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Working Memory Units are All in Your Head:

Factors that Influence Whether Features or Objects Are the Favored Units

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Abstract

We compared two contrasting hypotheses of how multi-featured objects are stored in visual working memory (vWM): as integrated objects or as independent features. A new procedure was devised to examine vWM representations of several concurrently-held objects and their features and our main measure was reaction time (RT), allowing an examination of the real-time search through features and/or objects in an array in vWM. Response speeds to probes with color, shape or both were studied as a function of the number of memorized colored shapes. Four testing groups were created by varying the instructions and the way in which probes with both color and shape were presented. The instructions explicitly either encouraged or discouraged the use of binding information and the task-relevance of binding information was further suggested by presenting probes with both color and shapes as either integrated objects or independent features. Our results show that the unit used for retrieval from vWM depends on the testing situation. Search was fully object-based only when all factors support that basis of search, in which case retrieving two features took no longer than retrieving a single feature. Otherwise, retrieving two features took longer than retrieving a single feature. Additional analyses of change detection latency suggested that, even though different testing situations can result in a stronger emphasis on either the feature dimension or the object dimension, neither one disappears from the representation and both concurrently affect change detection performance.

Keywords: working memory, objects, features, binding, retrieval

Working Memory Units are All in Your Head: Factors that Influence Whether Features or Objects Are the Favored Units

There is a growing interest in how information is stored and retained in visual working memory (vWM). People frequently encounter visual objects comprising multiple features such as shape, color, orientation and location. Theorists debate whether vWM uses as its basic units such features, or their aggregation into bound objects. Some combination of features and objects may have to be considered to describe vWM capacity limits (Cowan, Blume, & Saults, 2013; Hardman & Cowan, in press; Oberauer & Eichenberger, 2013).

We describe a new procedure to examine vWM representations of several concurrently-held objects and their features. To determine whether the stimulus representation is malleable, support for features versus bindings is manipulated in two ways: through instructions, and through the nature of probe presentations. Our main measure was reaction time (RT), allowing an examination of the real-time search through features and/or objects in an array in vWM (cf. Donkin, Nosofsky, Gold, & Shiffrin, 2013; Gilchrist & Cowan, 2014). To examine RT under high-performance conditions with multi-featured object arrays, we used a procedure in which a memorized set of colored shapes that the participant knew to be relevant to the current trial (thus, retrieved into vWM) was followed by a probe item to be judged present in the array or absent from it (cf. Wickens, Moody, & Dow, 1981). The basic issue is whether the time to search for probe items depends on the number of objects to be searched in vWM, the total number of features to be searched, or both. We present the background for this question and then explain the present study in more detail.

Background of the Object-Feature Controversy

Our procedure borrows some characteristics from studies of recognition accuracy and other features from studies of RT. We briefly examine these literatures in turn.

Studies of accuracy. Most studies of features and objects in vWM have relied on the accuracy of responding, but those studies have led to mixed results. Luck and Vogel (1997) carried out studies of vWM for arrays of objects using a probe recognition procedure and argued that vWM representations contain integrated objects rather than just collections of features. They did so on the grounds that when multi-featured objects appeared in multiple-object arrays, recognition accuracy was nearly identical in single-feature and multiple-feature conditions. In single-feature conditions there is a requirement to retain in vWM on a particular trial one feature from each item (e.g., color, orientation, length, or presence-vs.-absence of a gap), whereas in multiple-feature conditions the requirement is to retain in vWM more than one feature at the same time. Wheeler and Treisman (2002), however, disputed the interpretation of Luck and Vogel. They argued that individuals might use different feature-specific stores (a color store, an orientation store, etc.) that are independent of one another. If these stores can function in parallel, then multiple features of the same objects could be stored in vWM with no cost for any one feature, compared to storing it alone. Wheeler and Treisman further reported that poorer performance was obtained when participants must retain not only multiple features, but also their binding (i.e., which features occurred in the same objects), presumably because feature binding requires focused attention.

Results of subsequent studies using accuracy in array item recognition have been mixed. Sometimes multiple-feature performance levels are lower than for single-feature conditions, favoring features as the units of vWM for which there is a limited capacity (e.g., Olson & Jiang, 2002, Experiment 4). Other times, no difference has been observed, favoring the object-based view of vWM (e.g., Delvenne & Bruyer, 2004; Olson & Jiang, 2002, Experiment 3; Stevanovski & Jolicoeur, 2011; Vogel, Woodman, & Luck, 2001). The opposite findings in two different experiments of Olson and Jiang should lead to the suspicion that there might be separate limits for objects and for features within the objects that predominate under different conditions, and that indeed has been suggested in the literature (e.g., Anderson, Vogel, & Awh, 2011; Cowan et al., 2013; Hardman & Cowan, in press; Oberauer & Eichenberger, 2013; Xu & Chun, 2006).

Results have been mixed also regarding whether there is a cost of binding as Wheeler and Treisman (2002) suggested. The cost would be for binding compared to memory for two features but without binding information, and some studies have pointed to little or no additional cost of binding (e.g., Allen, Baddeley, & Hitch, 2006; Allen, Hitch, Mate, & Baddeley, 2012; Cowan et al., 2013; Cowan, Naveh-Benjamin, Kilb, & Saults, 2006; Johnson, Hollingworth, & Luck, 2008; Morey & Bieler, 2013; Vergauwe, Langerock, & Barrouillet, 2014). Examining the error pattern in detail, some studies have concluded that participants retrieve either both features of an object or neither feature (Gajewski & Brockmole, 2006), whereas other studies have supported the separate-feature view because memory errors for two features were largely independent (Bays, Wu, & Husain, 2011; Fougnie & Alvarez, 2011; Vul & Rich, 2010). Thus, across the different lines of research on accuracy in vWM recognition tasks, the results are inconsistent and theorists continue to disagree about the nature of the basic unit used in vWM.

Studies of RT. One limitation of accuracy studies is that they do not give a strong indication of what processes underlie performance. It is possible to use as an alternative measure RT for correct responses in recognition tasks with multi-featured objects. For that purpose it is desirable to have a high level of correct performance, which is difficult to obtain for multiple complex objects. One solution is to add support from long-term memory (LTM). For example, a memorized list can be retrieved into vWM and a signal can be given to retrieve its items into vWM to allow a probe comparison. This LTM support does not alter the short-term memory comparison process; advanced LTM knowledge of a memory set affects the intercept, but not the slope, of the search function across set sizes (Conway & Engle, 1994; Wickens et al., 1981).

Several prior studies have involved learned sets of two-feature objects for measures of RT tasks (color and shape, Gilchrist & Cowan, 2011; color and number, Oberauer & Bialkova, 2009). These studies suggest that under some circumstances, individuals can access features from the objects currently retrieved into vWM; but when the pairings are sufficiently well-learned, access to features disappears, and responses are then based on integrated objects. These studies, however, involved complex operations (mapping stimuli to a response grid or carrying out arithmetic), and the index of feature knowledge was indirect (the cost of switching neither, one, or both features of the operated-upon object from the previous trial).

To explore more directly the conditions under which features or objects will be used in the vWM representation, we developed a procedure based on learned objects to allow a stable RT response. Unlike the just-mentioned RT studies, however, we used a simple change-detection procedure resembling Luck and Vogel (1997), albeit with learned multi-featured objects. RT has been used successfully in change detection (Donkin et al., 2013; Gilchrist & Cowan, 2014) but to our knowledge has not been used with multi-featured objects.

The Present Study

Our participants were presented with a memory display containing 1-4 colored shapes, which they could study for an unlimited period of time. When they indicated that they were ready, memory for this set of colored shapes was tested on 24 consecutive trials. We studied recognition RT for probes with a color, a shape, or both. When both features were present we sometimes tested recognition of both features in the memorized set and sometimes tested recognition of an object (a particular colored shape matching the probe). After practice there were 16 such blocks of 24 trials, 4 for each set size. To manipulate the use of features versus objects, we varied whether the probe was presented in an integrated manner (Figure 1, top panel) or with features separated (Figure 1, bottom panel). We also manipulated instructions encouraging or discouraging the binding of features to form objects. To avoid confusing participants, these last two manipulations were carried out between subjects.

We expected that, if multi-featured objects are stored as integrated objects, then searching for two features (either with or without the binding information) should not take longer than searching for a single feature. This study is novel in several ways. First, while previous research on change detection has mainly focused on memory accuracy and error patterns, we study the timing of error-free performance in a new procedure. We examined RT for probes with color, shape or both. Second, and more precisely, we used our new procedure to focus on the speed of retrieval of information from vWM. We studied RTs to different probes as a function of the number of colored shapes that were presented in the memory display (i.e., the set size, which varied between 1 to 4 colored shapes). Third, in most previous research comparing one-feature conditions with multiple-feature conditions, it is not clear whether participants need to store binding information over and above feature information, but this was manipulated in our study (cf. Cowan et al., 2013).

