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Attention to Attributes and Objects in Working Memory

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Abstract

It has been debated on the basis of change-detection procedures whether visual working memory is limited by the number of objects, task-relevant attributes within those objects, or bindings between attributes. This debate, however, has been hampered by several limitations, including the use of conditions that vary between studies and the absence of appropriate mathematical models to estimate the number of items in working memory in different stimulus conditions. We re-examined working memory limits in two experiments with a wide array of conditions involving color and shape attributes, relying on a set of new models to fit various stimulus situations. In Experiment 2, a new procedure allowed identical retrieval conditions across different conditions of attention at encoding. The results show that multiple attributes compete for attention, but that retaining the binding between attributes is accomplished only by retaining the attributes themselves. We propose a theoretical account in which a fixed object capacity limit contains within it the possibility of the incomplete retention of object attributes, depending on the direction of attention.

Investigators disagree about a fundamental aspect of working memory (WM), namely the nature of capacity limits. Is the capacity best expressed in terms of the number of objects held in mind, or in terms of the number of independently relevant attributes of the objects? If it is the number of objects, does attention additionally play a role in how complete each object's representation is? In recent years, considerable work on these issues has been carried out using versions of the change-detection paradigm described by Phillips (1974) and refined by Luck and Vogel (1997). In this type of procedure, an array of objects is followed by a single probe object or a probe array, to be judged as belonging to the studied array or changed from it. We re-assess the implications of this work for the knowledge of attributes and their binding into objects in WM. Specifically, we address several questions with improvements in methods: (1) whether attending to two kinds of attributes of objects, color and shape, impairs WM of either attribute, despite earlier findings that they do not (Luck & Vogel, 1997); (2) whether memory for the binding or association between attributes amounts to anything more than memory for the two attributes themselves (see Vul & Rich, 2010); and (3) whether attending to the binding draws resources away from memory for the attributes themselves. The answers lead to a revised conception of WM processing and capacity limitations.

New models (developed in Appendix A) are used to assess how many attributes and bindings can be held simultaneously under a variety of different attention conditions, and what the outcome means for models of WM capacity. The methods, variations of the procedure of Luck and Vogel (1997) and a great deal of subsequent work, involve presentation of an array of colored shapes (Figure 1), followed by a mask and then a single-item probe to be judged present in the array or absent from it (Figure 2). The models are

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considered first approximations to actual processing, and departures from the models are used to draw further inferences about processing. We now explain the background of the inquiry into attention effects on information in WM, separately for attributes and attribute combinations.

Attribute Information in WM

Luck and Vogel (1997) proposed that what is stored in WM is integrated objects. In several experiments, they found that performance levels were similar no matter whether participants had to pay attention to one or several attributes[1] of the stimuli at the same time, a conclusion supported by several others (e.g., Luria & Vogel, 2011; Stevanovski & Jolicoeur, 2011). There are, however, other studies that are difficult to understand if the contents of WM are fully integrated objects. In two studies, it has been found that knowledge of the color and orientation of objects in an array are largely independent (Bays, Wu, & Husain, 2011; Fougnie & Alavarez, 2011). Fougnie and Alvarez further showed that this near-independence of color and orientation was not solely the result of mis-binding errors, inasmuch as it persisted after removing trials in which the color of one object was apparently bound with the orientation of another object. They suggested (p. 9) that "representations may sometimes be lost at the object level in addition to the feature level."

If attributes of an object can sometimes fail independently in WM, it should be expected that attention to one kind of attribute should produce better recognition of that attribute than when all attributes are attended, in contrast to the findings of Luck and Vogel (1997). Thus, there is an apparent contradiction in the literature in need of further study. In the present work, we re-examine the effects of attention on the retention of two common attributes of ordinary objects, color and shape. Is attention to both attributes at once detrimental to the recognition of either attribute?

One limitation of previous experiments of this sort is that they did not have as tools models of the number of items encoded into WM. Several models are needed because different task constraints require different logical arguments about the information available to participants (cf. Rouder, Morey, Morey, & Cowan, 2011). Pashler (1988) developed one model for situations in which the probe was a repetition of the array with one possible change, shown in Appendix A (Model 1: Pashler Model). We develop a variant of that model that is more appropriate for procedures in which a single probe is presented centrally (e.g., Allen, Baddeley, & Hitch, 2006; Wheeler & Treisman, 2002); this is Model 2 in the appendix, the Reverse-Pashler Model. Cowan (2001) developed a slightly different model for situations in which the probe was a single object from the array at its original location (Appendix A, Model 3, the Cowan Model). This modeling takes into account in each task how much of responding is the result of chance guessing alone. The models provide estimates of the number of objects for which a particular attribute is stored in WM, which can lead to improved assessments of the effects of selective or divided attention.

Attribute Binding in WM

Another important and related concern that we address is the memory for attribute binding. If a participant retains x colors and y shapes from an array of N objects, then how many

[1]We use the term *attributes* to refer to portions of the information about an object; in our experiments, the attributes are color and shape. We use this term instead of the term *features* because we are not interested in the question of whether our attributes are in some sense rudimentary or indivisible, as some would claim for features. An anonymous reviewer cautioned that the results, especially pertaining to shape, might not generalize to stimulus features that could be described as simple and unidimensional, such as line orientation. Perhaps allaying this concern, though, the superiority in performance for color as opposed to shape in this research was slight, and is mirrored in a study of color and orientation (Woodman & Vogel, 2008).

bindings does the participant know? If the colors and shapes are retained from the same objects, the answer is x bindings. If, however, there is no correlation between the objects from which colors and shapes are retained, the answer is xy/N, which is N times the likelihood that both color and shape are known for a particular object. Here again, however, there is disagreement in the literature. Gajewsky and Brockmole (2006) examined color-shape binding in a recall task and concluded that these bindings endure even when attention is switched away from the objects involved; color and shape recall were correlated. In contrast, Vul and Rich (2010) examined letter-color binding in a five-choice recognition task and argued that binding is nothing more than independent attributes that are retained for the same object by chance.

In our Experiment 1, we re-address this question of how binding information is retained in WM with reference to a type of probe that contains a color and a shape from the array, either correctly combined or newly combined, with the shape from one array object and the color from another (e.g., Allen et al., 2006; Wheeler & Treisman, 2002). We find that a new model of items in WM must be developed especially for this type of binding task (Appendix A, Model 4, the Binding Model).

We address the nature of binding in a different way in our second experiment, by asking whether attending to both color and shape concurrently is tantamount to attending to their binding. Thus, when binding information is required, sometimes new-attribute probes are presented. Performance on new-attribute probes can be compared when attention at encoding is restricted to that one attribute, spread across two attributes, and spread across both attributes and their binding. If remembering bindings requires resources, it should impair memory of attributes compared to when attention is focused on both of the attributes but not their binding.

Methodological Issues

We make methodological contributions to the solution of the issues we have raised, including concerns in stimulus presentation and analysis. A preview of these issues allows a better understanding of our test orientation.

Probe arrangement and models of WM

The type of probe used in a change-detection procedure has implications for the model of items in WM. Pashler (1988) developed a model of WM for a situation in which the entire array was repeated, with or without a change. Although *a priori* one might expect that situation to be simple because one is asked about the identity or difference between two arrays, in practice performance is considerably degraded relative to the use of a single item as a probe (Wheeler & Treisman, 2002). This degradation could come from interference with memory of the studied array by the probe array.

The subsequent model of Cowan (2001) was based on the situation in which the probe was a single object at the location of one array object, with probe attributes that may have changed from the corresponding array object. The logic was that the participant only needed to check that one item in WM. A potential problem, however, is that there is no proof that the participant actually approaches the task in that manner. If each array can contain the same attribute value (e.g., more than one red object in an array) then, of course, individual locations of the attributes must be used to answer the question. In that case, though, items with identical attribute values might be grouped together (e.g., Jiang, Chun, & Olson, 2004). When such repetitions are avoided (e.g., Rouder et al., 2008), participants might actually find it easier to search the entire array for the presence of a particular attribute rather than searching for the attribute at a particular location, given that the latter requires attribute-location binding. That is an empirical question.

The question can be addressed by presenting the probe sometimes at a central location (cf. Allen et al., 2006; Wheeler & Treisman, 2002) and sometimes at the location of a targeted array item from which the probe may have changed. There should be an advantage for items in location rather than at center, if the location information is used. Full evaluation of the central-probe situation requires that a model be developed, our Appendix A Model 2 (Reverse-Pashler Model). In this model, the sameness of the central probe to an array item can be detected, and if no match is detected the participant guesses. This is the converse of the whole-array-probe model of Pashler (1988), in which a discrepancy between the arrays is noticed or the participant guesses; the mathematical models are the same in form, but with hits and false alarms switching roles between the two models.

The central-probe situation also can be used to address the nature of performance when the probe is a recombination of attributes from a studied array item. When the probe is presented at the location of a target item, location information can be used to determine if other attributes are the same (e.g., color-location and shape-location binding information). When the probe is presented at center, though, location information cannot be used. These methods can be compared to determine whether location information is used. Again, a new model is needed and differs from the model for new-attribute trials. For colored shapes, a recombination can be detected if the participant has in WM either the object with the color of the probe or the object with the shape of the probe (again, specific to the situation in which there are no attribute repetitions within an array). An old item only requires the one identical item in WM for detection. We develop and apply the resulting model.

