squares were remembered, post hoc test, $t(8) = 5.2$, $p < .01$, $d = 0.99$.

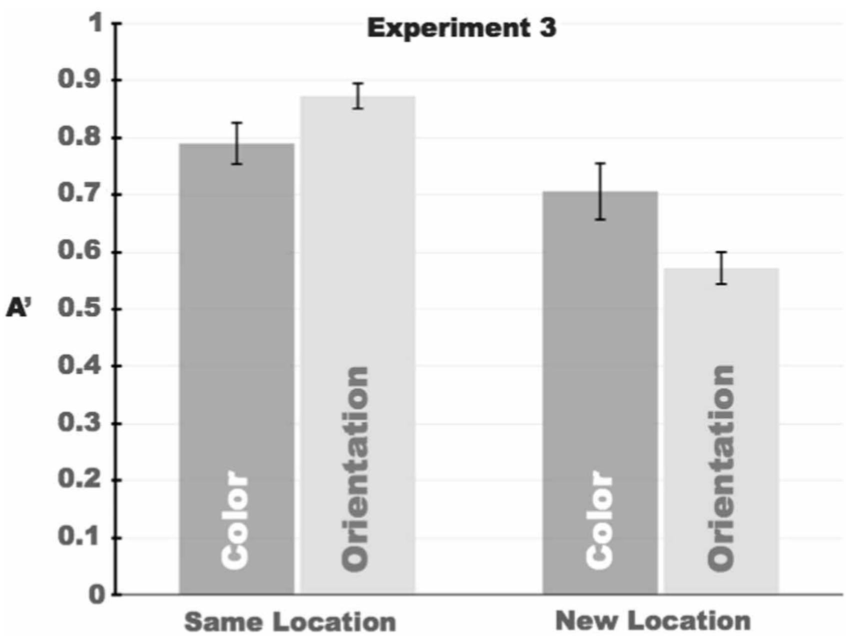

Figure 7. Experiment 3: Mean A' as a function of the type of feature to remember and the location of the items in the test array. Error bars show the standard deviation.

Discussion

This experiment, unlike Experiments 1 and 2, evidenced a repositioning cost for colour. This was because we chose only colours from a single category. Explaining the asymmetry between within category and between category colours should be relatively difficult for any theory that explains repositioning costs on the basis of the contents of visual working memory, for instance a theory that appeals to configurations. The particular feature values chosen should not have an impact on what contents are encoded into memory, at least not without a post hoc accommodation. In contrast, our suggestion that repositioning costs emerge because of correspondence challenges predicts the effects of Experiment 3. We argue that repositioning costs for shades of blue emerged because individual exemplars of blue are relatively confusable with one another, as are individual bars whose orientations may only differ by 20°, but unlike colours that are selected from distinct regions of colour space.

EXPERIMENT 4: DIRECT COMPARISON TASK

We have argued that a loss of accuracy is caused by repositioning items at test, but only when the items are not sufficiently distinct to make direct correspondence matches easily without a spatial anchor. At the core of the argument is the idea that repositioning effects are not really memory effects, but comparison or inference effects. Repositioning items at test does not alter the contents of visual working memory. Instead, repositioning just makes it more challenging to use representations in visual working memory in order to make a judgement about the world faced presently. To directly test this hypothesis, we designed a task in which spatial repositioning should have consequences for a comparison process, but with no explicit memory demands. Specifically, we asked participants to visually examine two simultaneous displays, both containing either three coloured squares or three oriented bars, with the goal of assessing whether the two displays included the same set of items (Egeth, 1966). We predicted that the time necessary to make such a judgement would be longer for oriented bars when they appeared in different relative positions in the two displays (as opposed to the same relative positions). In contrast, we predicted that for colour, relative position differences in the two displays should not have an effect on time to judgement.

Method

Participants. Eight new participants were tested.

Stimuli, procedure, and analysis. This experiment was identical to Experiment 1, with the exception that there was no retention interval between the "sample" and "test" displays. Instead, the two displays were presented side by side on the screen, and participants were instructed to judge, as quickly as possible, whether the two arrays included the same individual items. The displays remained on screen until the participant gave an answer. Response latencies were recorded from the moment the displays appeared until a keypress was made. In half the trials the two displays included all the same items ("no change"), and in half the trials one of the items was different across the two displays ("change"). In 50% of trials, items' relative locations were the same in the two displays (same location). In the other 50% of trials, items occupied different relative locations in the two displays (new location).

Each participant completed 20 trials for each change condition (change/no change) by location condition (same/new) by feature (colour/orientation), totalling 160 trials.