The most important innovation of our study was the manipulation of the use of features or objects through probe presentation and instructions. The relevance of binding was suggested by presenting each probe as a colored shape for some participants, and as separate color and shape for other participants. Moreover, each probe group was split into two groups that differed by instructions. Participants for whom binding was encouraged through instructions had to judge whether probes with both color and shape corresponded to one of the colored shapes that were present in the studied array. Those for whom binding was discouraged through instructions had to judge whether the color and the shape of the probes both were present in the studied array, either in the same object or in different objects. Consider, for example, a memory display showing a red circle and a yellow square, followed by a probe showing red and square (either as an integrated object or as two separate features next to each other). Participants for whom binding was encouraged were to respond "different" to this probe because it did not correspond to one of the objects they were maintaining. However, participants for whom binding was discouraged were to respond "same" because red is one of the colors they were maintaining and square is one of the shapes they were maintaining. The resulting four testing groups can be described as follows: (1) Binding-encouraged, unintegrated probing, (2) Binding-encouraged, integrated probing, (3) Binding-discouraged, unintegrated probing, and (4) Binding-discouraged, integrated-probing. In all testing groups, when probing memory for a single feature, we used probes for which the value of the irrelevant feature was constant and neutral. When memory for color was probed, a particular irregular blob of color was presented (signifying no shape). When memory for shape was tested, the black outline of a shape was presented (signifying no color). To infer the use of object vs. feature information, we examined three markers in each of these testing groups, as follows.

Marker 1: Memory search rates for probes with one versus two features. Our main marker was the comparison of memory search rates for two features with memory search rates for a single feature. Therefore, for one- and two-feature searches, we examined search functions. Each search function was relating correct response times to the number of colored shapes presented in the memory display (i.e., RT set size functions, see Sternberg, 1966, 1969). We expected that, if multi-featured objects are stored as integrated objects, then searching for two features (either with or without the binding information) should not take longer than searching for a single feature. That is, the search slope for multi-featured probes should not be steeper than the search slope for single-feature probes. An alternative possibility is that if participants must search for each feature in vWM one at a time consecutively, then searches for probes with two features should occur at a search slope twice as slow as for probes with one feature. Many intermediate results are also possible, such as searches that occur in parallel for the two features but in a resource-limited manner, so that the slope is slower for two-featured probes than for one-featured probes, but not twice as slow. This kind of intermediate pattern would point to some combination of feature-based and object-based storage in vWM, rather than pure object-based representations.

Marker 2: Color and shape combination in two-feature, target-absent probes. The current approach provided us with two additional markers that can be used to infer the use of object vs. feature information in a change detection task with multi-featured objects. Consider first the testing groups for whom instructions encouraged the use of binding information. Here, participants had to judge whether probes with both color and shape corresponded to one of the colored shapes that were present in the studied array. Three different types of probes required a *different* response in the binding-encouraged testing groups: (*1*) probes that had a color and a shape that were in the studied array but not in the same object (i.e., 2 old features); (*2*) probes that had either a color that was in the studied array with a shape that was not, or a shape that was in the studied array with a color that was not (i.e., 1 old feature); and (*3*) probes that had a color and a shape that were not in the studied array (i.e., 0 old features). We examined whether the time taken to correctly reject these target-absent probes varied as a function of the number of old features that were present in the probe. If it takes longer to correctly reject a two-feature probe when the probe consists of more old features, then this would provide us with evidence for the use of featural information.

Marker 3: Color and shape combination in two-feature, target-present probes. Now consider the testing groups for whom instructions discouraged binding. Here, participants had to judge whether the color and the shape of the probes both were present in the studied array, either in the same object or in different objects. We examined whether the decision to correctly accept a target-present probe took longer for probes with color and shape that pertained to two different objects at study than for probes with color and shape that pertained to the same object at study. If the time taken to judge a target-present probe depends on whether or not the features were presented in the same object at study or not, then this would provide us with evidence for the use of object information.

It is possible that the use of studied objects might induce objects as the favored units in vWM because LTM is typically associated with actual objects or concepts and with coherent units or chunks of information, rather than with the representation of independent features. Nevertheless, we found that in three out of the four testing groups, the basic unit for vWM retrieval was predominantly feature-based. Search was predominantly object-based only when all factors support that basis of search (in the binding-encouraged, integrated-probing testing group).

Method

Participants

Ninety-one undergraduate students (74 female) at the University of Missouri-Columbia participated and were paid $15 for their participation. They were native speakers of English and had normal or corrected-to-normal vision. Performance-based exclusions discussed in the Results section led to a final sample of 80 (66 female), with n=20 in each of four groups\.

Design

Participants were randomly assigned to one of the four between-participants experimental conditions, defined by crossing two factors: Binding Instructions (binding-encouraged versus binding discouraged) and Presentation of Two-Feature Probes (unintegrated probing versus integrated probing). For all groups, two factors were manipulated within participants: Set Size (4 levels: 1, 2, 3, or 4 colored shapes to remember) and Probed Memory (3 levels: color, shape or both features).

Materials and Procedure

Stimuli were presented to participants on a standard CRT monitor and participants sat at a comfortable distance from the screen while performing the experiment. Responses were collected by button presses on a Serial Response box connected to the computer.

Practice. Before the experimental trials, participants received instructions that included a visualization of the different kind of trials and probes. An array of three items was used for this visualization. This was followed by the presentation of a practice study set of another three items and one block of 24 practice trials that tested memory for the three items in the practice study set. The types of probes shown in these practice trials were the same as the following experimental set-size-three test trials in all respects.

Trial block progression. Following practice, the experiment consisted of 16 blocks of experimental trials, four blocks of each set size (1-4), with the 16 blocks presented in a totally randomized order. The kinds of events in a 3-item trial block are illustrated in Figure 1. Every block started with a screen asking the participant to push any button upon which the study items for that block appeared on screen. Study items were colored shapes presented on a grey background. To create the items, their color and shape were selected without replacement for each block from a pool of 8 shapes (square, circle, triangle, cross, star, hourglass, arc, hexagon) and 8 colors (red, blue, green, magenta, black, yellow, cyan and white). All study items had maximum height and width of 1.4 cm at a typical viewing distance of 50 cm, a visual angle of 1.6^{o}). They were presented simultaneously, arranged on an invisible horizontal line, symmetrically around the center of the screen, with their center separated by 4.67 cm. The study items stayed on screen until the participant reported being ready for testing by pushing any button upon which the test phase started.

Within the test phase of every block, memory was tested on 24 trials. On one third of these trials, participants were presented with a color probe consisting of a shapeless colored blob. On another third of the trials, participants were presented with a shape probe consisting of a colorless shape (black line drawing filled with the same grey as the background). On the remaining third of the trials, participants were presented with color and a shape. Depending on the between-participant variable Presentation of Two-Feature Probes, the color and shape were either presented in an integrated way (i.e., a colored shape, as in the last screen in the top panel of Figure 1) or in an unintegrated way (i.e., a shapeless color next to a colorless shape, as in the last screen in the bottom panel of Figure 1). In the latter condition, on half of the trials for each participant, the shapeless color was presented on the left side of the screen and the colorless shape on the right of the screen; in the other half, their positioning was the other way around.

Instructions. The specific instructions for these three kinds of memory probes were different between the testing groups; depending on the between-participant variable Binding Instructions, the specific instructions for these three kinds of memory probes were the following.

Participants in the binding-encouraged condition were asked to judge, (1) when presented with a shapeless colored blob as probe item, whether its color corresponded to one of the colors in the set of colored shapes that they were trying to remember; (2) when presented with a colorless shape as probe item, whether its shape corresponded to one of the shapes in the set of colored shapes that they were trying to remember; and (3) when presented with a colored shape (or, for two of the four testing groups, a shapeless color next to a colorless shape) as probe, whether the color and the shape went together in one of the colored shapes in the set that they were trying to remember.

Of the colored-blob probes, on half of the trials per block, the probe color matched a studied item; on the remaining four trials, the probe color did not match. When the probe color did match, each of the studied colors had equal chances of being presented as the probe. Similarly, of the colorless shape probes, on half of the trials per block, the probe shape matched a studied item; on the remaining four trials, the probe shape did not match. When the probe shape did match, each of the studied shapes had equal chances of being presented as the probe.

Finally the two-feature probes included various possible combinations. On half of the trials per block, the probe color and shape matched a single studied item; on the remaining four trials, the probe color and shape did not match. When the probe color and shape did match a studied item, each of the studied objects had equal chances of being presented as the probe. For the non-matching probes, there was one trial in which a matching probe color (from one of the studied objects) was shown with a new shape, one trial in which a matching probe shape was shown with a new color, one trial in which a matching probe color and probe shape were drawn from different studied objects, and one trial in which a new color was shown with a new shape.