Modeling limitations—Part of the contribution of the present work is the demonstration that different models are logically appropriate for different change-detection procedures and task demands. In order to accomplish this and to explore effects of attention, it was necessary to make some simplifying assumptions. The models all assume that the attribute values (different colors and shapes) were categorically distinct so that the precision of the WM representation of an item, if it was present, was adequate to notice a change to a different value. This is in contrast to other recent work examining the precision of the representations of continuously-varying objects (e.g., Anderson, Vogel, & Awh, 2011; Zhang & Luck, 2008). Our assumption of sufficient precision may not completely hold up for shape stimuli, but in Experiment 2 we show that the consequences of insufficient precision in this study are minor.

We further assume that WM consists of a fixed number of slots, an assertion that has been widely debated in recent research (e.g., Anderson & Awh, in press; Anderson et al., 2011; Bays & Husain, 2008; Cowan & Rouder, 2009; Gorgoraptis, Catalao, Bays, & Husain, 2011; Thiele, Pratte, & Rouder, 2011; Zhang & Luck, 2008). The alternative (after Bays & Husain, 2008) is that WM is a fluid resource that can be spread thinly among an unlimited number of items. This issue cannot be resolved here, though we strongly favor the discrete model given the recent data (see especially Anderson & Awh, Cowan & Rouder, and Thiele et al.). Even if the discrete assumption turns out to be inexact, the formulae are of practical benefit to yield estimates of the number of items in WM in sufficient detail to allow accurate performance in recognition memory tasks.

Finally, when the data depart from the models that we were able to design, these departures are taken as further clues to processing.

Elimination of extraneous memory codes

In our procedure, to eliminate extraneous memory codes, we include a pattern mask after the encoding of the stimulus array but before the presentation of the probe (Figure 2). It is possible that participants could respond to the probe on the basis of a sort of sensory memory information that has lasted longer than the quarter second that is usually assumed (see Cowan, 1988, 1995). To prevent that from occurring, a pattern mask is presented (cf. Saults & Cowan, 2007). Indeed, there is evidence of a "high-capacity, but fragile" visual short-term memory that is disrupted by a pattern mask (Sligte, Scholte, & Lamme, 2008, p. 1), at least after considerable practice (Matsukura & Hollingworth, 2011). Our masking display occurs after a post-array delay assumed to be more than sufficient to allow all of the array items to be encoded into WM, up to the participant's capacity limit (Vogel, Woodman, & Luck, 2006).

Experiment 1

The goal of the first experiment was to examine memory for attribute and binding information across a variety of attention conditions and circumstances to determine whether attributes within objects compete for attention. The natural attributes of color and shape were used, with a limited number of choices for each of these. There were 12 trial blocks that differed in the *probe type* (new-attribute or recombined-attribute), *probe location* (target-location or center-location), and *attention condition* (attend to color, shape, or both).

These variables are logically interrelated. Wheeler and Treisman (2002, Experiment 4B) found no difference between these attention conditions, whereas Allen et al. (2006) found a deficit for dual-attribute attention (but no further deficit for attending to the specific combinations of attributes). These studies, however, based their conclusions on the proportion correct. We re-examined this issue on the basis of the new models of items in WM.

We presented trial blocks with the cue at the target location or a central location in order to understand the use of location as an extraneous cue. For the trial blocks with new-attribute changes, all attention conditions make sense no matter whether the probe is central or at a target's location, but with an additional location cue in the latter case. With recombined-attribute changes, when the probe was at a target's location, attention to just color or just shape still made sense because the task could be accomplished on the basis of the binding between the attended attribute and location. (Only the attended attribute could be inappropriate for the location, belonging instead at a different location.) In contrast, when the probe was centrally located, attending only to color or only to shape made little sense; both color and shape were needed in order to determine whether these attributes were recombined in the probe. Nevertheless, as a check for the effectiveness of our attention instructions, we manipulated attention in this situation too.

Method

Participants—Forty-four undergraduate students (22 male, 22 female) received course credit for their participation. They were native speakers of English.

Design—There were 12 trial blocks that differed in the *probe type* (new-attribute or recombined-attribute), *probe location* (target-location or center-location), and *attention condition* (attend to color, shape, or both). The order of counterbalancing was systematic in a way that made the task easy to explain to participants, by minimizing the number of changes in instructions from one block to the next. Counterbalancing always took place with probe type as the slowest-moving variable, probe location as a faster-moving variable, and attention condition as fastest-moving. For example, a given participant might receive first all 6 recombined-attribute trial blocks and then all 6 new-attribute trial blocks; within each set of 6, first all 3 center-location probes and then all 3 target-location probes; and within each set of 3, first attend-color, then attend-both, and then attend-shape trial blocks. In each trial block, on half the trials the correct answer was that the probe item was present in the array.

Eleven participants received each of the four possible orders defined by the probe types along with the probe locations within each probe type, whereas the selection of the order of attention conditions was randomly determined from six possible orders for each participant, and held fixed within a participant.

Each of the twelve trial blocks began with an instruction screen that included a simple layout of the rules for the block, a visualization of a *same* and a *different* trial, and a short explanation of the type(s) of change that could occur. This was followed by several practice trials (four each for *attend-color* and *attend-shape* trials, and eight for *attend-both* trials), and last the test trials (16 each for *attend-color* and *attend-shape* blocks and 32 for *attend-both* trials). Over the twelve trial blocks, participants thus completed a total of 64 practice and 256 test trials.

Apparatus, stimuli, and procedure—The experiment was conducted by computer in one of two sound attenuation booths, with an experimenter present in the booth throughout the study. Participants were informed that the study would consist of a series of trials, each with a four-object visual array followed by a single probe object, to be judged *the same* as one of the four array objects or *different* from all four in either shape or color (see Figures 1 & 2), by pressing either the `*s*' or `*d*' key, respectively, on a standard keyboard. A trial began with a 1000-ms fixation character (x) followed by a 500-ms presentation of the array to be remembered. Next came a blank interval of 500 ms, followed by a 500-ms visual mask (multicolored squares with colors in irregular patterns, covering each of the four study item's previous locations). The test item was presented immediately after the mask and remained on the screen until a response was recorded, and feedback was then displayed reporting correct or incorrect responding and instructing the participant to press the spacebar key to begin the next trial.

The items presented on each trial were arranged as the four points of a square, their centers separated by 4.2cm on each side, making the full field of view at study 5.6 cm by 5.6 cm (at a typical viewing distance of 50 cm, 6.4 degrees of visual angle). They were selected without replacement on each trial from 7 shapes (circle, square, triangle, star, a simple concave shape [resembling an hourglass], a simple convex shape [resembling an eye], and a cross [i.e. a mathematical `plus' sign with thick lines]) and from 7 colors (white, yellow, blue, green, magenta, red, and black, on a grey background). All shapes had the same maximum height and Working Memory for Features and Objects, Page 13 width as the 1.4-cm square mask.

Probe type and probe location together defined the nature of the stimulus presentation (Figure 2). The study phase of the experiment was unchanged throughout all conditions but at the beginning of each trial block, participants were made aware of the rules of a possible *different* item at test. For the new-attribute probe type, participants were informed the test item, if *different*, would possess a new characteristic not previously seen in the four item study phase. For the recombined-attribute probe type, the test item, if *different*, would be a new combination of a color and shape already seen in the studied array. Within each probe type, for target-location probe trial blocks, the probe appeared at one of the four original study-item locations and was either identical to that item or differed from it in one attribute.

For the center-location probes, the probe appeared at the center of the display and was identical to one item or different from all of them.

Within each of these four stimulus conditions, there were trial blocks requiring attention to color, shape, or both. Although the attention condition was applied in the same way regardless of the stimulus condition, there were implications that differed according to the stimulus condition, as follows. (1) In the new-attribute condition, regardless of the probe location, the probe contained at most one attribute not present in the studied array, always an attended attribute. (2) In the recombined-attribute condition with target-location probes, if color was attended, then the shape was always correct for its location, whereas the color could be correct for its location or could come from a different studied location (on *different* trials); vice versa if shape was attended. If both attributes were attended, then either attribute could change from the probed location in the array, but at most one attribute did change. (3) Finally, in the recombined-attribute condition with center-location probes, there was only one possible kind of *different* trial, the incorrect combination of color and shape from two different array objects. In this condition, attention to only color or only shape was incompatible with successful performance, even if the instructions encouraged it.

Results

Proportion Correct—The means in every condition of the experiment are shown in Table 1. We carry out most analyses on the measures of items in WM but an exception is cases in which a model-free comparison is preferable. One model-free issue is whether the location of the probe makes a difference. In one ANOVA, target-location and central-location probes were compared, in each case including as another within-participant factor the seven conditions from attribute-change trial blocks (change and no-change trials from attend-color and attend-shape trial blocks; color-change, shape-change, and no-change trials from attend-both trial blocks). The probe location made no difference, $F(1,43)<1$. Another analysis was conducted on the attribute-combination trial blocks with both attributes attended, comparing the three conditions with a target location of the probe (color change, shape change, and no change) to the same three conditions with a central location. Again, the location of the probe made no difference, $F(1,43)<1$. This equality casts doubt on the premise that participants use location information to carry out just one decision, which would supposedly be more efficient than comparing the probe with the entire array.

