The allocation of visual short-term memory capacity: Evidence for a flexible storage mechanism

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The Allocation of Visual Short-term Memory Capacity: Evidence for A Flexible Storage Mechanism

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We have the ability to store a limited amount of visual information about a few visual objects for short periods of time. There is yet no consensus on the format of this representation. The present experiments test 3 possibilities: a fixed-resolution slot model, an independent feature stores model, and a flexible resource model. These models differ in their predictions of the effects that the complexity of an object will have on memory storage capacity. In Experiment 1 we found while subjects could store either about 3 colors or one complex shape, they could not store more than one complex shape. Experiment 2 shows that there is a cost in storage capacity for both color and shape when both features had to be stored in memory relative to when either feature alone had to be stored. These results are inconsistent with the fixed-resolution slot model and the independent feature store model, but are consistent with the hypothesis that visual short-term memory capacity can be flexibly allocated to objects. According to this model the amount of detail encoded per object is not fixed but depends on the demands of the task.

The ability to store information in memory has many obvious benefits: our capacity to recall and recognize objects enables us to act appropriately on current objects based on past experience, as well as to incorporate new information about those objects for future use. In fact, memory is such a useful function that it appears in several different forms in the human cognitive system. These different memory systems are usually distinguished by whether or not their content is consciously accessible (explicit vs. implicit, Schacter & Badgaiyan, 2001, by their temporal properties (long-term vs. short-term, James, 1950), by the modality of information content (e.g., auditory vs. visual, Baddeley, 1978, 1992), or by storage capacity (e.g., high capacity iconic vs. low capacity short-term memory, Sperling, 1960). The focus of the current paper is on visual short-term memory, which is characterized as a relatively robust but severely capacity-limited short-term store that can be maintained for several seconds with minimal degradation (Phillips, 1974).

Unlike long-term memory, visual short-term memory probably does not store conceptual information such as whether or not an object is edible. Instead, representations in visual short-term memory are probably closer to a 'snapshot' of the visual world, storing the visual details of objects. While some details might be lost, and perhaps some abstractions made, visual short-term memory essentially stores a visual image of what was seen, with little contribution from categorical information about the stored items (Pashler, 1988). What is the purpose of this short-term storage of visual information? One possible purpose is that the contents of visual short-term memory are essential for maintaining current goals and directing our attention to task relevant visual information. For example, it has been shown that the contents of visual short-term memory automatically guide attention to information that matches the stored object representations (Downing, 2000; Pashler & Shiu, 1999. Furthermore, when looking for a target object among a set of distracting objects, the target can be located much faster when a picture of that object was recently seen relative to when a verbal description was seen (Wolfe, Horowitz, Kenner, Hyle, & Vasan, 2004). Storing the visual details of something we are looking for seems to increase the efficiency with which we can focus our attention on relevant items.

Perhaps the most fundamental question we can ask about a particular storage system is how to characterize the format of the stored information. Recent research suggests that 'objects' are the basic unit of visual short-term memory storage. Specifically, some studies suggest that visual short-term memory capacity is set by the number of individual objects that can be stored in memory, independent of the number of features that must be remembered per object (Luck & Vogel, 1997; Vogel, Woodman, & Luck, 2001. For example, whether required to remember color alone, orientation alone, or both features simultaneously, visual short-term memory might be limited to the storage of approximately four objects. Strikingly, subjects are no worse at remembering four features than they are at remembering any single feature (Luck & Vogel, 1997). Perhaps visual short-term memory capacity is limited by the number of objects that can be stored in memory, not the number of features. Subsequent research verified that that the unit of capacity is the number of individual objects to-be-remembered, rather than the number of locations (Lee & Chun, 2001) by showing that memory

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storage capacity is the same whether objects are presented in overlapping spatial locations or separate spatial locations.

In the current study, we go beyond the basic question of what the units of memory storage are, and ask how memory capacity is allocated to those units. Specifically, we will address three alternative models for the allocation of memory capacity to objects: a fixed-resolution slot model, an independent feature store model, and a flexible resource model. Before describing the experiments, we provide a brief description of these models. We should emphasize that throughout this paper we use a spatial metaphor for memory capacity, with each of the different models proposing a different way of allocating a storage space to the representation of objects in memory. However, it is important to note that the spatial metaphor is meant only as an analogy to the structure, resource, or process that underlies visual short-term memory capacity limitations. We use the spatial metaphor for expository purposes because the exact nature of short-term memory storage is yet unknown, and this metaphor should never be taken literally to mean that there is necessarily a single storage site somewhere within the brain which is divided one way or another. Rather, space is used as a metaphor for those possible sources of short-term memory storage limits, such as limitations in attentional resources (Cowan, 1995; Engle, 2001), persisting activation in sensory areas via reverberatory connections with prefrontal cortex (Raffone & Wolters, 2001), fast Hebbian learning (Sandberg, Tegner, & Lansner, 2003), or the operation of oscillatory networks (Jensen & Lisman, 1996; Lisman & Idiart, 1995, each of which have been proposed to underlie the limits on our ability to maintain the visual details of objects over short time intervals.

The Fixed-Resolution Slot Model. One of the challenges to the object-based model of memory storage is that limit on the number of objects that can be stored varies depending on the type of object (Alvarez & Cavanagh, 2004). To address this concern, one can assume that memory always holds the same number of objects, but that there is a limit to the total amount of detail that can be stored for each individual object (Luck & Zhang, 2004 has proposed such a model). This fixed resolution slot model for the allocation of memory capacity holds that memory is divided into storage 'slots' with two independent factors limiting memory storage. First, there is a fixed number of 'slots' and each slot can contain exactly one object. This factor imposes an upper limit on the number of objects that can be stored in memory. Second, the resolution or detail with which each slot can store information about an object is fixed. This factor imposes a limit on the amount of detail that can be stored for each individual object in memory. When the task is to remember objects that are very different, say colors of categorically different hues, the number of slots available for storage will be the primary limit on storage capacity. However, if the task requires storing information with greater detail, say to make finer distinctions between different shades of red, then the resolution with which each slot stores information also imposes a limit on storage capacity. Critically, the resolution limit for one slot is fixed and independent of the contents of other slots in memory.

The Parallel, Independent Feature Stores Model. An important alternative interpretation for the finding that there is no cost to storing the conjunction of features relative to storing each feature alone (Luck & Vogel, 1997) is that there are independent memory stores for different feature dimensions (e.g., size, color, orientation, etc.). In fact, other researchers have made this conclusion based on similar results. For example, observers can remember both the spatial frequency and the contrast of a grating with little cost in accuracy relative to remembering either feature alone, suggesting that there are separate memory stores for these two feature dimensions (Magnussen, Greenlee, & Thomas, 1996). While there was a small cost to remembering both features relative to either feature alone, the cost in accuracy was small and in fact no greater than expected given the increase in decision uncertainty in the conjunction condition relative to the single feature conditions (see Pelli, 1985 for a model of decision uncertainty costs which can occur in the absence of capacity limitations, and Magnussen & Greenlee, 1997 for an extension of this model to a visual memory task). On this view, fully loading memory on one feature dimension, say color, will have no effect on the storage capacity of a separate feature dimension, say orientation.