When the probe color or probe shape matched studied objects, each of the studied colors and shapes had equal chances of being presented as the probe.

For participants in the binding-discouraged condition, the aforementioned stimuli and ratios were again used. The judgments to be made were the same as in the binding-encouraged groups, with one important exception. When two features were presented, instead of judging binding, the task was to judge whether both the color and shape corresponded to objects the participant was trying to hold in memory, regardless of whether this color and shape came from the same object in memory or from two different objects. Thus, if the features were in the studied set but they came from different objects, the correct answer was “different” for binding-encouraged groups versus “same” for binding-discouraged groups.

Further procedural details. In all testing groups, the different probe types were presented in a randomized order within each block. All probe items were preceded by a fixation symbol, displayed on screen for 1000 ms. All probe items had the same dimensions as the study items and were presented on the same grey background. When a shapeless color and a colorless shape were shown together, the left position was 2.33 cm left from the center on the screen, the right position 2.33 cm right from the center of the screen. Responses were made by pressing the rightmost button for ‘yes’ responses and pressing the leftmost button for ‘no’ responses. Participants were asked to respond as quickly as possible without making errors. The probe remained on screen until the participant responded or until 2000 ms elapsed.

Feedback was provided after every test trial and, at the end of each block, participants’ percentage of correct responses was displayed on screen. Participants knew that, if this percentage was lower than 90%, they had to do the block over again. In that case, they were presented with the same study items, followed by 24 new test trials. A given block was not repeated more than 3 times for a given participant. On average, we observed that the number of times a given study block was run increased with the number of colored shapes presented: 1.04 times (*SD* = .12) for 1 item, 1.15 times (*SD* = .26) for 2 items, 1.43 (*SD* = .44) for 3 items and 1.85 (*SD* = .53) for 4 items.

Response time analysis. Visual inspection of the RT search curves showed that RT increased with Set Size, and revealed a slight bend in the curves, indicating that the rate of change in our data increased more quickly between set size 1 and set size 2 than over the larger set sizes. This suggested that the memory search curves might be best described by a logarithmic trend rather than by a linear trend. A similar observation was made by Wolfe (2012), who demonstrated that memory search times varied logarithmically with memory set size rather than linearly when subjects were to maintain sets of 1 to 16 photographic objects[1]. Following Wolfe's procedure, we plotted RT as a function of $\log_2$(set size) and observed that mean RTs were a direct linear function of the logarithm of memory set size. To test whether our RT search curves were better captured by the linear trend relating RT to Set size or by the linear trend relating RT to log2(Set size), we calculated, for each individual, regressions for both functions, separately for the one-feature probe curves and the two-feature probe curves, distinguishing between target-present trials and target-absent trials. This was done for the four testing groups. The relevant mean RTs appear in Table 1. With the exception of one curve out of the 16 resulting trend lines, the logarithmic functions provided a fit that was either the same or better than the linear functions. As a result, in our analyses we used the slope values of the individual RT x $\log_2$(set size) functions. Slopes of the individual RT x log2(Set size) functions were calculated for each relevant experimental condition.

Results

The data of five participants were excluded from subsequent analyses because in at least one block, they did not reach error-free memory even in the last of three repetitions of the test phase of that block. The participants who passed had at least .75 correct in the final test phase of each block for each of the three probe conditions in the block: color, shape, or both probed. Thus, they passed all four of these blocks for each of the four set sizes. To ensure that participants were following the instructions when performing the task, only the data of participants who responded correctly to recombination probes were included in the following analyses. In this case, in the last test phase of a given block, proportion of correct old/new judgments averaged across set sizes had to reach a criterion of .67. This led to discarding the data of six additional participants. For the remaining 80 participants (20 per between-participant condition), responses of the last test phase of a block were analyzed (i.e., 384 test trials per subject in total, 96 test trials for each set size).

Accuracy

While our main focus was on response times, we first examined accuracy of the responses in the last block. Accuracy was .93 or above in every condition except one (binding discouraged, integrated presentation, two-feature probe, target absent: M=.83, SD=.07).

Response Times

RTs for correct responses were analyzed. Our three markers were examined in turn. The predictions for each of these markers can be found at the end of the introduction. Finally, for completeness, we will end the results section by reporting findings that did not directly concern the study of our three markers. Analysis of the intercepts of the RT x $\log_2$(set size) functions will be reported as well as remaining findings concerned with the search slopes that did not directly concern the main comparison of one-feature vs. two-feature memory search rates.

Marker 1: Memory search rate. As described before, we found that RT search functions were better described by a logarithmic trend than by a linear trend. Therefore, we studied slopes values of RT x $\log_2$(set size) functions to examine the difference between search rates associated with one-feature and two-feature probes. RT search functions associated with one-feature and two-feature probes for the four testing groups are shown in Figure 2. What can be seen immediately is that one can rule out the hypothesis that the color and shape features are searched one at a time consecutively. Rather than the slopes of two-feature searches being twice the slopes of one-feature searches, both types of searches produce rather similar search slopes. Despite this similarity in slopes, though, consistent group differences can be seen, which, if statistically confirmed, will indicate that the nature of representations varied between the different testing situations. In three out of four testing groups, two-feature searches produced steeper slopes than one-feature searches. Only in the binding-encouraged, integrated-probing testing group was there no difference in slope between two-feature and one-feature probes. The suggestion is that memory search was object-based in this testing group only.

To compare memory search slopes associated with one-feature probes and two-feature probes, we created a one-feature condition by pooling RTs for color and shape trials, for each participant and each relevant experimental condition. To allow for a comparison of target-present vs. target-absent trials across testing groups, recombination trials for which the correct response changed between testing groups were left out of analyses of the RT search functions. and analyzed by performing an ANOVA with two within-participants variables, Probed Memory (one-feature vs. two-feature) and Probe Type (Target-present vs. target-absent), and two between-participants variables, Binding instructions (binding-encouraged vs. Binding-discouraged) and Presentation of Two-Feature probes (integrated vs. unintegrated). The ANOVA of RT slopes revealed a significant effect of Probed Memory, $F(1, 76) = 26.19$, $p = .00$, $\eta_p^2 = .26$, a significant interaction between Probed Memory and Binding instructions, $F(1, 76) = 4.81$, $p = .03$, $\eta_p^2 = .06$, a significant interaction between Probed Memory and Presentation of Two-Feature probes, $F(1, 76) = 15.43$, $p = .00$, $\eta_p^2 = .17$, and a three-way interaction between Probed Memory, Binding instructions and Presentation of Two-Feature probes, $F(1, 76) = 5.31$, $p = .02$, $\eta_p^2 = .07$, indicating that the difference in slopes of one-feature searches versus two-feature searches is different between the testing groups. This effect did not interact with Probe Type, $F<1$.

Two-feature searches were associated with steeper slopes than one-feature searches in three out of the four testing groups [slopes of 130 ms vs. 97 ms in the binding-encouraged, unintegrated probing group, $F(1, 76) = 20.96$, $p = .00$, $\eta_p^2 = .22$; 127 ms vs. 94 ms in the binding-discouraged, unintegrated probing group, $F(1, 76) = 19.95$, $p = .00$, $\eta_p^2 = .21$; and 117 ms vs. 96 ms in the binding-discouraged, integrated probing group, $F(1, 76) = 8.09$, $p = .006$, $\eta_p^2 = .10$]. Only in the binding-encouraged, integrated probing group were two-feature searches not slower than one-feature searches, 110 ms vs. 122 ms, $F(1, 76) = 2.74$, $p = .10$, $\eta_p^2 = .03$. It is worth noting that, in those testing groups for which we observed that two-feature searches elicit steeper search slopes than one-feature searches, the ratio between the two-feature slopes and one-feature slopes was similar across the testing groups, with two-feature searches being about 30% slower than one-feature searches (slope ratio of 1.34 in the binding-encouraged, unintegrated presentation group, 1.35 in the binding-discouraged, unintegrated presentation group and 1.22 in the binding-discouraged, integrated presentation group).

In sum, when the use of binding information was discouraged through instructions, searching two features was associated with a 30% time-cost, compared to searching one feature. However, when the use of binding information was encouraged through instructions, and the use of binding information was further supported by presenting color and shape as an integrated probe object at test, searching for one feature became as slow as searching for two features. These data suggests some combination of feature-based and object-based representation in most of the groups, versus a pure object-based representation for these basic trial types when all factors favor integration (in the binding-encouraged, integrated probing group).