Given that, for attribute-recombination trials, the central probe made it impossible to attend to just one attribute and still do the task, these trials were run only for completeness of the design (footnote *a* in Table 1), but they also can serve as a manipulation check to determine whether participants attempt to obey attention instructions even when doing so is not strategic. Performance in this condition was indeed impaired by the instruction to attend to only one attribute as opposed to both attributes (see Table 1), $F(1,43)=8.18$, $p<.01$ in a planned comparison, $p<.01$, indicating diligent following of instructions rather than optimization of strategies.

Items in WM

Identifying the nature of processing: Given that color and shape in the divided-attention condition shared the same no-change trials, errors in no-change trials could occur because of suspected differences in color, shape, or both. Therefore, it was not possible to assess items in WM separately for color and shape in this experiment (a limitation that will be overcome in Experiment 2) and we collapsed accuracy across color and shape in the estimates that were used.

The first step in the analysis of items in WM was to assess once more the use of in-location information. For trials with the probe at the location of a target, when the participant watches for a change to a new color or shape (or both), the model of Cowan (2001) was based on the notion that the search of WM is restricted to the item probed. If so, there should be some benefit of this kind of probe compared to a central probe, which requires that the entire array be searched. On the other hand, the single-item memory search requires knowledge of the location of the attributes to be searched, whereas an entire-set search only requires that the attributes of the set be retained (given that there were no repetitions in the array, to avoid grouping; cf. Rouder et al., 2008). Do participants retrieve the correct location-color and/or location-shape binding of the probed item, or do they simply search for the attribute(s) of the probe among all array items without regard to location? We carried out an analysis of trial blocks with new-attribute changes using the Cowan (2001) model (Appendix A, Model 3) for target-location probes and the Reverse-Pashler model (Appendix A, Model 2) for centrally-located probes and found that the estimate of items in WM was higher for centrally-located probes (M=2.80, SEM=0.10), than for target-location probes (M=2.50, SEM=0.10), $F(1,43)=7.66$, $p<.01$, $\eta_p^2=.15$. There is no good explanation for this direction of difference unless the Cowan (2001) analysis is incorrect; there should not be fewer items held in WM when the probe is presented at the location of the target. When we use the Reverse-Pashler model for both central and target-located probes, though, the inferiority of target-located probes is abolished, $F(1,43)=1.70$, n.s., with a slightly higher mean for target-located probes. The working assumption we make therefore is that the entire array was searched in this experiment, for new-color and new-shape change situations regardless of the location of the probe. We thus use the Reverse-Pashler model (Appendix A, Model 2) for all new-attribute change trial blocks, and the binding model (Appendix A, Model 4) for attribute-recombination trial blocks.

New-attribute analysis: The new-attribute analysis of items in WM, with the type of probe (center or target) and attention (one or both attributes) as factors yielded only a main effect of attention, $F(1,43)=10.84$, $p<.01$, $\eta_p^2=.20$. Attention to one kind of attribute resulted in knowledge of 3.02 objects (SEM=0.10), whereas attention to both kinds of attributes resulted in knowledge of the probed attribute of only 2.72 objects (SEM=0.09). Thus, there is an attention cost to being held responsible for both kinds of attributes. The effect of the location of the probe did not approach significance, $F(1,43)=1.72$, n.s.

Target-location analysis: This analysis included estimates of items in WM for trial blocks with a target-location probe, with the type of change (new-attribute or attribute-recombination) and attention (one or both attributes) as factors. The result was a very large advantage for new-attribute changes (M=2.94, SEM=0.09) over attribute-recombination changes (M=1.40, SEM=0.07), $F(1,43)=239.01$, $p<.001$, $\eta_p^2=.85$. There was also once again an advantage for attention to one attribute (M=2.29, SEM=0.08), over attention divided between two attributes (M=2.04, SEM=0.07), $F(1,43)=12.21$, $p<.01$, $\eta_p^2=.22$.

The reason why new-attribute detection capacity estimates are much higher than attribute-combination capacity estimates, despite similar proportions correct in the two cases, has to do with the modeling assumption about what information can contribute to performance in our procedure. For new-attribute changes, only knowledge of the probed object is assumed to be relevant. For attribute-combination changes, knowledge of two objects is directly relevant. Specifically, the change can be detected if color-shape binding is known for either the object with the same color as the probe, or the object with the same shape as the probe. The absence of a proportion-correct advantage for attribute combinations despite the relevance of more objects per trial is what produces the lower capacity estimate for bindings compared to the new-attribute condition.

Probe location effect for attribute-recombination trials with dual attention: Although we have excluded trial blocks from our manipulation check of attention with centrally-located probes for attribute-recombination trials, we can examine the effect of probe location for trial blocks in which attention was to be spread across the two needed attributes. As was the case for new-attribute trial blocks, the items in WM with a central probe, M=1.41, SEM=0.11, were not significantly different from those with a target-located probe, M=1.25, SEM=0.10, $t(43)=1.39$, n.s.

Discussion

The experiment leads to a better evaluation of testing procedures, an initial comparison of item and binding information in WM, and an initial reassessment of effects of dividing attention between attributes. These will be discussed in turn.

Evaluation of testing procedures—This experiment has led to several important conclusions. First, it illustrates the limitations of various testing procedures. Most importantly in this regard, it suggests a limitation in the use of a method in which the probe is placed in the location of a target item. Specifically, for new-attribute change tests, it cannot be taken for granted that participants will restrict WM search to a single location as expected; that restriction requires binding of attributes with locations. At least, there was no evidence of a benefit from restricting search in this way in our procedure, and assuming that search is restricted in this way led to a significantly *smaller* estimate of items in WM with a probe in target location.

Search would have to be restricted to a single location if a target color occurred more than once in the same array. That kind of stimulus procedure, however, seems undesirable as it would make necessary encoding of the binding between the attribute in question with a location feature, and it also allows grouping between items in an array (Jiang & Chun, 2004), reducing the number of independent chunks to be recalled in a way that would require an extra parameter in the model to express the likelihood that array items that are identical on a relevant attribute are perceived as a single chunk (cf. Cowan, Rouder, Blume, & Saults, in press).

Another potential limitation of placing the probe in a target location occurs for attribute-recombination tests. The test for binding between attributes could be solved instead by jointly combining each attribute with its location (i.e., color-location and shape-location information used jointly). Placing the probe in a target location did not result in more items in WM than placing the probe in a central location, though, suggesting that any such strategy had little or no advantage.

One possible disadvantage of a centrally-placed probe, on the other hand, is that the probe must be compared to all items in the set, not just one item. There is a potential cost of multiple decisions (e.g., Palmer, 1995; Woodman & Vecera, 2011). Fortunately, the mathematical models of items in WM were designed with that processing mode taken into account (as was the model of Pashler, 1988). Also, the absence of repetitions within the arrays in the present procedure limits the chance of confusion or grouping; for example, there were no trials with a red square at one location and a red circle (or a green square) at another location. Given that there was little or no advantage of placing the probes at target location despite any drawback of the centrally-placed probes, overall the data suggest to us that a central probe may be the best probe placement, especially when the experimental goal is to include attribute-recombination trials to be compared to new-attribute trials. It is the placement we use exclusively in Experiment 2.

Item and binding information—The results clearly showed that the number of objects for which individuals could retain attributes was greater than the number for which they could retain attribute bindings. This difference should be viewed cautiously, though, inasmuch as it was necessary to collapse the data across color and shape because they shared the same no-change trials in the dual-attention condition, making it impossible to judge the memory strength separately for color and shape attributes. It is possible that binding memory is no worse than the attribute with the lower performance, which appears to be shape (see Table 1). Information about color and shape separately will be obtained in the second experiment, and it will therefore be possible to gain more detailed information about the difference between item and binding information in WM.

Effects of attention—The data clearly showed that there was an effect of dividing attention between attributes on the ability to retain any one attribute in WM. However, according to the new models of items in WM, the decrement in performance amounted to no more than about .2 to .3 items for each attribute. One way to understand the small magnitude of this effect is to assume that, most of the time, attention to an object in order to encode one attribute (color or shape) automatically resulted in the encoding concurrently of the other attribute. (This would have occurred for roughly 2.7 to 2.8 items on average). Making one attribute irrelevant allowed the relevant attribute to be encoded for approximately .2 to .3 additional items. There are many ways this could occur. As just one example, attention to only one attribute could allow participants to notice a spatial configuration of this attribute, a kind of new multi-item chunk formation. No matter how it occurs, this extra amount of information retained when only one attribute is task-relevant turns out to be a relatively small but significant factor in performance.

Experiment 2

The first experiment employed a typical divided-attention procedure, but that procedure does not distinguish between effects of attention at encoding versus retrieval. For new-attribute trial blocks, the retrieval task for divided attention differed from the task in focused attention, inasmuch as the participant needed to search for two kinds of changes at once (color and shape changes). In the attribute-recombination trial blocks, attention always necessarily included color-shape bindings at both encoding and retrieval if the task was to be performed successfully (with the possible exception that with probes in a target location, attention could be directed to color-location and shape-location binding).

In Experiment 2, a new method was used to learn whether the effects of dividing attention occurred during encoding or retrieval processes. On each trial, a verbal cue indicated which attribute change was possible: *color*, *shape*, or *color-shape combination*. This allowed the presentation of trial blocks in which the type of test was not known until the test probe was presented. In *attend-color* trial blocks, only color test probe trials occurred, and in *attend-shape* trial blocks, only shape test probe trials occurred. In *attend-both* trial blocks, both color and shape probes could occur but, at the time of test, it was made explicit which of these attributes could change. Finally, in *attend-combination* trial blocks, test trials included color, shape, and combination trials but the participant did not know until a probe was presented which information would be probed. Because of this arrangement, we could compare the same color (or shape) retrieval probes with three levels of attention at WM encoding: attention to the corresponding single-attribute, attention to both color and shape, or attention to the specific color-shape combinations.