Initially, some evidence appeared to be inconsistent with this independent feature model. Observers could remember two colors per object as well as one color per object, with storage capacity limited to about 4 objects in both cases (Luck & Vogel, 1997). This result suggested that memory capacity was set by the number of objects that could be stored, as the maximum number of features that could be stored depended on the type of object (up to 8 colors for bi-colored objects but only 4 colors for unicolored objects). If the number of colors that could be stored were fixed by the capacity of a 'color store', then the number of colors stored should have been the same regardless of the stimulus type (Luck & Vogel, 1997).

This demonstration that multiple values on the same feature dimension could be stored per object without reducing the number of objects that could be stored was strong evidence against the idea that memory consists of independent feature stores. However, this finding does not appear to be a general one, as the result does not hold for all bicolored objects (Vogel et al., 2001) and subsequent attempts to replicate the original finding have failed (Delvenne & Bruyer, 2004; Olson & Jiang, 2002; (Schneider, Deubel, & Wesnick, 2001); Wheeler & Treisman, 2002). Wheeler and Treisman (2002) conducted the most extensive follow up by testing seven different types of bicolored objects and found that performance was consistently set by the number of features to-be-remembered, and not by the number of objects (e.g., 2 bicolored objects or 4 unicolored objects can be stored, for a total of 4 colors for each stimulus type). These results indicate that it is possible to exceed the storage capacity for color without running into the upper limit on the number of objects that can be stored (about 4 objects, Alvarez & Cavanagh, 2004; Cowan, 2001; Luck & Vogel, 1997).

To date the discrepancy between Luck and Vogel's original findings for bicolored and unicolored objects and the subsequent failures to replicate them has not been explained.

Consequently, the possibility of separate memory stores for different feature dimensions remains an important alternative to the object-based slot model of memory storage.

The Flexible Resource Model. Unlike the slot model, the flexible resource model suggests that the number of objects that can be stored in memory depends on the amount of detail stored per object. Although there is a maximum upper limit on storage of about 4 objects for the simplest objects, memory is a flexible resource and it is possible to allocate more or less of this resource to each object, depending on the demands of the task (Alvarez & Cavanagh, 2004). According to this model, there is a limit to the total amount of detail that can be stored in memory. Consequently the more detail stored per object, the lower the number of objects that can be stored in memory. Thus, the limit on the number of objects stored in memory is determined by the amount of detail that must be stored per object to perform the memory task. Consistent with this model, we have previously found that as the amount of detail stored per object increases (as indexed by processing time in a visual search task) the number of objects that can be stored systematically decreases (Alvarez & Cavanagh, 2004). In the following experiments we pit these models against each other, comparing the fixed-resolution slot model and the flexible resource model in Experiment 1, and the comparing the independent feature stores model and flexible resource model in Experiment 2.

Experiment 1: Evidence Against the Fixed-Resolution, Slot-Like Model

The purpose of this experiment is to determine whether visual short-term memory is better characterized as a fixed-resolution slot system or as a flexible resource. The independent feature stores model will be discussed in Experiment 2. Observers performed a memory task in which several complex polygon shapes of different colors were briefly presented, followed by a brief blank interval, and then by a single object that served as a memory probe. On half of the trials, the probe object was identical to the corresponding object in the same location in the first display, and on the other half of the trials it was a different color or shape. In separate blocks of trials observers were required to remember only the color or only the shape of the objects and to indicate whether or not the test item was the same or different on the relevant dimension.

This task can be used to estimate storage capacity for the color and the shape of these polygons by evaluating accuracy as a function of the number of objects to be remembered. If we assume that storage capacity is the primary limit on performance in this task1 then performance should be perfect when subjects are required to remember fewer than the maximum number of objects that can be stored. For example, if memory storage capacity is three colors, then performance on this task should be perfect when three or fewer items are presented, and should then decrease as the number of items presented increases beyond three. Both Pashler (1988) and Cowan (2001) have formulated equations to estimate storage capacity from percent correct in similar tasks, and we adapt Cowan's method in our analyses.

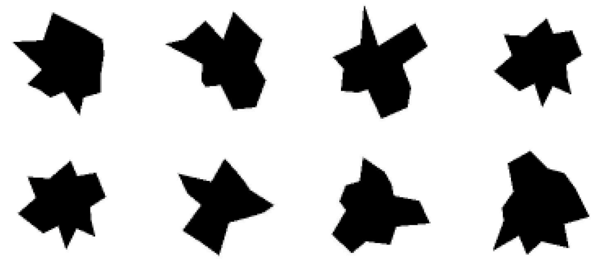

Figure 1. The set of polygon shapes used in Experiments 1 and 2. The shapes could be any of eight possible colors, including red, yellow, green, blue-green, cyan, blue, purple, or magenta.

Predictions based on the Fixed-resolution, Slot-like Storage Model. Recall that this model of memory claims that there are a fixed number of memory storage slots and that each slot has a fixed resolution. Thus, provided the amount of resolution needed to store a single color or shape does not exceed the resolution of a single slot (an assumption that is verified for these stimuli by showing that a single color or a single complex shape can be stored in memory equally well, with few errors), this model predicts that memory storage capacity for color and complex shape will be limited primarily by the number of storage slots and should therefore be the same for both features.

Predictions based on the Flexible Resource Model. The flexible resource model claims that the number of objects that can be stored in memory depends on the amount of detail that must be stored per object (Alvarez & Cavanagh, 2004). A single object can be stored with high fidelity, or several objects can be stored with a lower resolution. Thus, this model holds that memory is flexible in so far as more or less detail from each object can be encoded and stored in memory depending on task demands. According to this model, if the amount of detail required to store a color in memory is less than that needed to store a complex shape into memory, then more colors will be stored than complex shapes. Logically, other predictions can be made (e.g., if shapes require less detail than color, more shapes will be stored, etc.) but for simplicity we present only the more intuitive prediction that less detail is necessary to encode these particular colors than these particular complex shapes. Moreover, the assumption that these shapes are more complex than these colors is supported by reaction time in visual search tasks with similar stimuli which show that the rate of processing for colors is more than ten times faster than for complex polygon shapes of this type (Alvarez & Cavanagh, 2004).