Marker 2: Color and shape combination in two-feature, target-absent probes. As can be seen in Figure 3, the time taken to correctly reject a target-absent, two-feature probe in the binding-encouraged testing groups was a direct function of the number of old features present in the probe, with more matching features resulting in slower RTs. No difference was observed between integrated and unintegrated two-feature probes. These results suggest that features were important even though the instructions encouraged the use of binding information, regardless of how color and shape were presented at test.

To compare the correct response times for probes with zero, one or two old features in the binding-encouraged testing groups, we created a "one old feature" condition by pooling RTs for ""old color + new shape" and "new color + old shape". Due to the small number of observations per set size for the different types of two-feature, target-absent probes across the experiment, correct response times of each participant were averaged across set size. Since recombination probes (i.e., two old features) could only appear in set sizes 2, 3, and 4, we only included these set sizes for all probe types. That is, for each participant, we first calculated the average response time per set size and then we averaged across the three different set sizes. An analysis of variance (ANOVA) was performed on these RTs with Number of old features (0, 1, or 2) as within-participants variable and Presentation of Two-Feature Probes (unintegrated-probing versus integrated-probing) as between-participant variable. The ANOVA revealed a significant effect of Number of old features, $F(2,76)=207.84$, $p=.00$, $\eta_p^2 = .85$, that did not differ as a function of how the features were presented, $F<1$. In fact, the time taken to correctly reject a target-absent probe increased as a linear function of the number of old features that are present in the probe [linear trend, $F(1,38)=437.43$, $p=.00$, $\eta_p^2 = .92$]. The slope revealed that it took about 155 ms longer to reject a two-feature, target-absent probe for each additional old feature that was present in the probe ($R^2 = .97$). There was no main effect of Presentation of Two-Feature Probes, $F(1,38)=1.38$, $p=.25$. Taken together, correct rejection of two-feature, target-absent probes was slowed down by the presence of more old features, indicating the incorporation of some feature information along with object information even when the instructions encouraged binding.

Marker 3: Color and shape combination in two-feature, target-present probes. The time taken to correctly accept a target-present, two-feature probe in the binding-discouraged testing groups was shorter when the color and the shape of the probe pertained to the same studied object than when the color and the shape of the probe were drawn from two different studied objects, regardless of how probes were presented. Thus, even though the use of binding information was discouraged through the instructions, object information played a role. Importantly, this effect cannot be attributed to simple matching of the percept at test with the percept at study because it did not interact with the way in which color and shape were presented at the moment of test (as an integrated object vs. next to each other).

In the binding-discouraged groups, we compared the correct response times for recombination probes (i.e., when old features pertain to different studied objects) to the correct response times for the other two-feature, target-present probe type (i.e., when old features pertain to the same studied object). For both of these probe types, correct response times of each participant were averaged across different set sizes (2, 3 and 4). An analysis of variance (ANOVA) was performed on these RTs with Target-Present Probe Type (same vs. different object) as within-participants variable and Presentation of Two-Feature Probes (unintegrated-probing versus integrated-probing) as between-participant variables. Correctly accepting a target-present probe was faster when the old features pertained to the same object at the time of study compared to when the old features pertained to two different study objects, $F(1,38)=11.05$, $p=.00$, $\eta_p^2 = .23$, 751 ms vs. 709 ms, respectively. Although RTs were longer when color and shape were presented next to each other, compared to when they were presented as an integrated object, $F(1,38)=6.41$, $p=.02$, $\eta_p^2 = .14$, this effect did not interact with Target-Present Probe Type, $F<1$. Thus, correct acceptance of two-feature, target-present probes was faster when they are made up of features that pertain to the same studied object, indicating the incorporation of some object information along with feature information even when the instructions discouraged binding.

Additional findings. Here we report analysis of the intercepts of the RT x $\log_2$(set size) functions, and other findings of the aforementioned analysis of the slopes of the RT x $\log_2$(set size) functions. These additional results enrich our understanding of the processes involved in our procedure.

Intercepts. Intercepts indicate processes that occur just once per trial and, for example, probe type effects on intercepts could reveal processes involved in decoding of the probes. We observed that, in most situations, responses to two-feature probes were slower than responses to one-feature probes. This is not surprising given that judgments of one-feature probes require perception and consideration of a single feature while judgments of two-feature probes require perception and consideration of two features. An exception to this was the particular fast responses on target-present, two-feature probe trials when probes were presented in an integrated way (as seen in Figure 4). This most probably reflects the fact that on these trials, the percept at test matches the percept at study, resulting in fast recognition of the original study object. The difference in intercept between target-absent and target-present trials was much larger for integrated two-feature probe trials than for any other trial type, suggesting that the integrated presentation of two features at test resulted in making target-present responses easy while making target-absent responses more difficult.

Intercepts of the individual RT x log2(Set size) functions were calculated for each relevant experimental condition and analyzed by performing an ANOVA with two within-participants variables, Probed Memory (one-feature vs. two-feature) and Probe Type (Target-present vs. target-absent), and two between-participants variables, Binding instructions (binding-encouraged vs. Binding-discouraged) and Presentation of Two-Feature probes (integrated-probing vs. unintegrated-probing). The ANOVA revealed a significant effect of Probed Memory, $F(1, 76) = 158.34$, $p = .00$, $\eta_p^2 = .68$, that interacted with Presentation of Two-Feature probes, $F(1, 76) = 40.29$, $p = .00$, $\eta_p^2 = .35$, a significant effect of Probe Type, $F(1, 76) = 142.15$, $p = .00$, $\eta_p^2 = .65$ that also interacted with Presentation of Two-Feature probes, $F(1, 76) = 6.00$, $p = .02$, $\eta_p^2 = .07$, and a significant three-way interaction between Probed Memory, Probe Type and Presentation of Two-Feature probes, $F(1, 76) = 55.17$, $p = .00$, $\eta_p^2 = .42$. There were no other significant effects.

For most trials, the intercepts of the search functions associated with two-feature trials were significantly higher than the intercepts of the search functions associated with one-feature trials [intercepts of 554 ms vs. 495 ms on target-present trials with unintegrated probing, $F(1, 76) = 91.07$, $p = .00$, $\eta_p^2 = .55$; 613 ms vs. 529 ms on target-absent trials with unintegrated probing, *F*(1, 76) = 114.02, p = .00, η_p^2 = .60; and 603 ms vs. 518 ms on target-absent trials with integrated probing, *F*(1, 76) = 116.26, p = .00, η_p^2 = .60)]. Only on target-present trials when two-feature probes are presented as integrated objects, the intercept of the search function associated with two-feature trials was significantly lower than the intercept of the search function associated with one-feature trials, 470 ms vs. 508 ms, *F*(1, 76) = 38.42, p = .00, η_p^2 = .34. In fact, as can be seen in Figure 4, the triple interaction occurred because the difference in intercept between target-present and target-absent trials was much larger for integrated two-feature probe trials than for any other trial type, suggesting that the integrated presentation of two features at test resulted in making target-present responses easy while making target-absent responses more difficult.

Remaining findings concerning slopes. Helping to clarify the nature of the search process, the aforementioned ANOVA of RT slopes revealed a significant effect of Probe Type, *F*(1, 76) = 32.81, p = .00, η_p^2 = .30, a significant interaction between Probe Type and Binding instructions, *F*(1, 76) = 7.47, p = .008, η_p^2 = .09, a significant interaction between Probe Type and Probed Memory, *F*(1, 76) = 75.45, p = .00, η_p^2 = .50, and a significant three-way interaction between Probe Type, Probed Memory and Binding instructions, *F*(1, 76) = 6.26, p = .01, η_p^2 = .08. Figure 5 shows the slopes associated with the relevant experimental conditions. Visual inspection suggests that two-feature, target-present trials are associated with particularly steep search slopes and this was confirmed statistically, *F*(1, 76) = 59.87, p = .00, η_p^2 = .44, when instructions encouraged binding, and *F*(1, 76) = 34.99, p = .00, η_p^2 = .32, when instructions discouraged binding. As can be seen in Figure 5, this finding was more pronounced in binding-encouraged testing groups. No other main effects or interactions were significant.

The finding of steeper slopes for two-feature probes on target-present trials suggests to us that when sameness (i.e., no change) is detected, the search process for two-feature probes is supplemented with an extra step. Presumably, when participants judge two-feature probes, the detection of an absence of change detection is followed by a verification process to ensure that no change was missed and that the probe item therefore does match an item in memory. The data suggest that, in the current study, this process would only be used when a single decision is to be made based on the status of two separate features (i.e., for two-feature probes). The initial search for difference as opposed to sameness, and therefore slower search when there is a match between the array and probe, is discrepant from what is obtained in a typical list search task (e.g., Sternberg, 1966), but it has been observed before in array memory search tasks (e.g., Gilchrist & Cowan, 2014; Hyun, Woodman, Vogel, Hollingworth, & Luck, 2009). More research is necessary to firmly establish the existence and the nature of the proposed verification process.