If the effects observed in Experiment 1 occur during encoding into and/or maintenance of items in WM rather than during retrieval and response operations, then dividing attention between color and shape at encoding should reduce the number of objects with color (or

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shape) in WM, compared to the single-attribute color (or shape) condition. This second experiment allows the further question, which Experiment 1 could not address, of whether attention to bindings draws resources away from the entry of attributes into WM.

A benefit of this new method is that it provided change and no-change trials specific to each test probe situation, making it possible to examine separately the number of colors and shapes encoded into WM even in the dual-attention situations (see also Wheeler & Treisman, 2002). Until now this kind of information has not been used to support an explicit model of items in WM.

Although it is theoretically possible to test for a level of detail beyond what was encoded (e.g., asking for attention to color alone but probing the color-shape combination on such a trial), we omitted such conditions so that our instructions would be believed.

Method

The final sample of participants included 29 native speakers of English (15 female) who received course credit for their participation.

The displays on each trial were identical to the central-probe conditions of Experiment 1 except that each probe object had written just underneath it what kind of change may have occurred (i.e., *color?*, *shape?*, or *combination?*). The task was to indicate by button-press whether the change had occurred (*change* trials, with the response key marked *d* for *different*) or not (*no-change* trials, with the response key marked *s* for *same*).

There were attend-color, attend-shape, attend-both, and attend-combination trial blocks. For each trial block, the instructions indicated what kind of information might be needed on a particular trial, and examples of the possible kinds of probes were presented. The trial blocks were presented in an order that was randomly determined for each participant. In each trial block, on half the trials the correct answer was that the probe item was present in the array.

After the explanation of the kinds of changes that could occur in the trial block, with illustrations, the attend-color and attend-shape trial blocks each continued with 4 practice trials (compared to the studied arrays, 2 change and 2 no-change trials); the attend-both trial blocks continued with 8 practice trials (2 color change, 2 color no-change, 2 shape change, and 2 shape no-change); and the attend-combination trial blocks continued with 16 practice trials (4 binding change, 4 binding no-change, 2 shape change, 2 shape no-change, 2 color change, and 2 color no-change).

The test trials in the color, shape, both, and combination trial blocks included 32, 32, 64, and 128 trials, respectively, distributed in the same ratios as the practice trials at the beginning of the block.

Results

Proportion correct—Table 2 shows the proportion correct scores for all conditions. The accuracy was in a range comparable to Experiment 1. The comparisons carried out with proportion correct in Experiment 1 do not exist in Experiment 2, and the analyses are conducted in items in WM.

Items in WM

Attribute vs. binding information: The estimates of items in WM are again based on the models shown in Appendix A (the Reverse-Pashler model, Model 2, for color and shape change probes and the binding model, Model 4, for combination probes). The results are shown in Figure 3. A set of planned comparisons was conducted to compare color-shape combination probes (rightmost bar in the figure) to all of the other probe types. The number of color-shape bindings in WM was smaller than the number of colors or shapes in WM in any other condition, p<.001 in all six comparisons.

Attribute and attention effects: The remaining conditions were analyzed in a within-subjects ANOVA with two factors: type of probe (color or shape) and the attention condition at encoding (single-attribute, dual-attribute, and color-shape combination). This analysis produced two main effects and no interaction. First, the number of colors retained, M=2.66, SEM=0.14, exceeded the number of shapes retained, M=2.30, SEM=0.14, F(1,28)=7.17, p<.05, η_p^2=.20.

Second, the number of objects for which the tested attribute, color or shape, was retained with attention to only that one attribute, M=2.91, SEM=0.14, was greater than with attention to both color and shape concurrently, M=2.31, SEM=0.18, or with attention to the specific color-shape combinations, M=2.22, SEM=0.15, F(1,28)=9.49, p<.001, η_p^2=.25. Newman-Keuls post-hoc tests confirmed that the single-attribute attention condition mean was significantly higher than the attend-both or attend-combination conditions, which did not differ. The interaction term did not approach significance, F(2,56)=1.20, p=.31, n.s.

The advantage for single-attribute attention was numerically larger in this experiment than in the previous experiment, but a cross-experiment analysis showed no interaction of attention with experiment, F(1,71)<1.

Derivation of bindings from attribute WM: We carried out an additional analysis of the data from this experiment to determine whether two assertions in the literature can be reconciled. First, it has been asserted that divided attention does not impede memory for bindings any more than it impedes memory for attributes (Allen et al., 2006; for further support see Allen, Hitch, Mate, & Baddeley, in press). Second, it has been asserted by Vul and Rich (2010) that the objects for which one attribute is encoded are independent of the objects for which another attribute is encoded. These two statements could be compatible inasmuch as divided attention would then be able to interfere with the encoding of binding information only indirectly, by interfering with the encoding of the attributes needed for the binding test.

If the assertion of Vul and Rich (2010) is correct, then one can predict that if the proportion of colors in WM is x and the proportion of shapes in WM is y, then the proportion of bindings in WM is xy. If the assertion of Vul and Rich (2010) is correct, then one can predict that if the proportion of colors in WM is x and the proportion of shapes in WM is y, then the proportion of bindings in WM is xy. This calculation requires the assumption that each feature is associated with the correct object file (or location), so that the proportion of objects for which both color and shape are encoded is the product of the independent proportions of colors and shapes encoded. For example, if colors were encoded for 3/5 of the objects and shape were encoded for 2/5 of the objects, the prediction would be that 6/25 of the objects would include the information needed to notice a binding change.

Given our 4-item arrays, $4x$ colors and $4y$ shapes in WM leads to the prediction that there are $4xy$ bindings in WM. We calculated the prediction for every individual based on the attribute WM results in the attend-binding trial blocks (Figure 3, third and sixth data bars). The mean prediction, 1.32 bindings (SEM=0.17), is slightly, but not significantly, higher than the obtained result, 1.05 bindings (SEM=0.11), t(28)=1.55, n.s. If bindings were specifically encoded, the obtained result should be *higher*, not lower, than the prediction because at least some binding would then reflect the encoding of color and shape deliberately for some of the same objects, precisely in order to allow binding. We conclude that Vul and Rich may be essentially correct and that, in this experiment, binding information simply falls out when both color and shape of an object are encoded. (Later we qualify this statement with the notion that a certain number of object files can be open, each of which has at least one attribute encoded but still with no correlation between which ones have color encoded and shape encoded.)

Although there is no strong need to explain the non-significant difference between the predicted and obtained number of bindings in WM, it may be worth noting that it theoretically could occur because of a tendency to encode color at the expense of shape on some trials and shape at the expense of color on other trials, producing a slight negative correlation between colors and shapes in WM within individual trials. This hypothesis theoretically could be tested in a procedure in which both color and shape responses have to be made on the same trial, but that measurement procedure could change participants' motivation in such a way as to abolish any negative correlation.

Completeness of encoding: Related calculations offer a picture of the completeness of encoding of items in dual-attention conditions. The number of objects in WM for which only color is encoded is $4(x\text{-}xy)$, with x and y defined as above; for attend-both trials, M=1.01 (SEM=0.14) and for attend-binding trials, M=1.19 (SEM=0.11). The number of objects for which only shape is encoded is $4(y\text{-}xy)$; for attend-both trials, M=.65 (SEM=0.10) and for attend-binding trials, M=.62 (SEM=0.09). Last, the number of objects in WM for which both color and shape are encoded is $4(xy)$; for attend-both trials, 1.48 (SEM=0.19) and for attend-binding trials, M=1.32 (SEM=0.17). Figure 4 (last 2 bars) shows these different items in WM stacked upon one another, separately for each attention condition.

WM capacity expressed in objects: Assuming independence of color and shape coding also allows estimates of the number of objects for which at least one attribute is encoded into WM. The estimate of items in WM for each attention condition is the summed height of the bar shown in Figure 4. As the figure shows, the result is rather similar across conditions (attend color, M=2.98, SEM=0.21; attend shape, M=2.83, SEM=0.16; attend both, M=3.14, SEM=0.19; and attend binding, M=3.13, SEM=0.14) and the difference between them is non-significant, $F(3,84)<1$. The estimate of about 3 items is quite close to what has been observed in previous literature on visual array WM (e.g., Anderson et al., 2011; Rouder et al., 2008).

Discussion

Several findings emerge from this experiment. First, we replicated the finding that the number of bindings in WM was less than the number of attributes in WM. In this second experiment, we were able to say more definitively that the number of bindings was much smaller than either the number of colors or the number of shapes in WM, regardless of the attention conditions at encoding.

Second, we replicated the finding from Experiment 1 that there is an effect of dividing attention between two attributes of an object. Thus, it cannot be the case, as Luck and Vogel (1997) asserted, that all features or attributes of an object can be encoded at once, as easily as one feature or attribute can be encoded.

Third, we found that the effect of dividing attention on memory for attributes was essentially the same no matter whether participants were required to encode both attributes separately on each trial, or whether they also had to encode the specific color-shape combination (binding) information. This finding suggests that encoding the two attributes absorbed as much attention as encoding the binding.