Method

Subjects. Fourteen observers gave informed consent and were paid or received course credit in exchange for their participation in the experiment. All observers reported normal

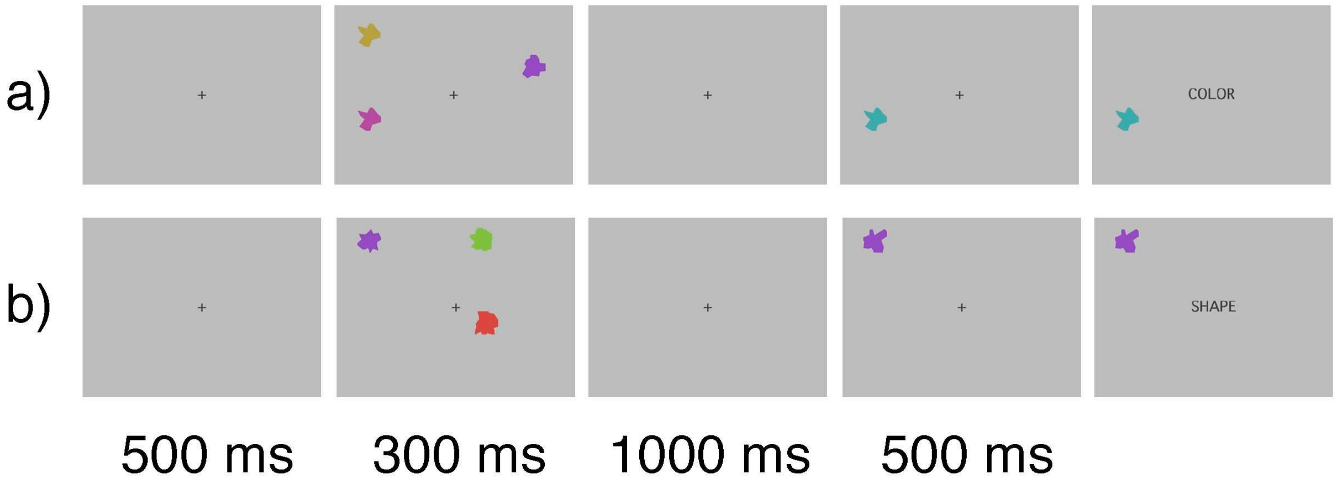

Figure 2. On each trial a variable number of objects were briefly presented, followed by a blank interval and then by a single test item. A post-cue then prompted observers to indicate whether the cued feature dimension changed. In Experiment 1 and in the single feature conditions of Experiment 2, observers always knew which feature would change within a block of trials (making the post-cue redundant in these cases, but it was presented to keep displays identical across conditions). In the conjunction condition of Experiment 2, observers knew that either color or shape could change and made their decision based on the cued feature dimension. a) An example of a color change trial. b) An example of a shape change trial.

or corrected-to-normal vision.

Stimuli. The stimuli were the eight polygon shapes shown in Figure 1. The shapes could be any of eight possible colors that appeared red, yellow, green, blue-green, cyan, blue, purple, or magenta. The colors were selected from 8 equally spaced positions along a color wheel and appeared distinct from each other.

Procedure. On each trial a variable number of polygons (1-3 during practice trials, and 1-9 during test trials) were presented for 300 ms. The color and shape of each object was selected randomly with replacement from the set of 8 possible colors and 8 possible shapes. Then all of the objects disappeared and a blank gray background was presented for 1000 ms, followed by the presentation of a single test object at the location of one of the items from the first display. This test object was presented for 500 ms, and then a post-cue (the word 'COLOR' or 'SHAPE') appeared at the center of the display to prompt the observer to indicate whether or not the cued feature of the test object was the same or different than the object in that location in the first display. The purpose of the post-cue was to encourage observers to make their decision based on the relevant feature dimension and to keep displays similar to those in Experiment 2. Figure 2 illustrates examples of a color change and shape change trial. Each observer completed 24 practice trials and 80 test trials in the color only and shape only conditions with the order of conditions counterbalanced across subjects.

Capacity in terms of the number of objects stored was estimated from percent correct in the change detection task using an equation based on Cowan (2001):

$k = (H - FA) * N$ (1)

Where k is the estimated storage capacity, H is the HIT rate (correctly indicating there was a feature change), FA is the false alarm rate (indicating there was a feature change when in fact there was no change), and N is the number of objects presented. The logic of this equation is that we can infer the number of objects stored from the HIT and FA rates. This model assumes that the probability a feature change will be detected is equal to the proportion of objects stored in memory. For example, if 3 out of 5 objects are stored in memory, then a feature change would be noticed on 60% of trials in which 5 objects are presented. Thus, given a hit rate of .60 at displays size 5, we can conclude that 3 of the 5 objects must have been stored. However, the hit rate will be inflated if observers have a tendency to sometimes guess there was a change, even when one was not detected. This guessing rate can be estimated from the FA rate, which can then be subtracted from the hit rate to correct for guessing.

The capacity limit was estimated as a function of the number of objects to be remembered. The average capacity estimate across all numbers of objects presented was then taken as each observer's capacity estimate. Note, however, that displays sizes less than the capacity limit do not provide appropriate estimates. For example, perfect performance at displays size one can only yield a maximum capacity estimate of one object, even if the true capacity is four objects. Thus, after taking the average estimate over all displays sizes, displays sizes smaller than this average were dropped and the average estimate from the remaining displays sizes was taken as the capacity estimate. This process was iterated until the estimate no longer changed.

This method of estimating capacity is appealing because it allows the results to be interpreted in terms of the number of objects stored, which is an intuitive unit of capacity. However, it is important to acknowledge that to quantify capacity

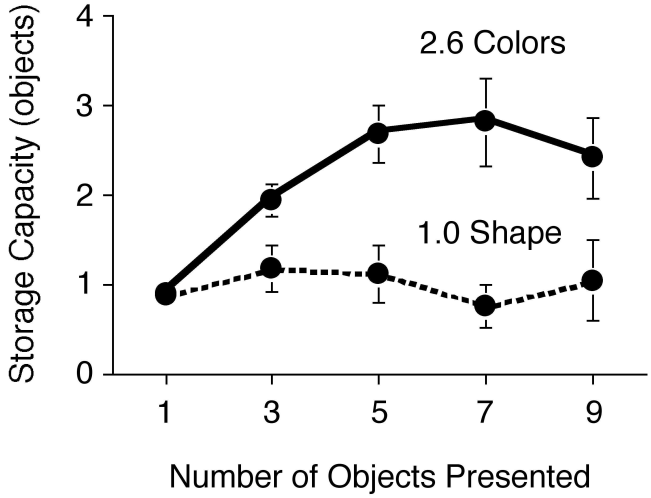

Figure 3. Estimated storage capacity as a function of the number of objects presented in Experiment 1. The solid line shows storage capacity for color and the dashed line shows storage capacity for shape. When only a single object is presented, the color and shape of the objects are stored equally well. However, as the number of objects to be stored increases beyond one, storage capacity increases for color but not for shape, reaching an asymptote at about 2.6 colors and 1 shape.

in terms of the number of objects stored is most likely an oversimplification because it ignores the possibility that encoding partial information from multiple objects could give rise to the same level of performance as fully encoding a smaller number of objects. Given these assumptions, it is important to note that the patterns of results reported here are qualitatively the same if the data are analyzed in terms of percent correct, sensitivity measures such as d' (Green & Swets, 1966) or A' citeGrier1971, or in terms of the number of objects stored. For interested readers we also report accuracy and d' for Experiment 1 (Table 1) and Experiment 2 (Table 2).