Discussion

The present study aimed at investigating the basic unit of vWM. Two contrasting hypotheses of how multi-featured objects are stored in and retrieved from vWM were compared by focusing on the timing of error-free performance in a studied-objects change detection task. Importantly, four different testing groups were created by varying the instructions and the way in which probes with both color and shape were presented. Instructions explicitly either encouraged or discouraged the use of binding information and probes with both color and shapes were presented either as integrated objects or as independent features next to each other. Three markers for object-based vs. feature-based views on vWM were examined. The observed pattern of results is summarized in Table 2, together with how each of the findings supports the use of object-based vs. feature-based information in our vWM task.

In short, the difference in search slope between response times to single-feature versus multi-featured probes depends on the testing situation. Retrieving two features took longer than retrieving a single feature, except in the binding-encouraged, integrated-probing group. This suggests that participants can use either object-based or feature-based retrieval of information from vWM and that search is pure object-based only when all factors support that basis of search: when the instructions stress the task-relevance of binding and this is further supported by showing two-feature probes as integrated objects. Thus, the basic unit of vWM is not fixed and relative small changes in testing situation can influence the favored unit.

Furthermore, analyses of color and shape combination in two-feature probes showed that that individual feature information causes slower responses when judging object information (binding-encouraged groups) and that bound object information causes slower responses when judging separate feature information (binding-discouraged groups). This suggests that while retrieval can be either object-based or feature-based, featural information was available when search was observed to be object-based and object information was available when search was observed to be feature-based. Together, this pattern suggests that representations in vWM include both features and objects so that, even though different testing situations can result in a stronger emphasis on either the feature dimension or the object dimension, both levels of representation affect change detection performance. These results have important implications for our understanding of the representations used in vWM.

In what follows, we discuss two main conclusions that can be drawn from our study: (*1*) that the unit used for retrieval from vWM is not fixed, and (*2*) that features and objects both affect change detection performance.

The Unit Used for Retrieval from vWM is Not Fixed

The foremost point about the present findings is that they challenge the assumption that the basic unit of vWM is always an integrated object (Luck & Vogel, 1997; Rensink, 2000; Vogel et al., 2001; Zhang & Luck, 2008). Instead, our results show that participants can use either object-based or feature-based retrieval of information from vWM and that search is object-based only when the instructions stress that binding is relevant and this task-relevance is further supported by presenting color and shape as integrated objects at test (binding-encouraged, integrated-probing testing group). When the instructions discouraged the use of binding information, participants did not use object-based retrieval. Instead, when the task ensured that only information about color and shape was available, without information about how they were combined into objects during the study phase, people seemed to use features as the basic unit of retrieval. While one might expect that people would choose object-based retrieval rather than feature-based retrieval when the task was such that binding information was available in addition to information about color and shape, this was only the case when probes with both color and shape were presented in an integrated way, i.e., as a colored shape. In that particular case, there was no difference between retrieving two features and retrieving a single feature. Thus, our data suggest that explicitly encouraging binding through instructions only makes people opt for object-based search if the probes are presented in a way that matches the idea of binding information being relevant. In that particular case, there was no difference between retrieving two features and retrieving a single feature.

Interestingly, when binding is encouraged through instructions and the task-relevance of binding is further supported by presenting two-feature probes as integrated objects at test, retrieving only a color or only a shape took longer than in the other testing groups. This indicates that while single features are directly accessible when features are emphasized in vWM, it might take an additional step to have access to the component features when objects are emphasized in vWM. Theoretically, when confronted with a one-feature probe (e.g., a yellow blob) while having objects in mind, participants could either turn the feature probe into an object representation or break down each of the objects in WM into its constituent features so that the extracted relevant features (e.g., colors) could be compared with the feature probe. The first option would be reflected in a change in the intercept of the memory search function (because it would involve processing of the probe), while the latter would result in a change of the slope (because it would involve processing of each item in vWM). Our data shows a change in slope, supporting the idea of feature extraction when objects are used in vWM.

The observation that features were the favored unit for search in vWM in three out of four testing groups in the current study is quite surprising if one takes into account the LTM contribution to our paradigm. Participants first studied the memory set as long as they wanted and after that, their memory was tested on a block of 24 probe trials. This was done because we aimed at error-free memory performance in our participants. By using this studied-objects variant of change detection, memory items were most probably encoded into LTM during the study phase and then, during test trials, the memorized list was retrieved into vWM with the support of LTM, after which subjects searched the content of their vWM before making a same/different judgment. One could argue that using this studied-objects variant might induce objects as the favored units in vWM because LTM is typically associated with actual objects or concepts and with coherent units or chunks of information, rather than with the representation of independent features. Even though the colored shapes might have been represented as objects in LTM, subjects favored features as the basic unit for vWM retrieval in three out of four test situations in the current study.

One possible reason why a feature-based representation was robust in vWM despite LTM support for the objects is that these objects changed from one trial block to the next throughout 16 blocks, with different pairings of color and shape in each block. As a result, for trial blocks after the first few, there often should have been considerable proactive interference with memory of studied objects from previous trial blocks. It has been argued that one function of working memory is to preserve representations that are current and help shield them from proactive interference (e.g., Cowan, Johnson, & Saults, 2005; Halford, Maybery, & Bain, 1988; Oberauer & Vockenberg, 2009). Therefore, the long-term support for the representations might have had less impact on the results than if the studied objects had stayed constant throughout the experiment. This is an important question for future study.

One might also wonder to what extent the current findings are specific to the use of single-item probes. Change detection studies have used both whole-display probes and single-item probes; we used a single-item probe on each trial because it produces better performance than a whole-array probe, probably by eliminating interference from attentional distraction, multiple decisions and conflicting features (see Cowan, 2005; Logie, Brockmole, & Jaswal, 2011; Luck & Vogel, 1997; Wheeler & Treisman, 2002). The use of centrally displayed single-item probes ensures that subjects could not use location information to support binding between color and shape. One might argue that this encourages the use of bound objects rather than features. Nevertheless, we found that in three out the four testing situations, the basic unit was predominantly feature-based.

In sum, the unit used for retrieval from vWM is not fixed and while the choice between object-based and feature-based retrieval seems a strategic one, influenced by instructions, this effect depends heavily on more subtle changes such as the way in which memory is probed. We believe this finding to be of special importance. Remember that our four testing groups do not differ in any way as far as the study phase is concerned. Colored shapes are simultaneously shown on screen, in an integrated way, vertically aligned, for as long as needed. Nevertheless, drastic changes in the kind of representation used when searching for information in vWM were observed by introducing relative small changes in testing conditions. This observation might help us in understanding why results of previous studies are inconsistent as far as the nature of the basic unit used in vWM is concerned.

Of course, our findings do not inform us in any way whether retrieval is object- or feature-based when there is no clear guidance from instructions or task demands. The current findings only indicate that instructions concerning the use of binding information can influence the nature of the representation used for retrieval from vWM, which also depends on how memory is probed. It might very well be that, in ambiguous situations, people assume that binding information will be important, leading them to adopt an object-based strategy of search provided that color and shape are presented as integrated objects at test. Our findings do, however, indicate that the basic unit of vWM is not fixed and that relatively small changes in testing situation can influence the favored unit used for retrieval.

Features and Objects Both Affect Change Detection Performance

Our data demonstrate that featural information was available and influenced reaction times even when search was observed to be primarily object-based, and that object information was available and influenced reaction times even when search was observed to be primarily feature-based. One the one hand, we observed in both binding-encouraged groups that it took longer to reject a two-feature, target-absent probe as more matching features were present in the probe. On the other hand, we observed in both binding-discouraged groups, that it took longer to accept a two-feature, target-present probe when it was made up of features that pertained to different studied objects than when it was made up of features that pertained to the same studied object. Thus, individual feature information slowed down responses that only required consideration of the object as a whole and object information slowed down responses that only required consideration of feature information. This pattern suggests that, even though different testing situations can result in a stronger emphasize on either the feature dimension or the object dimension, both levels of representation affect change detection performance and thus, representations in vWM include both features and objects (see Table 2; cf. Cowan et al., 2013; Hardman & Cowan, in press; Oberauer & Eichenberger, 2013).

One might wonder to what extent the current findings can be generalized to the more standard change detection paradigm. We would like to argue that our procedure should be viewed as an independent line of investigation. Future research might, however, explore the convergence/divergence between the two kinds of procedures, which, after all, seek to examine the functioning of the same cognitive system, vWM. A first step could be to apply our manipulations of the testing situation in a standard change detection paradigm. Given that accuracy will be lower, one would have to replace RTs for error-free performance with some method to combine RT and accuracy for a measure of overall response efficiency (e.g., the drift rate parameter of Wagenmakers, Van Der Maas, & Grasman, 2007).[2] The main difference between our studied-objects procedure and the standard change detection paradigm is in LTM support. Even though LTM is typically associated with objects, we found that in three out the four testing situations, the basic unit was predominantly feature-based. Therefore, we speculate that a similar pattern would be observed in the standard change detection paradigm.