Results

Figure 8 displays response latencies as a function of feature type and location condition. Inspection suggests a large effect of location changes on orientation judgements, but not colour judgements. These intuitions were confirmed statistically. A two-way repeated measures ANOVA on individual reaction time means revealed a main effect of feature type, $F(1, 7) = 509.29$, $p < .0001$, $\eta^2 = .71$, and location, $F(1, 7) = 67.36$, $p < .0001$, $\eta^2 = .07$, as well as a significant interaction between the two factors, $F(1, 7) = 39.19$, $p < .001$, $\eta^2 = .05$. A post hoc test revealed that same location trials produced significantly faster responses than new location trials when oriented bars were compared, post hoc test, $t(7) = -9.59$, $p < .001$, $d = 2.06$, but not when coloured squares were compared, post hoc test, $t(7) = -0.74$, $p = .98$, $d = 0.22$.

Discussion

When asked to directly compare two displays containing oriented bars, participants incurred a reliable latency cost when those bars occupied different relative positions in the two displays. In other words, they incurred the same kind of cost that they did for accuracy in Experiment 1, a working memory experiment. This suggests that the costs in that experiment were not memory costs per se. Instead they reveal that, for orientation comparisons, deciding which of two bars to compare—whether both are currently observed, or one is in memory—is considerably easier when this decision can be made on the basis of a shared location, as opposed to when the decision must be made on the basis of the orientation feature itself.

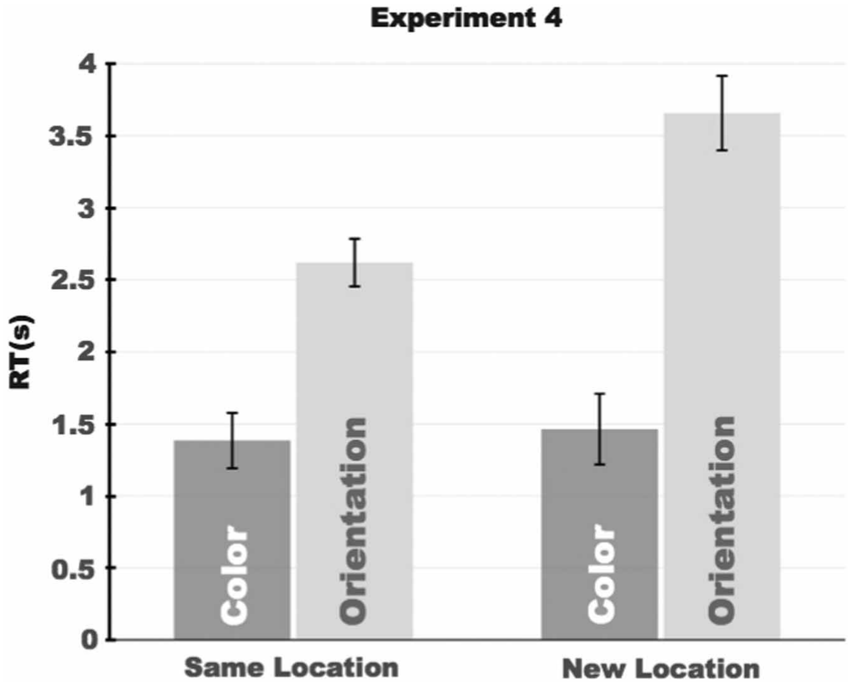

Figure 8. Experiment 4: Mean reaction time as a function of the type of feature to remember and the location of the items in the test array. Error bars show the standard deviation.

Experiment 4 created a task that demanded exactly the correspondence and comparison procedures we argue are necessary in a working memory change detection task, but without the same memory demands. The experiment may well involve some memory demands—participants may store and compare and then store and compare repeatedly until they find an answer. But the demands are not the same as in a standard working memory experiment because participants may choose how many items to store at any given moment or for any given comparison. But the same asymmetries emerged as in the prior experiments. Thus, we were able to isolate correspondence aspects of processing and assign them responsibility for repositioning costs. Given the procedural and stimulus similarity between this experiment and typical memory experiments such as Experiment 1, one should like to explain both kinds of experiments with the same theoretical model. The challenges associated with correspondence inferences supply such a framework.