Results

The results indicate that a single color and a single shape are stored in memory equally well, but that the upper limit on the number of objects that can be stored is greater for color than for shape (see Figure 3). A 2 x 5 ANOVA with feature (color vs. shape) and display size (1, 3, 5, 7, or 9) as factors. There was a significant main effect of condition ($F(1,13) = 32.5$, $p < .01$) and display size ($F(4,52) = 2.9$, $p < .05$), and the interaction was significant ($F(4,52) = 3.9$, $p < .01$). These tests confirm that more colors could be stored than shapes, that the estimated storage capacity increased with displays size, but more so for color than for shape.

Additional tests indicate there is no significant difference in storage capacity for colors and shapes at displays size 1 ($t(13) < 1$, $p = .39$). However, estimated storage capacity is significantly greater for colors than for shapes at each display size greater than 1 (displays size 3: $t(13) = 2.78$, $p < .05$; displays size 5: $t(13) = 4.23$, $p < .01$; displays size 7: $t(13) = 3.88$, $p < .01$; displays size 9: $t(13) = 2.36$, $p < .05$). The capacity limit for each feature was computed as described above, indicating that about 2.6 colors can be stored, but only 1 shape ($t(13) = 5.07$, $p < .001$). Table 1 shows the results in terms of percent correct and the sensitivity measure d'. The pattern of results with either measure of performance is qualitatively identical to that seen for the capacity estimates shown in Figure 3.

Discussion

In the current experiment memory storage capacity was greater for the color of objects than for their shapes, which is consistent with the results of previous experiments (Alvarez & Cavanagh, 2004). However, these earlier experiments tested memory for color and shape using different classes of stimuli (simple colored squares vs. random polygon shapes), and thus it was possible that the complexity of objects contributed to the differences in storage capacity. In the current experiment, we show a similar effect using exactly the same stimuli in the color and shape conditions. Thus, the difference in storage capacity can only be attributed to the difference in the efficiency with which these colors can be stored relative to the efficiency with which these shapes can be stored.

Most importantly, the results of this experiment are inconsistent with the fixed-resolution slot model of memory. This model claims that there are a fixed number of memory storage slots and that each slot has a fixed resolution. Thus, because about 3 colors can be stored in memory there must be at least three storage 'slots' in memory. This number is comparable to previous estimates of storage capacity and the number of objects that can be stored in memory (Cowan, 2001; Luck & Vogel, 1997). If there are at least 3 storage slots then it should be possible to store 3 complex shapes in memory as well. Contrary to this prediction, however, the current results indicate that only a single complex shape can be stored. One could argue the shapes are simply too complex and that any single storage slot does not have enough resolution to store one of these complex shapes. However, in the current experiment a single shape could be stored almost perfectly in memory - as well as a single color in fact - indicating that the resolution of memory is sufficient to store these complex shapes. Thus, the failure to store more than a single shape cannot be explained by either the limited resolution of storage slots, or by the number of storage slots.

The flexible resource model can account for these results. According to this model there is a tradeoff between the amount of detail stored per object and the maximum number of objects that can be stored. Specifically, as the amount of detail stored per object increases, the maximum number of objects that can be stored decreases. On this view, less detail is required to encode the colors into memory than the complex shapes of objects. Thus, when required to remember color only, less detail per object is stored enabling the storage of about 3 objects. In contrast, when required to remember shape only, more detail per object must be stored in order

Table 1
Percent Correct and d' as a Function of Display Size and Feature in Experiment 1.

	Percent Correct		d'	
Display Size	Color	Shape	Color	Shape
1	95.1 (1.0)	93.3 (2.3)	4.1 (0.2)	3.9 (0.4)
3	82.1 (3.0)	69.2 (4.5)	2.5 (0.4)	1.4 (0.4)
5	76.8 (3.2)	59.8 (3.6)	1.8 (0.3)	0.7 (0.2)
7	70.1 (3.5)	53.6 (2.4)	1.3 (0.3)	0.2 (0.1)
9	62.5 (3.0)	51.8 (3.4)	0.9 (0.2)	0.1 (0.2)

Note: The difference between color and shape in both percent correct and d' was not significant at display size 1, but was significant at each display size greater than 1 (all p values less than .05).

to encode the shape with enough spatial precision to detect a change, thus reducing the total number of objects stored to just one. Of course it is possible that a more complex object would exceed the memory storage capacity, but the objects tested in the current experiments were purposely selected (based on pilot experiments) so that a single complex shape requires just about the full allocation of memory such that 1 shape can be stored in memory almost perfectly, but no more than 1.

The claim that these particular colors and shapes are available at different levels of detail makes an interesting prediction for the level of performance expected when the conjunction of a simple color and complex shape must be stored in memory. Specifically, there is a conflict between the amount of detail that is sufficient for encoding these colors (low resolution) and the amount of detail needed to encode these shapes (high resolution). Thus, the flexible resource model predicts that there will be a cost to remembering both features. Several items can be stored with a low resolution at which the colors are stored with enough detail but the shapes are not. Alternatively, fewer items can be stored with higher resolution so that the shape will be stored with enough detail, but by storing fewer items the number of colors stored will be reduced. Of course, intermediate levels of detail might be stored, resulting in storage costs for both color and shape. Experiment 2 tests this prediction.

Experiment 2: A Test of the Flexible Resource Model

The purpose of this experiment is to determine whether it is possible to store the conjunction of color and complex shape as well as either feature alone. Previous research has shown that color and orientation can be stored together as well as either feature alone (Luck & Vogel, 1997). However, storage capacity for color and orientation alone is similar (about 3 or 4 objects), suggesting that the same level of detail is required to store these features. In contrast, the results of Experiment 1 show that storage capacity for color and complex shape appear to require different levels of detail, with more detail required to store the complex shape than the color of these objects. By requiring memory storage for two dimensions that require different levels of detail, we can directly test the predictions of two different models for the allocation of visual short-term memory capacity: the independent feature stores model and the flexible resource model.

Observers performed the same memory task as in Experiment 1. In separate blocks of trials, observers were asked to remember color only, shape only, or both color and shape (conjunction). The post-cue was always 'COLOR' in color only trials and 'SHAPE' in shape only trials. In shape and color conjunction trials, however, the cue was always 'COLOR if there was a color change, 'SHAPE' if there was a shape change, and randomly either 'COLOR' or 'SHAPE' if there was no change. Thus, observers were never cued to determine whether there was a shape change if color had changed, or vice versa, thus eliminating decision uncertainty limitations (Pelli, 1985). The independent feature and flexible resource models each have different explanations for the variation in storage capacity for color and complex shapes observed in Experiment 1, and consequently they make different predictions about the level of performance that should be observed when the conjunction of these colors and shapes must be stored in memory.