Conclusion

This study has explored how multi-featured objects are stored in vWM by focusing on the timing of error-free performance in a studied-objects variant of the change detection paradigm in which objects were learned during the training phase of each trial block. We have shown that participants use either object-based retrieval or feature-based retrieval, depending on the testing situation; retrieval was object-based only when binding between color and shape was encouraged through instructions while presenting probes with color and shape as integrated objects. However, even though different testing situations can result in a stronger emphasis on either the feature dimension or the object dimension, neither one disappears from the representation and both affect change detection performance.

Footnote

[1] Like in a typical Sternberg task, responses in our procedure took longer when there were more items in working memory to search through. However, we observed response times to vary logarithmically with memory set size in the current study, whereas response times in the Sternberg task are typically found to be linearly dependent on the size of the memory set (e.g., Sternberg, 1966, 1969). Wolfe (2012) noted that logarithmic memory search functions are compatible with the idea of half of the items being eliminated on the first step, another half on the next step, and so on. It might be possible that memory search operates differently for material of higher complexity such as the photographic real-life objects used by Wolfe and our colored shapes, compared to material of lower visual complexity such as letters or digits.

[2] We thank Chris Donkin for suggesting this insightful idea.

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Tables

Table 1

Observed RT Mean Response Times and Standard Deviation (in parentheses), as a function of Probed Memory (One-Feature vs. Two-feature), Probe Type (target-present vs. target-absent), and Set size (1 to 4), for the four testing groups resulting from crossing the factors Binding instructions (encouraged vs. discouraged) and Presentation of Two-Feature probes (unintegrated vs. integrated).

		One-feature probes				**Two-feature probes**			
		Set Size (number of items in the probed memory set)							
Testing group	**Probe Type**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
Binding-encouraged, unintegrated presentation	**Target-present**	506 (86)	596 (83)	657 (88)	690 (106)	546 (87)	742 (101)	792 (121)	869 (142)
	Target-absent	548 (100)	617 (92)	684 (111)	757 (122)	621 (89)	706 (112)	795 (147)	819 (125)
Binding-encouraged, integrated presentation	**Target-present**	517 (62)	631 (64)	715 (95)	750 (101)	469 (70)	659 (87)	731 (111)	747 (125)
	Target-absent	531 (84)	600 (80)	703 (96)	781 (80)	618 (114)	659 (103)	733 (125)	764 (144)
Binding-discouraged, unintegrated presentation	**Target-present**	483 (54)	574 (73)	625 (83)	656 (70)	543 (77)	698 (127)	770 (101)	811 (130)
	Target-absent	528 (63)	605 (71)	697 (74)	722 (79)	617 (82)	709 (89)	804 (139)	848 (104)
Binding-discouraged, integrated presentation	**Target-present**	498 (77)	602 (124)	639 (117)	692 (127)	466 (92)	570 (122)	661 (146)	744 (182)
	Target-absent	535 (106)	598 (112)	681 (121)	730 (135)	603 (133)	683 (148)	760 (138)	792 (194)

Table 2

Overview of key aspects of our results and what they suggest concerning the use of features and objects (italic) for each of the four testing situations defined by Binding instructions (Encouraged vs. Discouraged) and Presentation of two-feature probes (Integrated vs. Unintegrated).

Testing situation	**Analysis of RT search slopes**	**Analysis of color and shape combination (target-absent, two-feature probes in Binding-encouraged groups)**	**Analysis of color and shape combination (target-present, two-feature probes in Binding-discouraged groups)**
Binding-encouraged, unintegrated presentation	Two-feature slope > One-Feature slope ***feature-based search***	correct rejection is slowed down by the presence of more old features ***featural information plays a role***	
Binding-encouraged, integrated presentation	Two-feature slope = One-Feature ***object-based search***	correct rejection is slowed down by the presence of more old features ***featural information plays a role***	
Binding-discouraged, unintegrated presentation	Two-feature slope > One-Feature slope ***feature-based search***		correct acceptance is faster when features pertained to same studied item ***object information plays a role***
Binding-discouraged, integrated presentation	Two-feature slope > One-Feature slope ***feature-based search***		correct acceptance is faster when features pertained to same studied item ***object information plays a role***

Figure Captions

Figure 1

Illustration of the paradigm. Examples of trials with set size 3. The study phase is followed by at least one test phase of 24 trials. Examples are shown of two one-feature probe trials (one color probe and one shape probe) and two two-feature probe trials (i.e., probes with color and shape). For the two-feature probe, two examples are shown: (1) an example of a recombination probe, together with the correct response (same or different) which changes between testing groups, and (2) an example of a two-feature probe for which the correct response is "different" in all testing groups (i.e., *different* two-feature probe). **Upper panel**: two-feature probes are presented in an integrated way; **Lower panel**: two-feature probes are presented in an unintegrated way.

Figure 2

Mean RT (reaction time, in ms) as a function of $\log_2$(Set size) for one-feature and two-feature probes. **Upper-left panel**: binding-encouraged, unintegrated probing testing group; **Lower-left panel**: binding-encouraged, integrated probing testing group; **Upper-right panel**: binding-discouraged unintegrated probing testing group; **Lower-right panel**: binding-discouraged unintegrated probing testing group. The graph parameter indicates whether the probe had one features (circles) or two (triangles). Error bars show standard error.

Figure 3

Mean RT (in ms) as a function of the number of old features present in two-feature, target-absent probes in binding-encouraged testing groups (0, 1, or 2). Error bars show standard error.

Figure 4

Mean intercepts (in ms) of RT-$\log_2$(Set size) functions as a function of Presentation of Two-Feature probes (top panel, unintegrated vs. bottom panel, integrated), Probed Memory (x-axis, One-feature vs. Two-feature), Probe Type (graph parameter, target-present vs. target-absent). Error bars show standard error.

Figure 5

Mean slopes (in ms/item) of RT-$\log_2$(Set size) functions as a function of Binding Instructions (top panel, encouraged vs. bottom panel, discouraged), Probed Memory (x axis, One-feature vs. Two-feature), Probe Type (graph parameter, target-present vs. target-absent). Error bars show standard error.