Fourth, we were able to provide a simple model suggesting that the information available on binding trials was quite similar to what would be expected if the color and shape attributes were independently coded, and were present in WM for the same object only by chance given the number of colors and shapes encoded in WM. Note that we are not asserting that color and shape are randomly paired to form objects. Each color and each shape in our procedure presumably is encoded within an object file with a particular location attached to it, so that what is random is the frequency with which both color and shape happen to be encoded for the same objects.

Fifth, this model also yielded an estimate of the number of objects for which at least one attribute was encoded into WM, and that number was not significantly different across conditions. Across all attention conditions, the number was about 3 items, as in past research on WM for objects in arrays (e.g., Anderson et al., 2011; Rouder et al., 2008). This finding, especially, contributes to the overall conception of capacity limits that we will offer.

Sixth, and last, we found that there was a slight but significant advantage for color over shape. Given a theoretical assumption of a constant capacity regardless of the nature of the attribute (Awh, Barton, & Vogel, 2007), the inference is that the encoding of shape was sometimes not precise enough to differentiate one object from another by shape as well as was possible by color. This difference in number of objects encoded in sufficient detail to allow a correct response was rather small, though (0.36 items across attention conditions) and was not large enough to alter significantly the estimated number of objects in WM in the attend-shape condition relative to the other three attention conditions.

General Discussion

The present results go beyond most other studies of change detection for object arrays by including a wider range of encoding and retrieval conditions, and by assessing the results with reference to new models to estimate the number of items in WM. Previous studies have often overlooked the point that the correct model depends on procedural details (cf. Rouder et al., 2011). We first summarize what we see as the most important findings. Second, we elaborate on our rationale for characterizing the findings in the way we do, including evidence for a constant capacity and evidence for attention-dependent inclusion in WM of the color and shape attributes that we used. Then we propose a theoretical account to explain these results, and last, we clarify implications of this research for the object concept.

Summary of Main Findings

We believe that the evidence presented here warrants a revised theoretical account. The most important findings based on models of items in WM that we believe must be accommodated include (1) a fixed number of objects represented in WM, about 3 on average, regardless of the allocation of attention to particular attributes within these objects; (2) partial completion of objects in WM, with some having only color representation, others having only shape representation, and still others having both color and shape representation; (3) variation in the relative proportion of objects having color versus shape representation, depending on the direction of attention to one or both attributes; and (4) knowledge of color-shape binding only to a degree that would follow if the distribution of color and shape information among the objects in the array is uncorrelated (cf. Vul & Rich, 2010). The first three of these findings are compactly illustrated together in Figure 4; for the attention effects, see also Tables 1–2 and Figure 3. A more complete compendium of findings regarding items in WM is presented for convenience in Table 3.

In Experiment 1, analysis of accuracy (proportion correct) also provided important information about processing. Most importantly, the equivalence of accuracy for trials with the probe in a target location versus centrally presented indicates that little or no benefit was obtained from location information. Therefore, when Model 2 (the Reverse-Pashler model) was applied to new-attribute trials from both probe locations, they yielded equivalent estimates of items in WM, and when Model 4 (the binding model) was applied to attribute-recombination trials from both probe locations they, too, yielded equivalent estimates of items in WM.

Constant capacity for objects—The present research applies new models of the number of items in WM and, in doing so, addresses some key unresolved issues regarding the nature of WM storage, at least for visually-displayed arrays of colored shapes. The results of the second experiment suggest that the number of objects that are included in WM is fixed across variations in the direction of attention, at approximately 3 objects on average, in accord with previous research (Anderson et al., 2011; Luck & Vogel, 1997; Rouder et al., 2008). This kind of conclusion would not have been possible without the new modeling of items in WM for various task demands (Appendix A), and without a method to examine both change and no-change trials separately for color and shape within dual-attribute-attention trials, as in Experiment 2.

Attention-dependent inclusion in WM of attributes within each object—Even though the number of objects in WM is fixed, though, the completeness of the representation of each object in WM is clearly not fixed, with some amount of competition between shape and color, as both experiments showed. This finding contradicts the notion stated by Luck and Vogel (1997) that when an object is encoded into WM, all features or attributes will be retrieved just as well as they would have been if attention had been directed to only that one feature or attribute. This notion, raised by Duncan (1984), already had been disproven for objects consisting of pairs of colors (Wheeler & Treisman, 2002; Xu, 2002a, 2002b) but is disproven here even when the two attributes are different in kind (color and shape). The findings cannot be accounted for by a theory in which separate features have their own capacity limits (Wheeler & Treisman, 2002).

In Experiment 2, we found that the frequency of encoding of bindings was slightly lower than what would be expected if the selection of objects for the encoding of color and shape were independent. With an object-capacity constraint, the discrepancy between observations and encoding-independence-based predictions become even larger. For example, suppose that 3/5 of the colors and 2/5 of the shapes are encoded. With no object-capacity constraint, the expectation would be that 6/25 of the bindings are encoded, or $6/25 \times 5 = 1.2$ bindings on average for a five-item array. With a capacity constraint of 3 objects with at least one attribute encoded for each object, it is expected that 2.0 bindings are encoded (in this numerical example, with color encoded for all three objects and shape encoded for two of them). The fact that bindings were fewer than expected according to either of these predictions strengthens the notion that there was a competition between color and shape encoding, even in the attention condition in which binding was relevant.

On the surface, some previous studies have led to conclusions that appear to contradict the attention effects of the present study. Bays, Wu, and Husain (2011) and Fougnie and Alvarez (2011) found that errors on two attributes of an object are largely uncorrelated with one another. Vul and Rich (2010) found that the ability to retrieve the binding between features is a chance occurrence that depends on whether the two attributes happen to be present for the tested object. However, the present results suggest that the collection of attributes available for comparison depends on attention.

Johnson, Hollingworth, and Luck (2008) previously found that a search task affected WM of the binding between attributes (color and shape or color and orientation) only to the same extent as it affected WM of the attributes themselves, reinforcing the conclusion of Allen et al. (2006). The present research extends these findings to a situation in which the division of attention is between attributes and/or their bindings rather than between the array memory task and a separate attention-demanding task. It also is first to confirm the findings using a principled measure of items in WM instead of accuracy and signal detection measures.

Locus of the attention effect: Encoding, maintenance, or retrieval?: The conclusion that there are attention effects on the attribute composition of items in WM leads to the further question of how these attention effects occur. Theoretically, they could occur at the time of encoding of items into WM, maintenance of items in WM, or retrieval of items from WM. Together with the existing literature, the present results offer clues toward the answer to this question. First, we doubt if any of the arrays were incompletely encoded because of a time limitation. Vogel, Woodman, and Luck (2006) showed that the time course of consolidation of information into WM was about 50 ms per object. If we make the conservative assumption that each colored shape in the present study takes 100 ms to encode, it should take 400 ms to encode the entire array, whereas our arrays were presented for 500 ms, with another 500 ms for further processing of the iconic image before a mask was presented.

Another possibility is that the situation at test determines performance. shape new-attribute tests, we know that this is not the locus of the attention effects inasmuch as the situation at test was exactly the same in the attend-single-attribute, attend-dual-attribute, and attend-attribute-combination conditions, yet the results of these conditions differed. By process of elimination, the attention effect seems to influence the information stored and maintained in WM.

The model we have used as the analysis of items in WM for attribute changes with a center probe (Appendix A, Model 2, the Reverse-Pashler model) is based on the idea that the task is carried out by the process of detecting the identity between the probe and one of the array items in WM, or by failing to find such an identity. It is worth noting that Hyun, Woodman, Vogel, Hollingsworth, and Luck (2009) found a different pattern of results for difference-detection versus sameness detection. The results suggested that difference-detection can occur in parallel for all items in WM, whereas sameness-detection occurs more slowly in a capacity-limited fashion. The point seems moot, inasmuch as the process of using that change detection for a motoric response was still capacity-limited. Beyond that, moreover, Hyun et al. used a whole-array comparison procedure, which meant that the sameness of each studied array element had to be compared to the corresponding probe element in order to answer the question. In contrast, the present procedure was one in which the items in WM had to be compared to only a single probe element. According to the theoretical points raised by Hyun et al. (e.g., in their Footnote 3), this type of procedure would not be expected to produce a difference between in-location probes and central probes, and indeed none was obtained (our Experiment 1).

In principle, as well, the similarity in processes between in-location and central probes should apply not only to new-attribute tests, but also attribute-recombination tests. Indeed, we obtained similar results for attribute-recombination (binding) tests with in-location or central probes in Experiment 1, provided that attention was directed toward both color and shape. Hyun et al. (2009, Experiment 5) found that attention could be directed toward one attribute in two-attribute stimuli. We found that attention could be directed toward one attribute or toward both, and the chance conjunction of color and shape information in the same object was enough to account for the ability (and limitations thereof) in answering attribute-recombination questions; hence, the superiority of new-attribute judgments over attribute-recombination judgments has to do with WM storage, not factors involved in comparing WM representations with the probe item.

A Theoretical Account: Object and Attribute Limits

For the sake of parsimony we at first attempted to find a theoretical account of the data using the same single capacity limit to account for all of the evidence discussed in the summary of main findings. For example, a single capacity limit might be applied iteratively to color apprehension and shape apprehension. The problem with this type of model is that the binding data indicate that it is not routinely the same objects for which color and shape are encoded; if these attributes were encoded for the same objects, the binding or attribute-combination trial performance would approximate the same number of items in WM as in the new-attribute trial performance. Instead, binding performance is much worse. This implies that, in dual-attention trial blocks, the number of encoded items must include some for which only color is encoded and some for which only shape is encoded. Indeed, in the attribute-combination attention condition of Experiment 2 we were able to estimate that encoding included both attributes for less than half of the items in WM (color only, 1.19 items; shape only, 0.62 items; both color and shape, 1.32 items).