Predictions Based on the Independent Feature Store Model. The independent feature stores model proposes that there are separate feature stores for color and the features underlying the encoding of the complex shape of an object (perhaps including orientation and spatial frequency components). According to this model, each shape requires the storage of only a single value on the color dimension, but requires multiple values to be encoded on the features underlying shape. For example, encoding shape might require encoding several orientations and spatial frequencies per object. Thus, each object imposes a minimal load on the color store, and a high load on the shape store, resulting in different storage capacities depending on the dimension being remembered. This parallel, independent feature stores model predicts there would be no cost of combining color and complex shape because each imposes a load on an independent feature store (or set of stores in the case of shape).

Predictions Based on the Flexible Resource Model. According to this model there is a conflict between the amount of detail necessary to encode the colors (low resolution) and the shapes (high resolution). Consequently there will be a cost to remembering both features relative to either feature alone: with low resolution representations the colors will be stored with enough detail but the shapes will not, whereas with higher resolution representations, a single shape can be stored with enough detail but consequently fewer objects (hence fewer colors) will be stored. If an intermediate level of detail is stored there will be costs for both color and shape.

In sum, when simple colors and complex shapes must both be stored in memory, the independent feature stores model predicts no drop in storage capacity for either color or shape. In contrast, the flexible resource model predicts that there must be a decrease in capacity for either color or shape, or both.

Method

Subjects. Fourteen observers gave informed consent and were paid or received course credit in exchange for their participation in the experiment. All observers had normal or corrected-to-normal vision.

Stimuli. The stimuli were the same as in Experiment 1.

Procedure. The procedure was the same as in Experiment 1 except that in addition to remembering color only or shape only, observers were also required to remember both color and shape. Each observer completed 2 blocks of 24 practice trials (one each for color only and shape only), and a total of 8 test blocks of 60 trials (2 color only blocks, 2 shape only blocks, and 4 blocks of the conjunction condition) with the order of conditions counterbalanced across subjects.

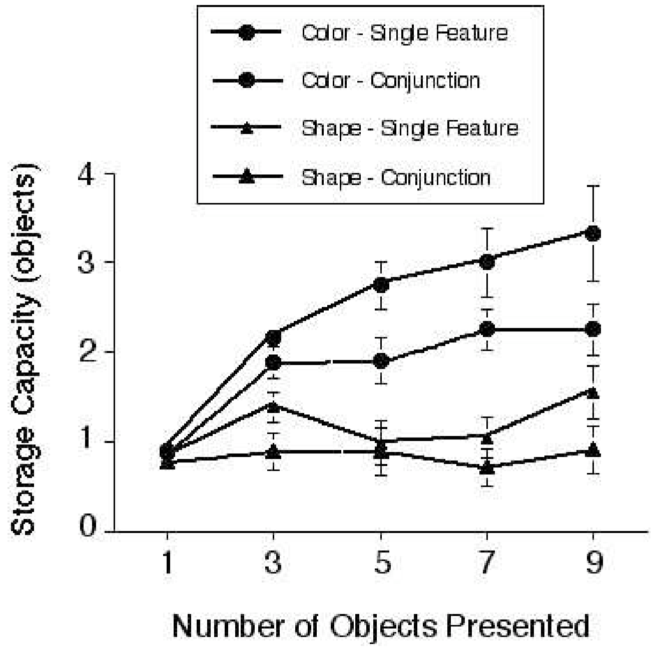

Figure 4. Estimated storage capacity for color and shape in the single feature and conjunction conditions as a function of the number of objects presented in Experiment 2. There was a significant drop in storage capacity for color and for shape when both features had to be stored (conjunction condition) relative to when only a single feature had to be stored.

Results

There was a significant drop in accuracy in the conjunction condition relative to the single feature condition for both color and size. Figure 4 illustrates storage capacity versus the number of objects presented for color and orientation in the single feature and conjunction conditions. A 2 x 2 x 5 ANOVA with condition (single feature vs. conjunction), feature (color vs. shape) and number of objects presented (1, 3, 5, 7, 9) was run on estimated storage capacity. There was a significant main effect of condition ($F(1,13) = 17.8$, $p < .01$) indicating that the decrease in storage capacity in the conjunction condition was significant. Consistent with the results of Experiment 1, storage capacity was greater for color than for shape (main effect of feature ($F(1,13) = 41.5$, $p < .01$), capacity estimates increased with display size (main effect of number of objects presented, ($F(4,52) = 12.3$, $p < .01$), and the greater increase in storage capacity with the number of objects presented was greater for color than for shape (significant interaction between feature and number of objects presented, ($F(4,52) = 6.9$, $p < .01$).

The asymptotic estimates of capacity were determined for each individual observer with the same procedure as in Experiment 1 (see Figure 5). A 2 x 2 ANOVA was run on estimated storage capacity with condition (single feature vs. conjunction) and tested feature (color vs. shape) as factors. There was a significant main effect of condition ($F(1,13) = 21.4$, $p < .01$) indicating that the decrease in storage capacity in the conjunction condition was significant. There was also a significant main effect of feature ($F(1,13) = 35.84$, $p < .01$) confirming that storage capacity was greater for color than for shape. The interaction between condition and feature was also significant ($F(1,13) = 5.27$, $p < .05$) indicating that the decrease in accuracy in the conjunction condition was greater for color than for shape. T-tests verified that the drop in storage capacity was significant both for color ($t(13) = 4.05$, $p < .01$) and for shape ($t(13) = 2.56$, $p < .05$). Table 2 shows the results in terms of percent correct and the sensitivity measure d' as a function of display size for each condition. The pattern of results with either measure of performance is qualitatively identical to that seen for capacity in terms of the number of objects.

Discussion

There is clearly a cost to storing color and complex shape together relative to storing either feature alone. The independent feature stores model cannot account for the current results. According to this model, the color and complex shape of objects are stored in parallel, independent memory stores. This model would hold that the polygons used in the current experiments place minimal memory demands on the color store, allowing several colors to be stored, but that each shape places a large memory load on a separate feature store (e.g., orientation or spatial frequency, or both). However, separate feature stores handle color and shape, and therefore according to the independent feature stores model, there should be no cost when required to store both features in memory.

Table 2
Percent Correct and d' as a Function of Display Size and Condition in Experiment 2.