Figure 1, upper panel

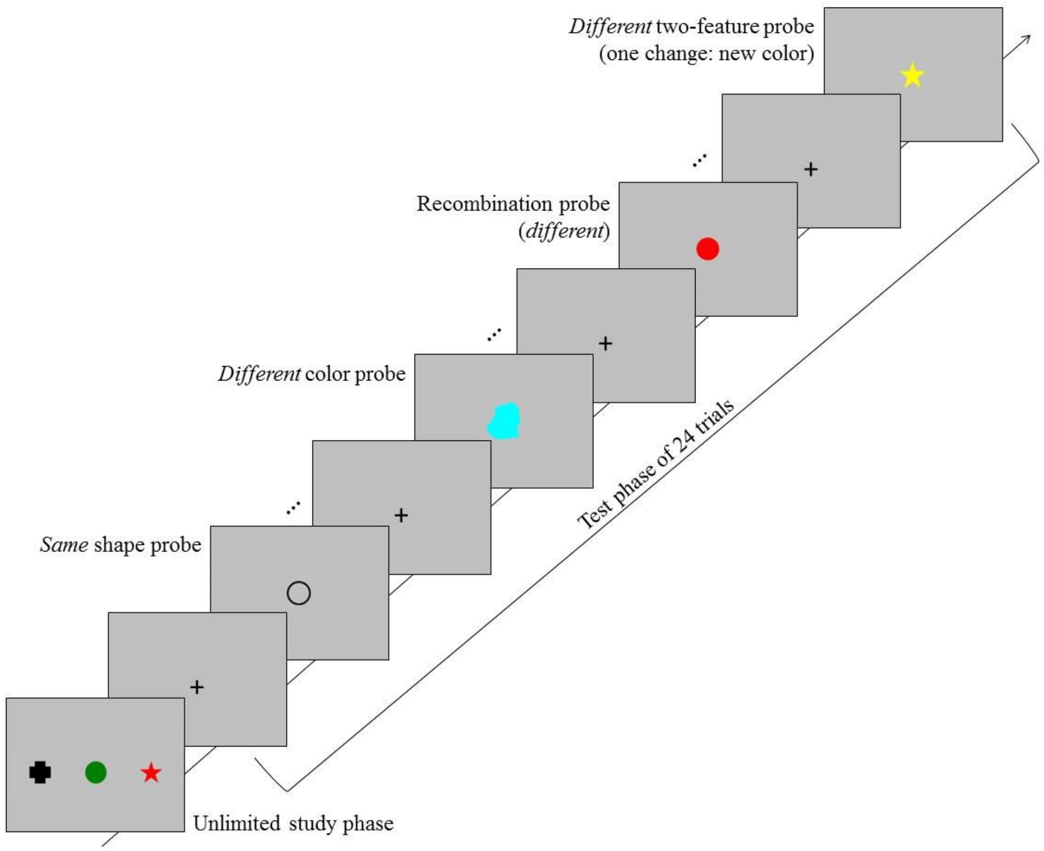


Figure 1, lower panel

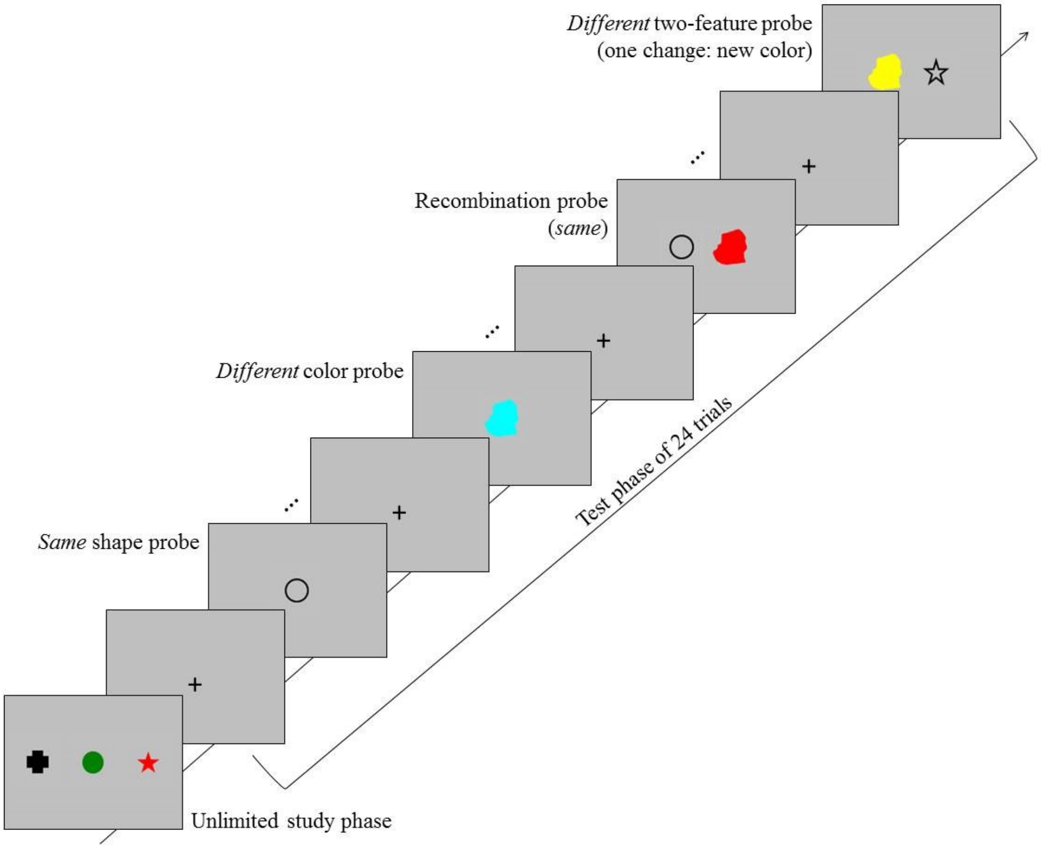
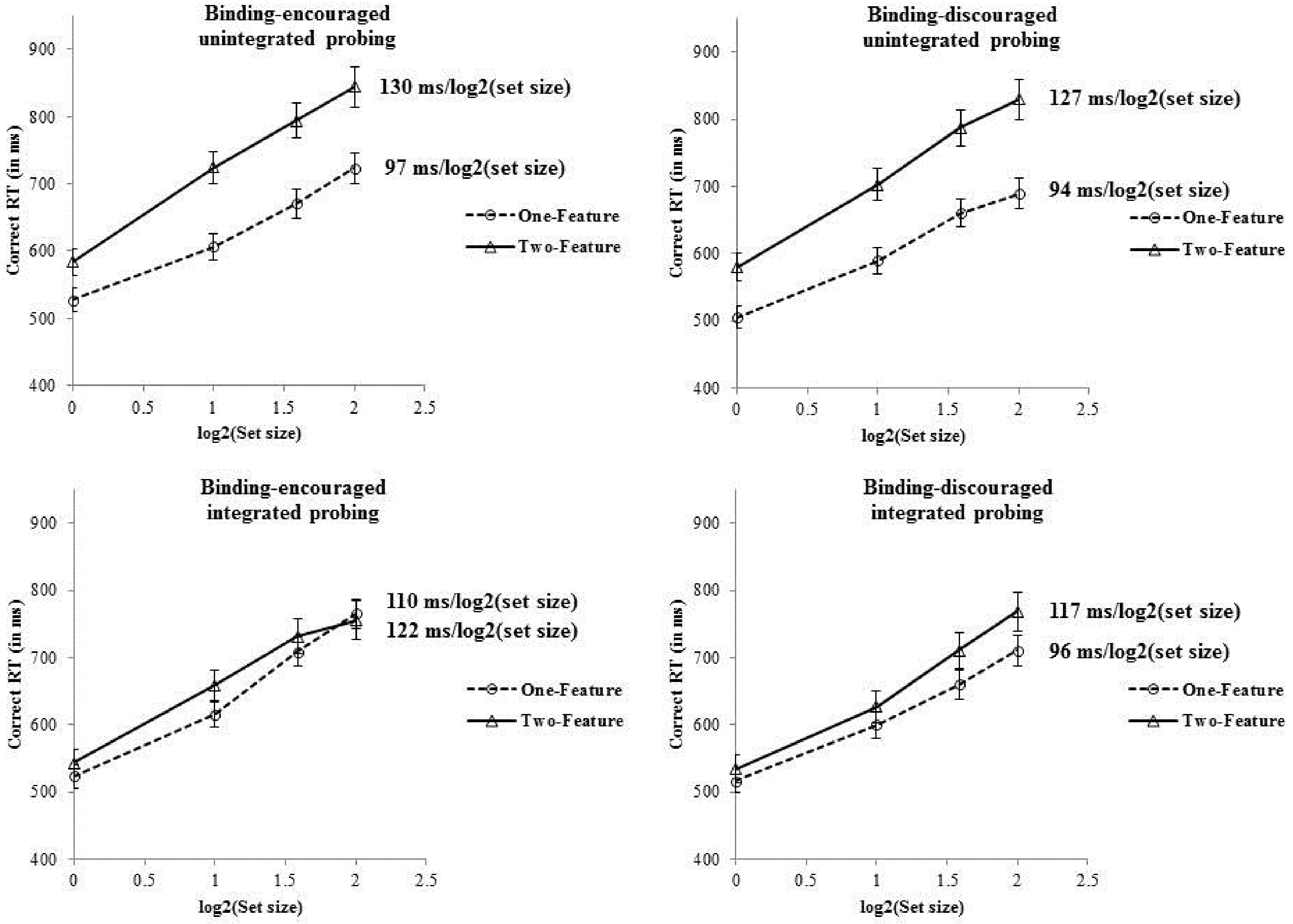