GENERAL DISCUSSION

The current study sought to explore the hypothesis that repositioning costs in visual working memory tasks emerge by creating correspondence problems for decision making—an inability to know which representations to compare with which observed objects in order to make a judgement. We predicted that if correspondence errors are the causes of repositioning costs, then those costs should only emerge when exemplars within a memory sample are relatively confusable with one another, but not when they are readily distinguishable. Thus, we predicted asymmetries in repositioning costs depending on the set of exemplars used to construct a memory sample. Experiments 1–3 all demonstrated reliable repositioning costs with predicted asymmetries. Specifically, we found costs for orientation memory and length memory, but not for highly distinguishable colours and shapes. However, we did find a cost when we rendered colour less distinguishable, by selecting only shades of blue. Finally, to demonstrate that repositioning costs are caused by the challenges of inferring correspondences, Experiment 4 demonstrated the same costs and asymmetries in a comparison task with no explicit memory requirements. This collection of evidence supports the claim that spatial repositioning costs arise because of the correspondence inferences that one must make when comparing two displays.

Correspondence inferences and repositioning costs in visual working memory

We have suggested that repositioning can create a sever challenge for correspondence inferences, and that this challenge accounts for the costs observed in this study and in related reports (Jiang & Kumar, 2004; Jiang et al., 2000; Logie et al., 2011). Surprisingly, no other study has implicated correspondence inferences in explaining repositioning costs. Yet correspondence inferences are an inescapable step in completing any change detection trial. When items are repositioned, one simply cannot make a change detection judgement without making correspondence inferences. A thought experiment makes this clear. Imagine that, after a sample display disappears, we could print the contents of a participant's visual working memory, and then ask a different observer to use the printout in order to make a change detection decision about the test display. Even if the printout included a perfect, high-fidelity replica of each item in the sample display, the second observer would still need to draw correspondences between items in the printout and the items in the test display in order to compare them and report a summary judgement. The process of assigning correspondences could be error prone. Thus, errors could arise even with perfect memory encoding and storage. In fact, errors may arise independent of the contents of working memory (as demonstrated by our direct comparison experiment). Accordingly, we should not draw any conclusions about the contents of working memory without first accounting for errors that may be caused by correspondence mechanisms.

How might correspondence mechanisms operate in repositioned trials? Mathematical implementations of such mechanisms abound (Doucet, de Freitas, Murphy, & Russell, 2000; Gustafson et al., 2002; Ma & Huang, 2009; Vul, Frank, Alvarez, & Tenenbaum, 2010), but the fundamental issues are as follows. An item must be selected from among memory representations and compared to each new observed item until a high probability match is found. When such a match is found, the next memory item is selected, and that one is compared to the remaining observations. By identifying a pairwise match for each item in memory with one individual in a test display, change detection judgements can now be made. The critical issue that will determine how successful such an operation is—i.e., how accurately it assigns correspondences—will be the distinguishability of items in a sample. When items are highly distinguishable, a high probability match can be assumed to be correct, and the pair of items in any given match can be excluded from further analysis. In contrast, when items are not highly distinguishable, all pairwise considerations should be made in light of all possible pairwise assignments. Doing this to find a mutually exclusive set of pairwise assignments is computationally intensive and highly error prone. Indeed, even for a set size as small as three (as in the current experiments), three different correspondence assignments are possible for each memory item and the set of test items.

This analysis naturally supplies an explanation for observed asymmetries in repositioning costs. Among the features that we tested, only those where inter-item confusability was high were affected, namely, orientation, length, and shades of blue. As we noted, by repositioning items, location becomes unusable as a basis for correspondence, leaving the features themselves as the necessary substrate. For highly confusable features, correspondence mechanisms should fail frequently because the goodness of a match between a memory and test item may be hard to assess, and will often require reference to other possible matches. This is particularly true if the precision of a representation in that dimension is inherently poor relative to the differences between objects. For example, say a person remembers an orientation of about 20° in a sample display. We know from other work that precision in orientation representations can be rather low, and that it may even decline precipitously with set size (Anderson et al., 2011; Bays & Husain, 2008). If the standard deviation of her representation is for example, 20° (conservative by reported estimates at set size 3), what should she think when she observes a test item that is actually oriented at 40°? Whether or not she counts the item as a correspondence for the remembered 20° item should clearly depend on the other items she encounters in that display. Thus, any final decisions about whether a trial includes a change or not depends on which set of correspondence assignments a participant makes, and this in turn depends on the composition of the memory set, as well as on the precision of a participant's representations.

In contrast, if the memory and test sets are made up of highly distinguishable individuals, then correspondence mechanisms should be relatively successful, motivating good change detection judgements. In our colour experiments (apart from Experiment 3), when a red item was remembered, and a red item was observed at test, it was fair for participants to assume that those items amounted to a correspondence match, and then to exclude those items from consideration when evaluating matches among other items.