	Condition			
Display Size	Color Alone	Color Conjunction	Shape Alone	Shape Conjunction
	Percent Correct			
1	95.3 (1.3)	93.9 (1.3)	91.7 (1.6)	89.4 (2.3)
3	86.7 (2.2)	81.7 (3.4)	72.8 (2.6)	64.7 (3.9)
5	78.9 (2.9)	68.9 (3.3)	58.6 (2.9)	56.4 (3.4)
7	72.8 (2.9)	67.2 (2.6)	56.4 (2.0)	53.1 (2.6)
9	70.0 (3.4)	63.1 (2.5)	56.9 (2.1)	53.1 (2.0)
	d'			
1	4.1 (0.3)	3.9 (0.2)	3.5 (0.3)	3.3 (.3)
3	2.7 (0.3)	2.3 (0.4)	1.6 (0.2)	1.3 (.3)
5	2.1 (0.3)	1.3 (0.2)	0.8 (0.2)	0.8 (.2)
7	1.5 (0.2)	1.2 (0.2)	0.7 (0.1)	0.6 (.1)
9	1.4 (0.3)	0.9 (0.2)	0.7 (0.1)	0.4 (.1)

Note: The difference between color and shape in both percent correct and d was not significant at display size 1, but was significant at each display size greater than 1 in both the single feature and conjunction conditions (all p values less than .05). The drop in performance for the conjunction condition relative to the single feature alone condition was also significant for either performance measure for both color and shape (all p values less than .05).

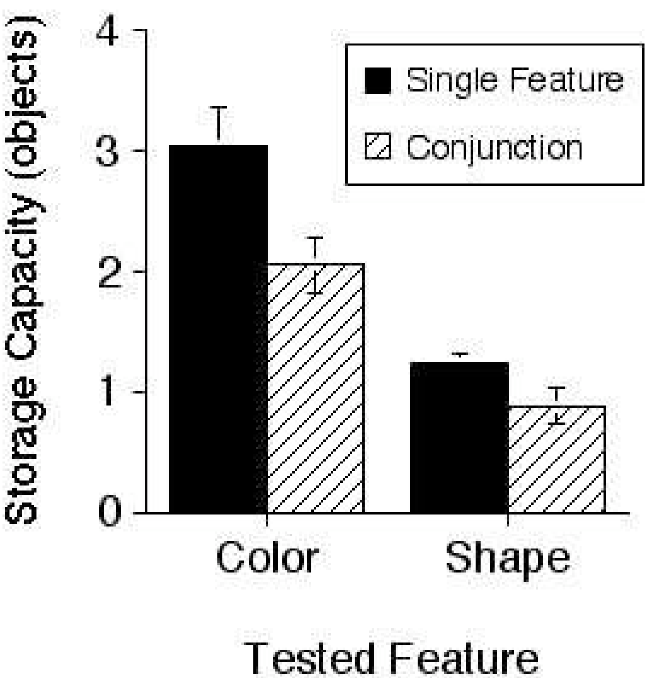

Figure 5. Estimated storage capacity for color and shape in the single feature and conjunction conditions of Experiment 2. There was a significant drop in storage capacity for color and for shape when both features had to be stored (conjunction condition) relative to when only a single feature had to be stored.

One might argue that the cost in the conjunction condition relative to the single feature conditions does not reflect differences in storage capacity, but reflects the costs of decision uncertainty (Pelli, 1985). For example, performance costs for remembering both spatial frequency and contrast relative to either feature alone can be accounted for by such uncertainty effects (Magnussen & Greenlee, 1997). However, it is important to note that in our experiments there is always a post-cue prompting the observers to make their decision based on a specific feature dimension. Thus, there is no more uncertainty about the relevant feature dimension in the conjunction condition than in the single feature condition, and thus, uncertainty effects cannot explain the observed performance cost. Given that there was a significant cost in storage capacity for both color and shape when both features had to be stored relative to when either feature alone was stored, and given that decision uncertainty cannot explain this cost, we can rule out any model that claims completely independent storage capacity for these colors and shapes.

The flexible resource model can account for the current results. This model assumes that the more detail you must encode per object, the fewer the total number of objects that can be stored in memory. On this view, 3 colors can be stored because each color requires little detail to be stored in memory, but only a single shape can be stored because more detail per shape must be encoded to represent them with enough spatial precision to discriminate between shapes. Thus, when both must be remembered together, there is a tension between the amount of detail needed to store color (low detail), and the amount of detail needed to store shape (high detail). This requires that there would be a tradeoff if both color and shape must be stored: storing more objects with less detail enables the colors to be stored but sacrifices the precision with which shapes are stored (resulting in a storage cost), storing fewer objects with more detail enables the shapes to be stored but sacrifices the number of colors stored, and encoding an intermediate number of objects with an intermediate level of detail results in storage costs for both features (the observed pattern). The cost in the conjunction condition for both features in the current experiment is evidence for such flexibility in the allocation of memory capacity: an intermediate level of detail can be encoded in which not quite as many colors or shapes can be stored as when either feature is remembered alone.

General Discussion

The current experiments employed a memory task in which observers were required to remember the color only, the shape only, or both the color and shape of a variable number of polygons. In Experiment 1 we found that it was possible to store approximately 3 colors in memory. Although it was also possible to store a single complex shape, it was not possible to store more than one such shape. These results are inconsistent with a fixed-resolution slot model in which memory stores fixed number of objects with a fixed resolution. In Experiment 2, we found that there was a cost in storage capacity for both color and shape when both features had to be stored in memory relative to when either feature alone had to be stored. These results are inconsistent with a model of memory storage in which there are completely independent stores for different features of an object. In the remainder of this paper we will discuss the implications of these findings for the allocation of visual short-term memory capacity to objects and propose two possible mechanisms for the flexibility in the allocation of memory capacity.

Implications for the Allocation of Visual Short-term Memory Capacity

We have described three different models for the allocation of memory capacity to objects, including an independent feature stores model, a fixed-resolution slot model, and a flexible resource model. Each model makes a different claim about how memory capacity is allocated to objects for the storage of visual information. Again, as emphasized in the introduction, these models of resource allocation are presented in terms of dividing a 'storage space' in different ways, but it is important to note that space is used only as a metaphor for the structure, resource or process underlying short-term memory storage.

The independent feature stores model, in which there are separate memory stores for each feature dimension is clearly inconsistent with the current results. This model holds that there are separate memory stores for color and the features underlying the encoding of the polygon shapes. On this view, each feature imposes a load on a separate feature dimension and thus there should be no cost to encoding and storing both features, yet we see a significant drop in accuracy for both color and shape when both features must be stored together relative to when either feature had to be stored alone. Thus, we can reject any model that holds that there are completely independent memory stores for color and shape. How then can we account for the results of experiments that show a limit to the total number of features that can be stored and not the number of objects (Delvenne & Bruyer, 2004; Olson & Jiang, 2002; Schneider et al., 2001; Wheeler & Treisman, 2002)? We have previously demonstrated that increasing the amount of detail that must be stored per object systematically decreases the number of objects that can be stored in memory (Alvarez & Cavanagh, 2004), suggesting that there is an upper limit on the amount of detail that can be stored in memory. Thus, increasing the number of features per object (e.g., bicolored versus unicolored objects) will decrease the number of objects that can be stored. We discuss possible mechanisms for varying the amount of detail encoded per object below.