Figure 2



Binding-encouraged unintegrated probing

Binding-discouraged unintegrated probing

Binding-encouraged integrated probing

Binding-discouraged integrated probing

Figure 3

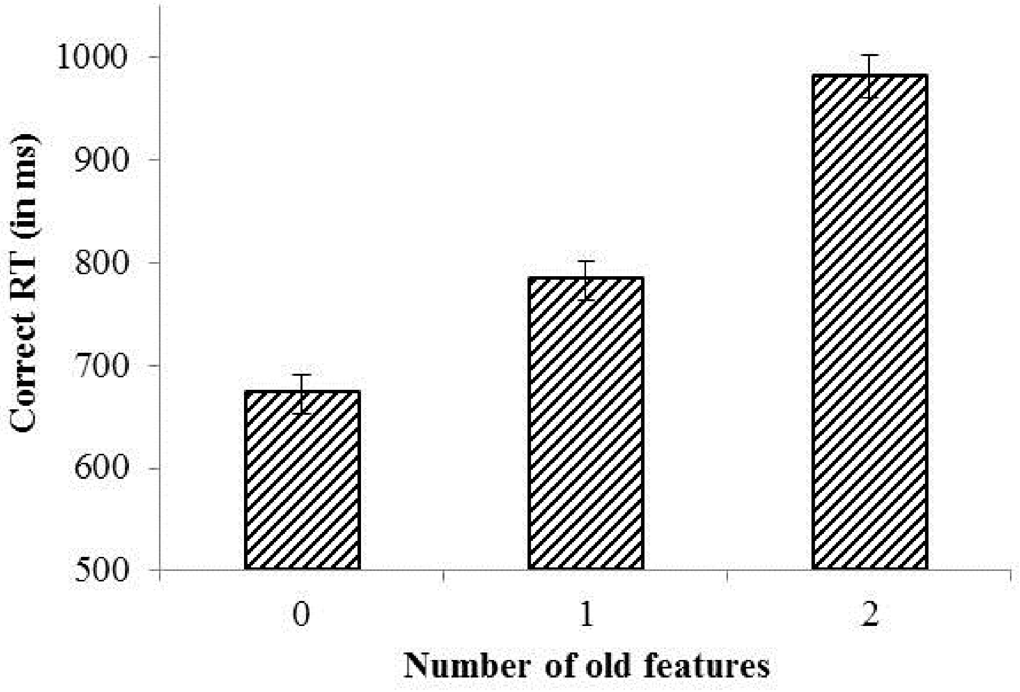

Correct RT (in ms)
1000
900
800
700
600
500
0
1
2
Number of old features

Figure 4

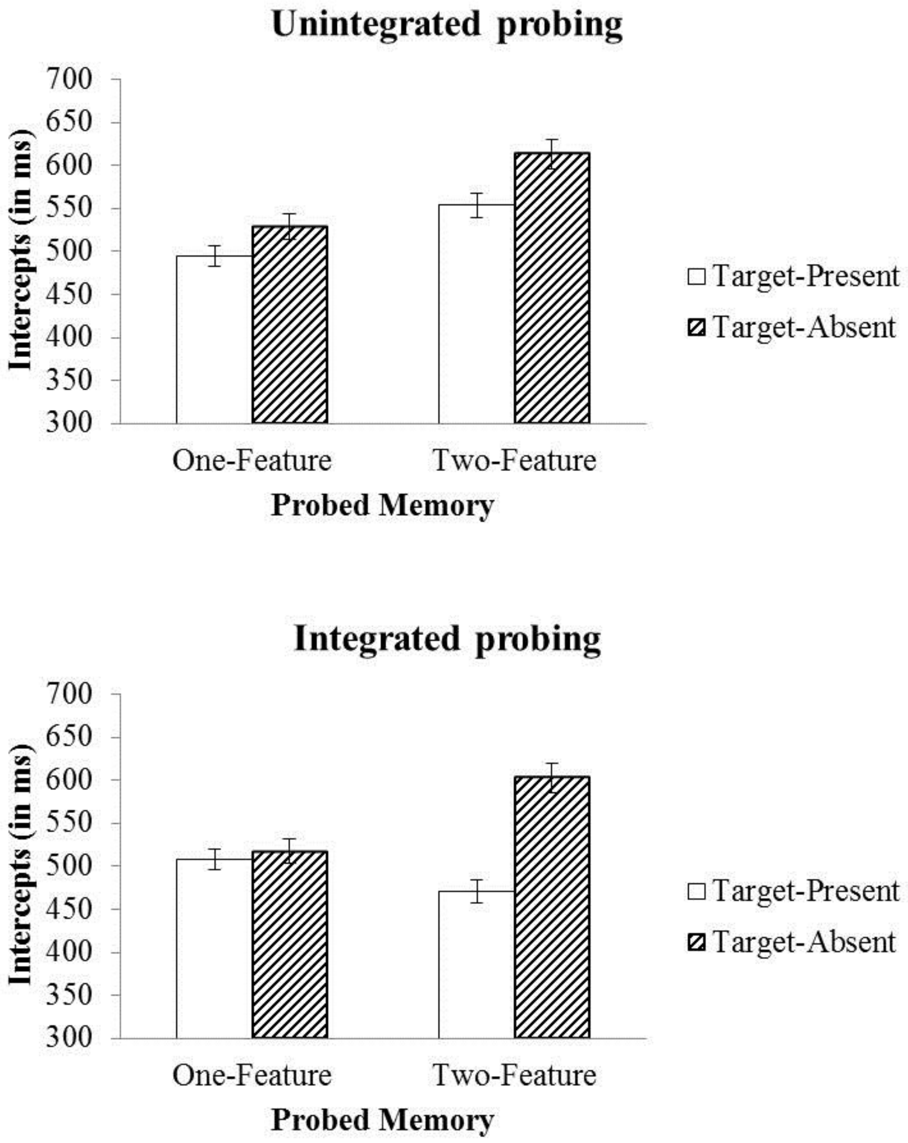
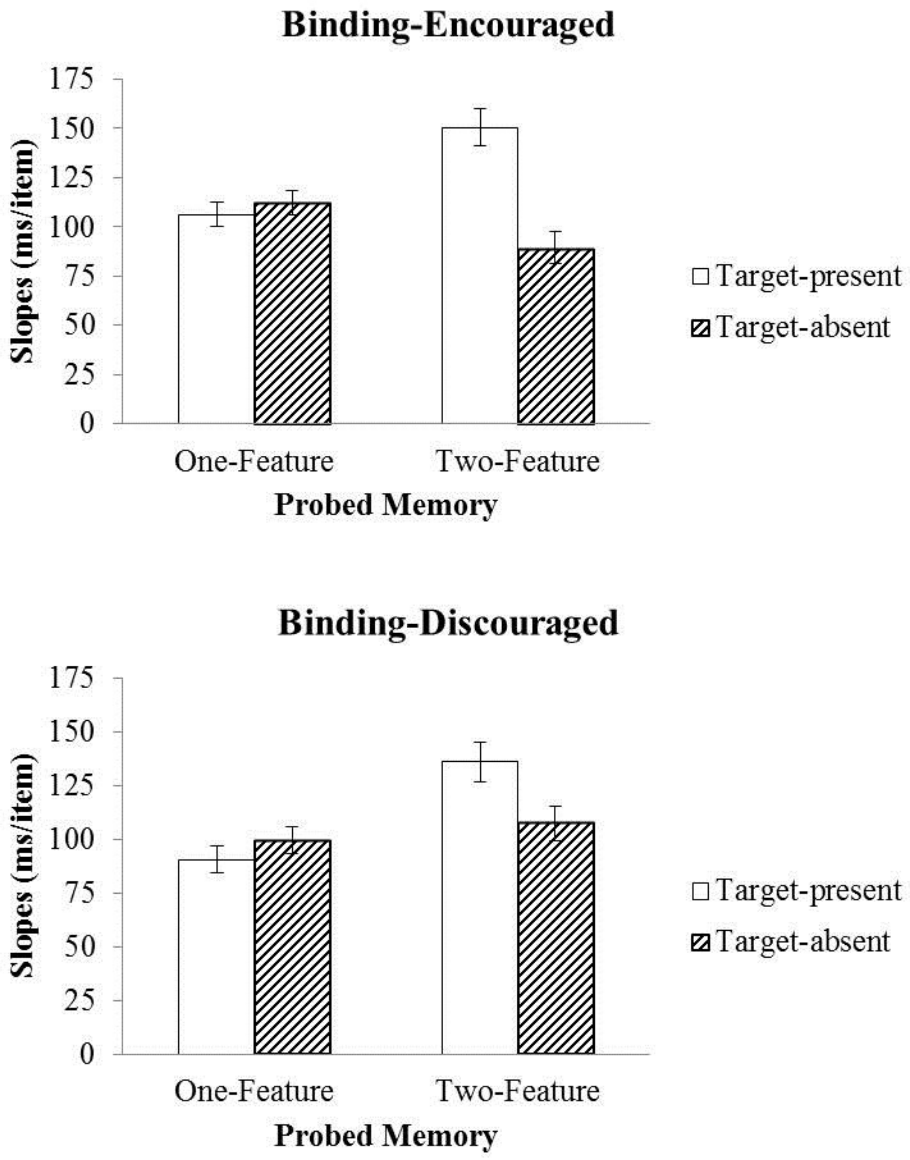

Unintegrated probing
Intercepts (in ms)
700
650
600
550
500
450
400
350
300
One-Feature
Two-Feature
Probed Memory
□ Target-Present
▨ Target-Absent
Integrated probing
Intercepts (in ms)
700
650
600
550
500
450
400
350
300
One-Feature
Two-Feature
Probed Memory
□ Target-Present
▨ Target-Absent

Figure 5


Binding-Encouraged
Slopes (ms/item)
175
150
125
100
75
50
25
0
One-Feature
Two-Feature
Probed Memory
□ Target-present
▨ Target-absent
Binding-Discouraged
Slopes (ms/item)
175
150
125
100
75
50
25
0
One-Feature
Two-Feature
Probed Memory
□ Target-present
▨ Target-absent