Our general theoretical account of these results is summarized in Figure 5. The figure includes two different capacity-limiting factors: the limit k in how many objects are apprehended, and the limit in how many attributes can be filled in for those objects (cf. Fougnie, Asplund, & Marois, 2010). In conditions involving attention to only one attribute, the observed number of items in WM is presumably the same as the number of items for which the attended attribute is in WM. In this account, the slight inferiority of shape compared to color suggests that the encoding of shape is not always completely sufficient for a discrimination to occur. This asymmetry is also found with other attributes. For example, Woodman and Vogel (2008) found an asymmetry for color and orientation that was quite similar to what they found for color and shape.

We leave open the exact manner in which the processing shown in Figure 5 occurs. One way it could occur is if participants in dual-attention conditions attend to the two types of attributes in series. For example, they could most often attend to colors first, retrieving k colors, and then later attend to shapes, but only for objects whose color was already apprehended, and then sometimes only for some of the objects. On other trials, shape would come first and color second, but only for objects whose shape is already apprehended. Alternatively, colors and shapes could be apprehended in parallel, but with the constraint that any object for which either a color or a shape (or both) is apprehended results in an object file (Kahneman, Treisman, & Gibbs, 1992) that counts toward the individual's fixed numerical limit in the number of objects in WM for that trial.

The calculations that serendipitously led to the fixed object limit shown in Figure 4 are based on the assumption that no objects in WM are devoid of both color and shape information (i.e., empty objects). Such empty objects would result if the objects were established first in WM and the attributes were filled in later on a probabilistic basis. We assume, in contrast, that such empty objects do not occur, uselessly cluttering WM, given that the task is to apprehend color and/or shape information.

Role of location information?—In our account, as in Vul and Rich (2010), the ability to know that a color and a shape belong together occurs for objects that happen to have both color and shape attributes encoded. There are two ways in which this could occur. It would be possible for the color and shape of the same object to be associated because both of them correspond to the same location in a map of spatial locations (cf. Wheeler & Treisman, 2002). Alternatively, though, an object file (Kahneman et al., 1992) could be formed without regard to the location of each object. In this alternative, the color and shape associated with a common object would be directly associated with one another, without incorporating location information (given that this information was not explicitly needed for the task). In Experiment 1 there was no benefit of placing the probe at the location of the target that may have changed, either in new-attribute blocks nor in attribute-recombination blocks. Therefore, we favor the account in which the color and shape can be directly associated without location as an intermediary. This account also is in accord with the finding that the capacity limit is the number of objects, not the number of spatial locations (Lee & Chun, 2001).

Relation to past accounts—This separation of the number of objects in WM from the precision of the representations has been proposed before. For example, Xu and Chun (2006) showed that one brain region, the inferior parietal sulcus, responded to a number of objects with a fixed limit, whereas other regions, the superior intraparietal sulcus and the lateral occipital complex, responded to a number of objects that changed with the complexity of the objects. Anderson et al. (2011), after Zhang and Luck (2008), used a task in which the precision of recall could vary to show that the precision of representations decreases as the number of objects increases from one to two to three, reaching a plateau after that number of objects. Thus, resources for processing object complexity must be shared among items but can be shared among only about 3 items on average.

The present account is compatible with these prior works but adds three distinctions. First, we suggest that the role of multiple attributes may be comparable to the role of the complexity of a single attribute (e.g., Chinese characters for non-Chinese-speaking participants: Awh et al., 2007) or the precision of the representation of an attribute (e.g., recall of the orientation of a bar: Anderson et al., 2011). When there are insufficient resources available for the analysis of an object it can lead to insufficient precision of the representation (e.g., insufficient detail about the Chinese character or insufficient specification of a bar's orientation) or, as in the present study, it can lead to partial encoding of the object (e.g., knowledge of an object's color but not shape, or vice versa).

Second, we assert that, by manipulating attention, it is possible to alter the type of encoding of an object, in this case with an emphasis on colors, shapes, or some of each. Analogously, it was found recently that the precision of the WM representation of bar orientations can be altered at will when the number of items to be retained is not large (Machizawa, Goh, & Driver, in press).

Third, unlike most prior accounts, but like Vul and Rich (2010), we also subscribe to the notion that attribute binding information is simply the result of conjoint information about the attributes for an object.

WM for Attributes and the Object Concept

The present findings still need to be reconciled with evidence that attributes form objects with special properties. That is done with respect to several phenomena below.

Within- and between-object division of attention: Vul and Rich (2010) and the present data indicate that questions about the binding of two attributes of objects can be answered only to the extent that would be expected if the attributes were independently encoded. There are two subtly different interpretations of that finding. Attributes may remain mentally separate until the time of test. Alternatively, though, pairs of attributes that are encoded for the same object may be mentally bound, so that the contents of WM include objects, some of which are more completely described than others (see Figure 5). We favor the latter interpretation (cf. Allen et al., 2006) because it is more consistent with evidence on the existence of objects within mental representations. Duncan (1984) showed that two successive judgments of different attributes can be made without loss of fidelity if the attributes come from the same object, but not if they come from different objects occupying an overlapping spatial area. Awh, Dhaliwal, Christensen & Matsukura (2001) showed that pre-cueing leads to a spatial source of advantage but that without a pre-cue, this special advantage for objects remains. Woodman and Vecera (2011) extended this conclusion to an array memory procedure more comparable to the present work. Therefore, we favor an interpretation in which attributes are acquired independently but are sorted into objects that are represented in integrated fashion in WM. This interpretation also accommodates the finding that shape and color conjunction stimuli yield the same contralateral delay activity as simpler stimuli and depend only on the number of objects in WM (Luria & Vogel, 2011). We suggest that sometimes the representation of attributes within an object is incomplete because of attentional limitations, though, in contrast to the complete encoding of multiple objects that Luck and Vogel (1997) proposed.

Irrelevant attribute variation within objects: The present finding that attention can be directed toward or away from attributes of objects might seem at odds with findings of a disruptive effect of irrelevant attributes, but actually the findings converge nicely. In particular, Logie, Brockmole, and Jaswal (2011) examined memory for location, shape, and color, making one attribute irrelevant but varying and examining memory for the binding between the other two attributes. At short retention intervals, varying an irrelevant attribute, and especially varying location as an irrelevant attribute, had a very detrimental effect on performance. At longer retention intervals (1000–1500 ms), however, the effect of the irrelevant attribute variation was dramatically diminished. This effect can be viewed as illustrating the time necessary for a visual object to be transformed by cognitive processes into an abstract representation. In our study, the array onset to test onset interval was 1500 ms, a point on the function at which the effect of the irrelevant attribute has disappeared according to Logie et al. This may be why we found no evidence of the use of location to enhance information about color or shape attributes or their binding (cf. Woodman, Vogel, & Luck, 2012). In future work, it would be helpful to examine the time course of the selective attention effect, in particular the exclusion of irrelevant attributes and the consolidation of relevant attributes in WM.

Selectivity between and within objects: It is an open question whether our observations of selectivity among attributes within objects taps into the same attention processes used for selectivity among objects. Vogel, McCollough, & Machizawa (2005) found that individuals with high spans could ignore bars of one color in order to concentrate on bars of another color. It is not clear what the time course of this selectivity is. Ueno, Mate, Allen, Hitch, and Baddeley (2011) found that, following an array to be remembered, an additional object or suffix cannot be ignored, provided that at least one attribute is from the response set. We suspect that both between and within objects, there is a minimal time period necessary for the selection process to work.

If selectivity between and within objects relies on the same attention processes, the task is to describe what the overarching limitations are in the use of this attention. Perhaps the key processing occurs in the focus of attention, whereas some information can be retained temporarily outside of attention, in the activated portion of long-term memory (Cowan, 1988, 1999, 2001). Thus, the initial apprehension of objects in the focus of attention may be susceptible to an attention limit of about 3 items (Anderson et al., 2011; Rouder et al., 2008) but in the case of items with complex or multiple relevant attributes, the processing of each apprehended item may be incomplete. Once the items are apprehended, it is possible that attention can be removed from some of the items temporarily in order to gain a more precise or complete representation of other items; attention to particular attributes can vary (cf. Machizawa et al., in press). For example, it is possible that a single attended object could occupy two slots in WM as the participant mentally processes the color and shape features of that objects. Meanwhile, the unattended item or items would be retained in a temporarily activated store outside of attention, though there would be limits to how long this could go on without a return of attention to these objects as well. Some sort of rotation of attention from object to object could occur at a rate limited by some capability of the participant (cf. Barrouillet, Portrat, & Camos, 2011). It still must be worked out, however, why the contralateral delay activity of event-related potentials would represent the number of objects but not the number of attributes within an object including color and shape (Luria & Vogel, 2011).

Conclusion

The data we have covered may be considered complex, but they ultimately lead to a simple resolution. There appears to be compelling evidence that attributes contribute to a limited number of objects in WM, but that the set of attributes can be incomplete and depend on the direction of attention. This conclusion comes from prior work but has been integrated here across several different, previously separate lines of research. The conclusion also benefits from the presentation of a wide variety of WM encoding and retrieval conditions in the present work, and from the development of models of items in WM suited to the various test conditions. Future work must determine whether our results apply to objects varying in simple features, such as line orientation. Further work is needed as well to determine whether the selection of objects and of attributes within objects for entry into WM both occur in a single processing step, or in multiple steps separated in time.