Thus, the current results are in fact consistent with the hypothesis that there are parallel feature stores and that it is possible to overload the storage capacity of one feature store without overloading other feature stores, but they also require that the basic unit of storage is the "object", not individual features. If individual features could be selected independently, then it would be possible to remember, say, the color of one set of 4 objects and the orientation of a separate set of 4 objects without cost as well as remembering color and orientation from the same set of 4 objects. That is, only the number of features stored per dimension would impact storage capacity, and not the number of objects over which those features are distributed. However, remembering both the color and orientation of one set of 4 objects is easier than remembering the color of one set of 4 objects and the orientations from a separate set of 4 objects (Olson & Jiang, 2002). Similarly, remembering both the shape and texture of one set of 2 objects is easier than remembering the colors of 2 objects and the textures of 2 separate objects (Delvenne & Bruyer, 2004). In both cases, performance drops as the number of objects over which the features are distributed is increased even though the total number of features to-be-remembered is the same. These results are consistent with those of the current experiments: even if there are separate memory stores for different feature dimensions, memory cannot be allocated to one feature completely independently of other features.

The current results are also inconsistent with the fixed-resolution slot model. According to this model, memory is divided into a fixed number of storage slots, each storing a single object with a fixed resolution, with the storage capacity of each individual slot independent of the other storage slots. We found that 3 colors could be stored in memory, indicating that there are at least three storage slots. However, we also found that a single complex shape could be stored almost perfectly, indicating that the resolution of storage is sufficient for encoding these shapes, but no more than 1 such shape can be stored in memory. If the storage slots have enough resolution to store the shapes, then at least 3 shapes should be stored (matching the number of colors that can be stored, which sets a lower bound on the number of storage slots that must be available).

It is important to consider alternative explanations or modifications that could salvage the slot model. First, we assume that change detection errors in the current experiments primarily reflect storage capacity limitations. Although this assumption is commonly made, either explicitly or implicitly, in experiments on visual short-term memory (e.g., Luck & Vogel, 1997; Rensink, 2000) this assumption has not gone unchallenged (Landman, Spekreijse, & Lamme, 2003; Mitroff, Simons, & Levin, 2004). There are several alternative sources of change detection errors, including the failure to encode items into memory (even when there is enough capacity to do so) or a failure to make the comparison between the stored representation and the test display (Simons, 2000).

Given these possible alternative sources of errors, one could explain the lower capacity for shape than for color by arguing that there are a fixed number of slots with a fixed storage resolution, but that it is more likely that these slots will not be filled, or that the relevant comparison will not be made, when the complex shape is to-be-remembered than when color is the target feature (Luck & Zhang, 2004). However, there are aspects of the data and experimental procedure that suggest these alternative sources of change detection errors do not account for the current results. First, the possibility that the slots are less likely to be filled when remembering the shapes than when remembering color cannot account for the results of the conjunction condition in Experiment 2. In this condition both the color and shape had to be remembered and the estimated storage capacity for color was 2, suggesting that two slots were consistently filled, and yet the estimated storage capacity for shape was only 1. The tested feature in the conjunction condition was randomly determined, and thus the actual number of ”objects” encoded into memory must have been the same regardless of which feature was tested. We suggest that the difference in estimated storage capacity for shape and color must then reflect a difference in the precision with which each features was stored. On average, only 1 shape was stored with enough precision to detect a shape change, even though on average at least 2 objects were stored (based on the number of colors stored) with enough precision to detect a color change.

Second, the test procedure was optimized to insure that the relevant comparison between the stored representation and the test display was made. Specifically, only a single item was presented in the test display, and thus observers knew specifically which object to compare to memory. Moreover, there was a post-cue that prompted observers to make their comparison based on the cued feature dimension. Probing questions have been shown to help observers remember stored information even when changes were not explicitly detected (Simons, Chabris, Schnur, & Levin, 2002). While Simons et. al. used a much different paradigm than we used in the current experiments, their results nevertheless suggest that a specific probing question can ameliorate the occurrence of errors due to a failure to make the comparison between a stored representation and the test display in our experiments. These aspects of the experimental procedure minimize potential errors due to the failure to make the relevant comparison, at least to the extent that observers have voluntary control over the decision process.

Assuming that the observed differences in change detection performance actually reflect storage capacity differences, the slot model must be modified in order to account for the current results. Specifically, one could abandon the strong claim that visual short-term memory stores integrated objects, and modify the slot model so that each slot stores a single part of an object, rather than a whole object. It would then be possible to divide a single complex object into parts and store a single complex shape by dividing it into, say, three parts. Thus, the parts of a single complex shape could be stored, but there would be no room in memory for additional parts, limiting the total storage capacity to just a single object. Note that this model assumes that storing a part of an object requires lower resolution than storing the entire object, a claim we have no direct evidence to support. However, even if we grant this assumption, a storage system in which all parts of an object are divided and stored in separate slots cannot explain the current results. If this were the case, then a single complex shape must fill all of the storage slots (because no more than 1 shape can be stored in the current experiments), so it would never be possible to remember more than 1 color (because each part has the same color), but the results of Experiment 2 show that it is possible to remember two colors while simultaneously remembering just 1 complex shape.

A final modification of this part-based, fixed-resolution, slot model can account for the current results. Specifically, if it were possible to break an object into parts and encode a subset of those parts rather than the entire object, say 2 parts from 1 object and 1 part from another (giving 2 colors in memory, and some cost to shape storage relative to storing all 3 parts from a single object - the exact pattern observed in experiment 2) we could explain the current results. However, we argue that this type of model is indistinguishable from the flexible resource model. The bottom line is that the ability to store partial information about objects is exactly what is meant by ”flexibility” in the flexible resource model, and we claim that breaking objects into parts and storing only some parts of an object but not others is one possible mechanism of flexibility (see below).

In sum, the current results place strict constraints on any model of memory storage that suggests there are independent feature stores or that the number of objects and the amount of detail that is encoded per object is fixed regardless of the demands of the task. It appears that the allocation of visual short-term memory is flexible, in the sense that it is not bound to store objects with a fixed amount of detail. It can store a little detail per object allowing many objects to be stored (as with color), a lot of detail per object reducing the number of objects stored but increasing the precision with which each object is stored (as with shape), or an intermediate level of detail (as in the color x shape conjunction condition) depending on the demands of the task.

What is the Mechanism of Flexibility?

Given the apparent flexibility with which memory capacity can be allocated to objects, it is important to consider what the mechanism of this flexibility could be. Here we introduce two possible mechanisms: variable resolution by spatial scale, and partial encoding of objects by breaking them into parts. While these mechanisms are purely speculative, and there might be other plausible alternatives, we present these two possibilities here as there exist experimental findings that suggest these mechanisms are viable.