Also consistent with our findings, correspondence mechanisms should not lead to featural asymmetries when items are not repositioned between sample and test. When items maintain their position, their locations supply a feature-independent basis for making correspondence assignments. In a typical colour memory task, for example, the process might go something like this: "The object in memory at 3,5 is red and the object observed at 3,5 is red as well. But the object in memory at 7,12 is green while the object observed at that location is blue." Crucially, for highly confusable features, such as orientation, the same kind of procedure can apply. Imprecise representations may lead change detection judgements to fail, but they should not have an impact on correspondence judgements. The observer no longer needs to ask, for instance, "which item corresponds to the one I saw at 3,5, before?" She can now simply ask, "Is the orientation I remember at 3,5 the same as the one I see at 3,5 now?"

Finally, two unique predictions emerge by analysing repositioning costs in light of correspondence mechanisms. First, location should not be special. Any feature that uniquely identifies individuals in a scene and remains invariant in a trial can facilitate correspondences and should be used by observers. For instance, if an experiment demanded change detection for colours, but included items with unique shapes that remained invariant over the course of a trial, participants should use shape as an additional basis for correspondence. If shape changed from sample to test, however (i.e., if there were 'repositioning' in shape space), then we would expect a cost associated with this manipulation, since it should produce a cost to correspondence mechanisms. Two previous reports include results which may be consistent with this prediction. In one of several experiments, Vidal and colleagues (2005) found a cost to colour change detection when nontarget items changed shape from sample to test. Similarly, Logie and colleagues (2011) contrasted colour change detection when items either maintained their shapes, or took on new, random shapes between sample and test. They found a cost (at shorter exposures) when shape was not maintained. However, in contrast with our results, these studies did generally find costs to colour performance, whereas we found none for colour. These differences may have arisen because of a variety of other differences between our studies. Specifically, both sets of studies included larger set sizes than we did, and of course, correspondence problems become considerably more error prone with increasing set size (because the number of possible correspondences grows exponentially). And Vidal and colleagues used a cue procedure that may also interact with set size and feature changes. Overall, future work should further explore the role of nonspatial dimensions in correspondence inferences.

The second prediction that arises from an analysis of correspondence challenges is that repositioning costs are not actually memory costs per se. We confirmed this prediction in Experiment 4. In our direct comparison task, participants were asked to directly compare, in full view, images previously used as sample and test displays, determining whether they comprised the same individuals (Egeth, 1966). We observed the same repositioning cost for orientation as in our prior experiments, as well as the same asymmetry with colour, albeit through a reaction time measure. Previous studies have observed repositioning costs in working memory tasks and drawn conclusions about the contents of working memory, the limits on those contents, and the features encoded into those contents in a mandatory way. But of course, in the direct comparison task, one should not appeal to any of these factors to explain the results. The similarity between the direct comparison task and standard change detection begs for a single explanatory framework. Correspondence challenges supply such a framework, moreover, one that begins with first principles. Correspondence decisions are an ineluctable computational step when accomplishing either task.

Are configurations encoded?

Throughout this paper we have argued that repositioning costs arise because of correspondence challenges, and not because of difficulties associated with configurational representations. We want to emphasize that this is not to say that configurations are not, or cannot be stored. Simply, that they are not the causes of these particular kinds of effects. Indeed, considerable evidence supports the idea that we perceive and can report configurations, that configurations can be emphasized or disrupted by task manipulation, and, moreover, an inchoate but quickly growing literature has identified a variety of group-based, or summary-representations that seem to play a role in visual cognition (Alvarez, 2011; Ariely, 2001).

In fact, we must acknowledge that on trials where items are not repositioned, participants may use configurational representations to support correspondence inferences. The issue, however, is not what causes them to perform well when no position change takes place, but what causes them to perform poorly when a change does. If position changes render configurations unusable as a basis for correspondence matching, then the general point remains that correspondence failures are the proximate cause of repositioning costs. Future research should explore the relationship between correspondence procedures and configurational representation.

Imprecision and inference in visual working memory

A recent wave of research has applied a signal detection approach to understanding the limits of visual working memory (Bays & Husain, 2008; Wilken & Ma, 2004). At the core of this research is the idea that there is intrinsic imprecision in the representation of object features, imprecision that results from neural noise. As a consequence, comparing observed and remembered objects amounts to probabilistic inference. This emphasis on imprecision and inference has been very productive in accounting for a variety of phenomena and limits associated with standard visual working memory tasks (Bays & Husain, 2008; Bays, Catalao, & Husain, 2009). We have attempted to apply the benefits of this emphasis to a phenomenon previously described, but not well accounted for, costs to memory performance associated with item repositioning. We suggest that conceiving of visual working memory in terms of imprecision and inference may be the crucial catalyst for understanding performance limits in a variety of contexts under a single explanatory paradigm.

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