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Appendix A

Derivation of Models for Items in Working Memory

The following models should not be considered capacity models inasmuch as the capacity cannot be estimated if it exceeds the set size of 4 items. They are, however, useful estimates of the number of items held in working memory. They are specific to the situation in which features are not repeated within the array; no color or shape appears in more than one object in an array.

Model 1: From Pashler (1988)

This model is not appropriate for the present study but it is an important starting point. The model is appropriate for a situation in which the probe is an array that is the same as the studied array except that a feature of one item may have changed. In this situation, a change can sometimes be detected with certainty because the k items in working memory include the item that has changed. If no such change is detected and the number of array items, N, exceeds k, then a change still could have been missed and the participant must guess whether that happened or not. The participant will guess "yes, changed" with some probability g.

The term h is defined as the probability of a hit, i.e., change detection, and the term f is defined as the probability that a change was indicated in the response when in fact none occurred. The premises stated above imply that

$$h=\left(\frac{k}{N}\right)+\left(1-\frac{k}{N}\right)g$$

and

$$f=g$$

By combining these equations it can be shown that

$$k=N\left(\frac{h-f}{1-f}\right).$$

Model 2: Pashler (1988) Modified for a Single, Central Probe (“Reverse Pashler” Model)

When a single, central probe is presented and $k<N$, the participant may be able to tell that the probe item is not new because the probe item matches one of the items in working memory. If this sameness is not detected, the participant cannot tell whether that is because the probe is new or because the probe corresponds to an item that was presented but is not in working memory. That is, the logic is the same as for Pashler's (1988) model except that target-present and target-absent trials have switched roles. The correct indication of sameness, $(1 – f)$, occurs if the probe item is in working memory or if a correct guess of “no change” is made, which occurs with probability $(1 – g)$:

$$1-f=\left(\frac{k}{N}\right)+\left(1-\frac{k}{N}\right)(1-g)$$

whereas an incorrect indication of sameness can occur only based on guessing:

$$1-h=1-g$$

Combining these equations,

$$k=N\left(\frac{h-f}{h}\right).$$

If there were a probe presented at a target location but the participant ignored the location information, again this model would apply.

Model 3: From Cowan (2001)

This model is appropriate if there is information about which item is tested and that information is used. The formula for h is as in Pashler's model (Model 1):

$$h=\left(\frac{k}{N}\right)+\left(1-\frac{k}{N}\right)g$$

but the formula for f is now different:

$$f = \left(1 - \frac{k}{N}\right) g$$

because on k/N of the trials the participant knows that the probe is the same as the corresponding item in the test array and therefore avoids producing a false alarm, given that the item is in working memory. Combining these equations yields

$$k = N \left(h - f\right).$$

Model 4: Color-Shape Binding Model

This model is appropriate when the probe for every trial is either identical to one of the array items or consists of features from two of the array items recombined. When there has been such a change in feature binding, the participant presumably will detect the change if working memory contains either of the objects that made up the probe. For example, if the array included a green triangle and a red circle and the probe item is a red triangle, this can be detected as a change if either the green triangle or the red circle is known. The probability that the participant has at least enough knowledge to detect a change, c, is the sum of probabilities that the items included among the k items in working memory include both those with the shape and color of the probe, just the one with the color, or just the one with the shape:

$$c = \left(\frac{k}{N}\right)\left(\frac{k-1}{N-1}\right) + 2\left(\frac{k}{N}\right)\left(1 - \frac{k-1}{N-1}\right)$$

Then the probability of a hit is

$$h = c + (1 - c)\, g.$$

A false alarm, a response indicating a change in binding when there was no change, can occur only if the probe item is not in working memory. Thus,

$$f = \left(1 - \frac{k}{N}\right) g.$$

One can combine the last two equations to yield a formula that includes both hits and false alarms:

$$h = \left(1 - \frac{k}{N}\right) = c\left(1 - \frac{k}{N}\right) + (1 - c)\, f.$$

Filling in the value for c, we obtain an equation that includes k, k^2, and k^3 terms and is not convenient to solve for k. Instead, we selected the value of k for each participant and condition that corresponded to h and f with N=4. This value is unique provided that k<3.0. This makes sense because it takes knowledge of only 3 items to be sure of being correct in the binding trial blocks within our procedure. If the probe item does not include a feature from one of three items in working memory there cannot have been a switch in binding; the item must be unchanged from the studied array. A simplified lookup table is presented below (Table A1).

This model applies no matter whether the probe is presented at center or at a target location because the target location information is redundant. The binding between color and shape defines which item is being considered, as do the bindings between color and location and between shape and location, considered jointly. If, however, capacity estimates are higher with the probe presented at a target location, this indicates that the redundant location information is being used, a possibility that falls outside of the model as stated here.

Note that Allen et al. (2006) used a subset of trials with repetitions within an array to attempt to ensure that memory for all four items was required. The assumption in the binding model that only 3 representations are needed to identify binding change trials is accurate for the present data but may need adjustment with respect to Allen et al.

Table A1

Estimates of k for the color-shape binding model corresponding to each combination of correct rejections (1-f) and hits (h).

1-f	*h*	*k*
0.1	0.9	0.0
0.2	0.8	0.0
0.2	0.9	0.4
0.3	0.7	0.0
0.3	0.8	0.3
0.3	0.9	0.7
0.4	0.6	0.0
0.4	0.7	0.3
0.4	0.8	0.6
0.4	0.9	1.0
0.5	0.5	0.0
0.5	0.6	0.3
0.5	0.7	0.5
0.5	0.8	0.9
0.5	0.9	1.3
0.5	1.0	2.0
0.6	0.4	0.0
0.6	0.5	0.2
0.6	0.6	0.5
0.6	0.7	0.8
0.6	0.8	1.1
0.6	0.9	1.6
0.6	1.0	2.4
0.7	0.3	0.0
0.7	0.4	0.2
0.7	0.5	0.5
0.7	0.6	0.7

1-*f*	***h***	***k***
0.7	0.7	1.0
0.7	0.8	1.4
0.7	0.9	1.8
0.7	1.0	2.7
0.8	0.2	0.0
0.8	0.3	0.2
0.8	0.4	0.4
0.8	0.5	0.6
0.8	0.6	0.9
0.8	0.7	1.2
0.8	0.8	1.6
0.8	0.9	2.0
0.8	1.0	2.9
0.9	0.1	0.0
0.9	0.2	0.2
0.9	0.3	0.4
0.9	0.4	0.6
0.9	0.5	0.8
0.9	0.6	1.1
0.9	0.7	1.4
0.9	0.8	1.7
0.9	0.9	2.2
0.9	1.0	2.9
1.0	0.0	0.0
1.0	0.1	0.2
1.0	0.2	0.4
1.0	0.3	0.6
1.0	0.4	0.8
1.0	0.5	1.0
1.0	0.6	1.3
1.0	0.7	1.5
1.0	0.8	1.9
1.0	0.9	2.3
1.0	1.0	2.9

Note. These estimates are for four-item arrays. For combinations of 1-*f* and *h* not shown, there is no unique, positive value of *k*. *A* logical limit of the model is $k<3.0$.

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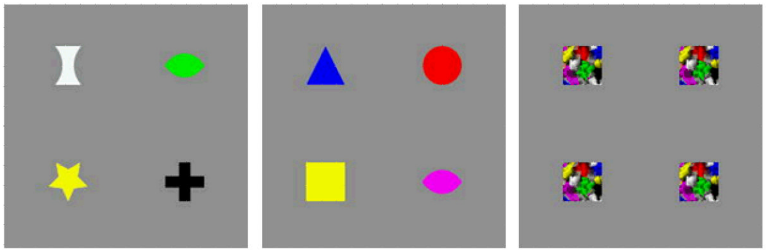

Figure 1.
Three screen shots exemplifying the study stimulus arrangement, background color, seven object colors, seven object shapes, and mask (third panel).

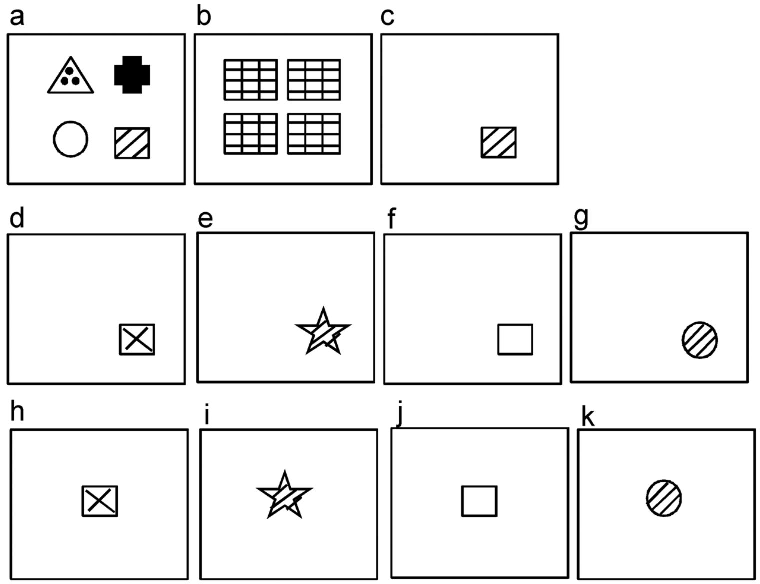

Figure 2.