Variable Resolution by Spatial Scale. This mechanism assumes that visual attention is necessary to encode objects into visual short-term memory and that the scale or spatial precision with which information is encoded into memory is inversely related to the area or number of objects attended. That is, the more objects that are selected for encoding into memory, the more coarse the encoding for each item. For illustrative purposes, Figure 6 shows the effect of varying spatial resolution on the representation of color and shape for two of the stimuli used in the current experiments. The representation of each item decreases in spatial precision from left to right. This figure illustrates that even a spatially coarse description of the objects (when more objects are encoded) is sufficient to discriminate the colors but that only a fine description (when fewer objects are encoded) is sufficient to discriminate between the shapes. Thus, varying the spatial scale that is attentionally selected is a possible mechanism by which memory capacity is flexibly allocated to objects. If this were the case, then the precision with which spatially defined features are stored in memory, such as orientation and spatial frequency would depend critically on spatial precision. However, spatial precision for features that are not defined over space, say color and luminance, would not depend critically on spatial precision. Note that this mechanism requires that the visual system must represent images at several scales or degrees of coarseness in terms of spatial resolution. Burt and Adelson (1983) as well as Sakitt and Barlow (1982) have proposed that such a multi-resolution representation exists in early visual analysis and this claim is consistent with physiological findings (de Valois, Albrecht, & Thorell, 1982). There is also evidence that attention increases the spatial resolution with which visual information is encoded (Yeshurun & Carrasco, 1998), indicating that attention and spatial resolution are tightly linked. Finally, other research suggests that the resolution with which information is stored in visual short-term memory depends on the number of attended objects (Palmer, 1990). In Palmer's study, observers viewed two displays and had to make a discrimination between them (e.g., to determine whether one of the lines in the display increased or decreased in length). The number of objects presented in this task was always the same, but a cue indicated a subset of those items to be encoded into memory. As the number of cued objects increased, the precision with which shape, orientation, and line length were stored in memory decreased (discrimination thresholds increased), suggesting that attending to more items results in a decrease in the spatial precision of memory representations. Thus, the visual system appears to represent an image at several spatial scales, attention appears to increase the spatial precision with which information is selected, and spreading attention over a larger number of items results in a coarser spatial representation of each item in memory. These findings lend credence to the possibility that the flexibility in allocating memory capacity to objects is achieved by varying the spatial scale with which items are stored (see Nakayama, 1990, for a related model for visual pattern recognition).

Partial Encoding By Breaking Objects Into Parts. Another possible mechanism for the flexibility of allocating memory capacity to objects assumes that the basic unit over which visual short-term memory operates is object parts rather than integrated objects. This mechanism requires that objects are first segmented into parts, perhaps based on low-level visual rules (e.g., minima of curvature, Hoffman & Richards, 1984) that can be computed rapidly (Xu & Singh, 2002), and that changing the number of parts encoded per object varies the amount of detail encoded per object. This mechanism is illustrated in Figure 7 in which two polygon shapes are first segmented into parts, and then 2 parts are encoded from the object on the left and only 1 part is encoded from the object on the right.

Figure 6. Variable Resolution by Spatial Scale . Illustration of the effect of decreasing spatial resolution on the discriminability of the shapes and colors of two objects used in the current experiments. Note that as the resolution decreases from left to right, the difference in shape for the polygons in the top and bottom rows becomes less noticeable, whereas the difference in color is relatively unaffected. It is possible that the resolution with which items are stored decreases as the spatial area or number of objects selected increases, and that varying the spatial scale that is attentionally selected is the mechanism by which memory capacity is flexibly allocated to objects.

There is evidence that visual short-term memory is sensitive to the part structure of objects. For example, two features are remembered best when they are on the same part of an object, worse when they occur on different parts of the same object, but worse yet when they occur on separate objects (Xu & Singh, 2002). These results indicate that visual short-term memory registers the part structure of objects and that this structure plays an important role in determining memory capacity. It has also been demonstrated that changes in the shape of an object are detected with much greater sensitivity if the change suggests a change to the part-structure of an object than if it does not (Barenholtz, Cohen, Feldman, & Singh, 2003). Although these previous findings suggest that the part-structure of objects plays an important role and visual short-term memory representations, there is no evidence of which we are aware that suggests it is possible to selectively encode one part of an object into memory without encoding other parts of the object as well. Thus, there is less evidence to support this possible mechanism than the variable resolution by spatial scale mechanism outlined above.

The important point is that the results of the current experiments require that there is some mechanism for varying the amount of detail encoded per object, such that increasing the amount of detail encoded per object decreases the total num-

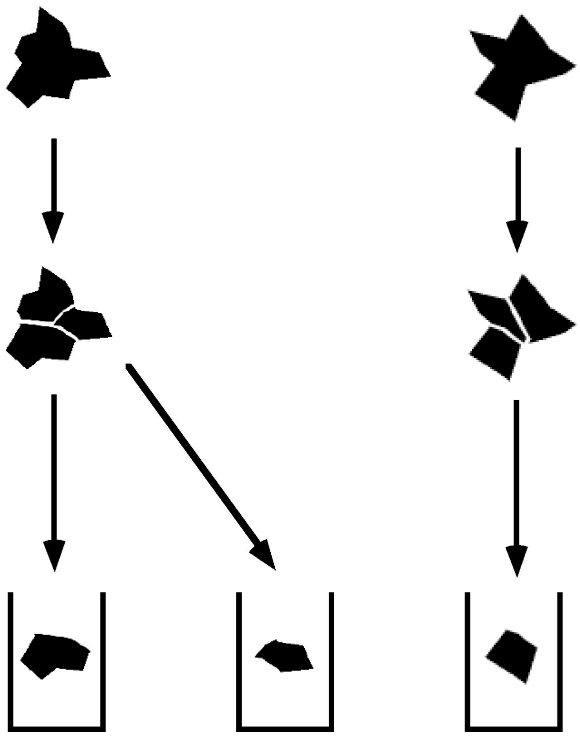

Figure 7. Partial Encoding By Breaking Objects Into Parts. Illustration of an alternative mechanism of flexible encoding. In this model, objects are segmented into parts and each slot in memory can store a single part. According to this model, the amount of detail encoded per object depends on the number of parts that are stored. In this example, more parts of the object on the left are encoded than for the object on the right.

ber of objects that can be stored in visual short-term memory. Future research will be necessary to determine whether either of these proposed mechanisms underlies the flexibility with which memory capacity is allocated to objects.

Conclusion

One of the most basic questions we can ask about any limited-capacity process or resource is how that capacity is allocated to the basic units of operation. The current results suggest that there is a great deal of flexibility in the allocation of visual short-term memory capacity and that it is possible to represent several objects with low resolution, or fewer objects with relatively high fidelity. Future work will be necessary to uncover the exact mechanism of this flexibility, and it appears that a potentially fruitful direction for this future work is to investigate the relationship between the allocation of memory capacity and the mechanisms of attentional selection.

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