Examples of the types of stimulus displays in Experiment 1(not to scale; with pattern fills representing colors). **Top row**: Example of a trial in which there is a single-item probe in the same location as the probed target item. Panel **a**, study display; **b**, masking display composed of multicolored squares; **c**, no-change probe in the same location as the target item. **Second row**: types of change probe that can occur in trial blocks with probes at the target location. Panel **d**, change to a new color; **e**, change to a new shape; **f**, change to a color from a different location; **g**, change to a shape from a different location. **Third row**: types of probe that can occur in trial blocks with central probes. Panel **h**, change to a new color; **i**, change to a new shape; **j** and **k**, two examples of changed binding between color and shape.

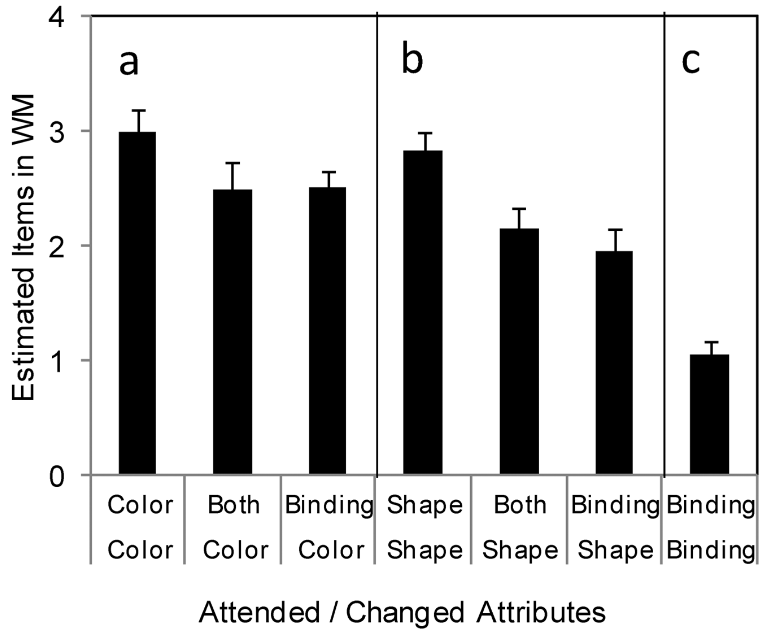

Figure 3.

Effects of dividing attention in Experiment 2, seen in estimates of the number of items in working memory. **Part a**, color probes; **Part b**, shape probes; and **Part c**, recombination probes. Estimates are according to the Reverse-Pashler Model (Appendix B, Model 2) except for color-shape recombination probes, which are according to Appendix B, Model 4. Error bars are standard errors of the mean.

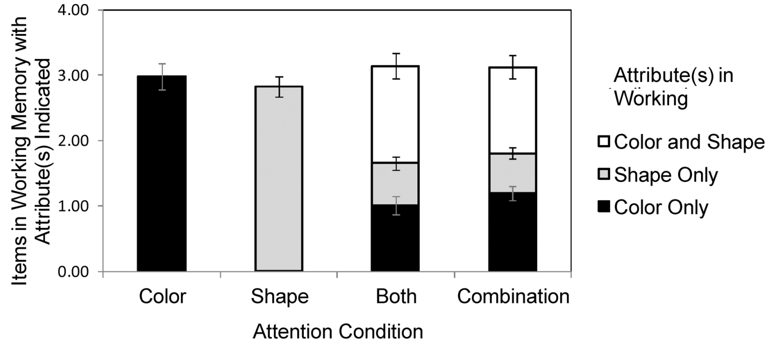

Figure 4.

Estimates of the number of items in working memory with each combination of color and shape attributes in each attention condition of Experiment 2. The estimates are based on the assumption that color and shape attributes are acquired independently and that each object in working memory includes at least one of these attributes.

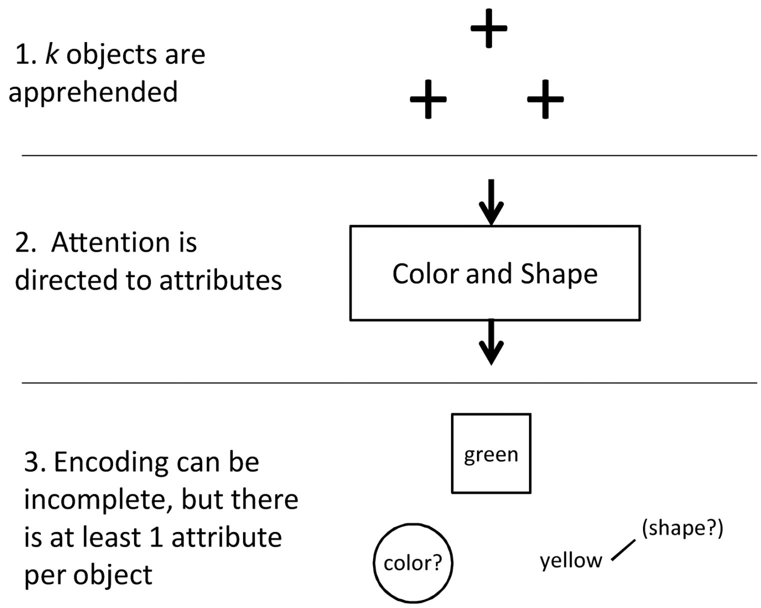

Figure 5.
A schematic model of fixed capacity with incomplete attribute encoding in a dual-attention situation.

Table 1

Proportion Correct in Each Condition of Experiment 1

	Probe Type of Trial Block	
Attention in Trial Block and Changed Attribute	**New-Attribute**	**Attribute-Recombination**
	Probe at Target Location	
Attend Color		
Color Change	.93(.02)	.83(.02)
No Change	.81(.03)	.80(.03)
Attend Shape		
Shape Change	.80(.03)	.75(.03)
No Change	.80(.02)	.83(.02)
Attend Both		
Color Change	.91(.01)	.84(.02)
Shape Change	.73(.03)	.70(.03)
No Change	.77(.02)	.70(.03)
	Probe at Center Location	
Attend Color		
Color Change	.95(.01)	.65(.04)[a]
No Change	.82(.03)	.74(.03)[a]
Attend Shape		
Shape Change	.78(.03)	.67(.03)[a]
No Change	.76(.03)	.71(.03)[a]
Attend Both		
Color Change	.89(.02)	.77(.03)[b]
Shape Change	.77(.03)	.76(.03)[b]
No Change	.72(.02)	.74(.02)

Note. Standard error of the mean is in parentheses.

[a]For recombination changes with a center-location probe, it is logically necessary to encode both color and shape in order to do the task, so focusing attention on just color or just shape is counterproductive at best.

[b]There is no difference in principle between color and shape changes in this condition, so in the attend-both condition, color and shape changes are replicates.

Table 2

Proportion Correct in Each Condition of Experiment 2

	Presence or Absence of Change	
Attention in Trial Block	**Change**	**No Change**
	Color-Change Probes	
Color	.89(.02)	.80(.03)
Both	.86(.03)	.71(.03)
Recombination	.87(.02)	.68(.03)
	Shape-Change Probes	
Shape	.78(.02)	.78(.03)
Both	.72(.03)	.68(.03)
Recombination	.69(.04)	.68(.03)
	Recombination-Change Probes	
Recombination	.70(.03)	.66(.02)

Note. Standard error of the mean is in parentheses.

Table 3

Summary of Results for Items in WM According to Appendix A Models

Experiment 1: Trial blocks for 12 attention / probe type / probe location combinations
No indication that location information was used. In new-attribute trial blocks, more items in WM for centrally-located probes using the Reverse-Pashler model (M=2.80) than for target-location probes using the Cowan model (M=2.50), contrary to the expectation for the use of location information. Using the Reverse-Pashler model for both probe locations, no longer a probe-location effect. In attribute-recombination trial blocks with dual attention (binding model), again no effect of probe location.
Effects of attention. In the analysis of new-attribute trial blocks, attention to one kind of attribute resulted in 3.02 objects in WM; attention to both kinds of attributes resulted in fewer objects for either probed attribute (2.72). In the analysis of new-attribute and attribute-recombination trial blocks for target-location trials, there was again an advantage for attention to one attribute (M=2.29), over attention divided between two attributes (M=2.04).
Effect of the type of comparison. There was a large advantage for new-attribute changes (M=2.94) over attribute-recombination changes (M=1.40).
Experiment 2: Center probes; trial blocks for 4 attention conditions
Effects of attention. The number of objects for which the tested attribute, color or shape, was retained with attention to only that one attribute, M=2.91, was greater than with attention to both color and shape concurrently, M=2.31, or with attention to the specific color-shape combinations, M=2.22. (See Figure 3.)
Effect of the type of comparison. The number of items in WM was much smaller for attribute-recombination trials (M=1.05 bindings) than for new-attribute trials in any attention condition.
Attribute-type difference. The number of colors retained, M=2.66, exceeded the number of shapes retained, M=2.30.
Binding knowledge as derivative. The number of bindings present in WM could be reasonably well estimated on the basis of the assumption that color and shape were independently encoded rather than correlated, and that the presence of both allowed binding knowledge.
Fixed object capacity across attention conditions. The number of items in WM with encoding of at least one attribute was not significantly different across attention conditions.