THE DECAY CHARACTERISTICS OF SIZE, COLOR, AND SHAPE INFORMATION IN VISUAL SHORT-TERM MEMORY

by

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Abstract

Previous studies of the decay of information in visual short-term memory have made the assumption that all visual properties decay in the same way. The present study challenges this assumption by investigating the individual decay characteristics of size, color, and shape information in visual short-term memory using a partial report method. Twelve observers were shown a display of six objects that were either small or large, red or blue, and a circle or a triangle. After a certain delay period (inter-stimulus interval), observers were cued to report the size, color, or shape of one of the six objects. In experiment one, inter-stimulus intervals (ISIs) ranged from 100 ms to 700 ms; in experiment two, 100 ms to 1900 ms; and in experiment three, 100 ms to 5700 ms. The experimental logic was that a pattern of decreasing accuracy across ISIs reflected a decay of the visual short-term memory representation. In each of the three experiments, unique decay characteristics were found for these three visual properties. Color information showed significant decay between 100 and 700 ms, and then it stabilized and showed no further decay up until an ISI of 5700 ms. Size information showed no decay between 100 and 1900 ms, after which it decayed gradually until the longest ISI of 5700 ms. Shape information gradually decayed after 100 ms across all the ISIs. The discovery of different decay characteristics for size, color, and shape information has implications for how properties are stored in visual short-term memory, as well as how properties are integrated in object representations in visual short-term memory.

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Introduction

The study of visual short-term memory has been of interest to psychologists since the late 19th century (eg. Jevons, 1871, Wundt, 1899; Bentley, 1899). The bulk of this research makes an implicit assumption that as visual short-term memory decays, all of the properties maintained by it decay in the same way. The purpose of this paper is to challenge this assumption by investigating the individual decay characteristics of size, color and shape information in visual short-term memory. Finding unique decay characteristics for different visual properties would contribute to what is known about how visual information is represented in visual short-term memory.

Defining Visual Short-Term Memory

Before beginning a discussion about this issue, it is important to clarify how the term *visual short-term memory* will be used. There is little agreement between studies as to what term is used to describe memory for a visual stimulus that is no longer present, which is problematic in that it results in a body of literature with inconsistent terminology. For example, visual memory that lasts for durations between 0 and 1000 ms after the visual stimulus is removed has been called preperceptual memory (Clark, 1969), iconic memory (Turvey & Kravetz, 1970), visual information storage (Sperling, 1960), short-term visual memory (Phillips, 1974), and very short-term visual memory (Palmer, 1988), to name but a few. For the purpose of expedient discussion, visual short-term memory (vSTM) will be used as an umbrella term that refers to memory that lasts for up to several seconds after the visual stimulus has been removed from view.

It is important to note, however, that using vSTM as an umbrella term does not imply that it is a homogenous process. In fact, the characteristics of vSTM change as a function of memory duration. It can be divided into three separate phases of post-stimulus duration, each with unique storage and representation properties. In brief, the first phase is *sensory storage* or *visible persistence*, which occurs at delays of up to 80 to 100 milliseconds after the stimulus is removed (eg. Phillips, 1974). In this first phase, visual short-term memory is of a high capacity and tied to spatial location. The second phase of visual short-term memory has been referred to as *iconic memory* (Neisser, 1967), and lasts for delays of up to 250 to 1000 milliseconds after removal of the visual stimulus, depending on the methods and stimuli used (eg. Averbach & Sperling, 1960; Averbach & Coriell, 1961). It has a smaller capacity than sensory storage, but is similarly tied to spatial location The third phase of short-term memory is known as *visual working memory*, and occurs at delays of longer than approximately 600 ms (eg. Vogel, Woodman & Luck, 2001). Its capacity is thought to be equivalent to the amount of information that can be processed within the scope of attention (eg. Cowan, 2000). This paper will study the decay of size, color, and shape information across all of these three phases, with special consideration given to the different phases in the discussion portion.

The Decay of Information in vSTM

In order to learn about the contents of vSTM, it is important to have a reliable way of accessing its contents. In 1960, Sperling provided a new way to study the contents of vSTM with the introduction of the *partial report method.* He identified that the inherent problem with studying the contents of vSTM was that in the time it took to provide the report, the contents of it decayed. Hence, whole reports underestimated the actual amount of information available for report in vSTM. To circumvent this problem, he devised a way of estimating the true content of vSTM by asking observers to report just a portion of it and called this the partial report method. He showed observers a display containing three rows of four letters for 50 milliseconds (ms), and then after a certain delay, sounded a high, medium or low tone. The tone cued the observer as to which row of letters to report. On average, he found that observers were able to correctly report four out of the four letters in a row 76% of the time when the tone sounded immediately after the offset of the letter display. Based on the assumption that the partial report is a random sample of the letters that the observer has available in iconic memory, he calculated the total number of letters available to be 9.1, by multiplying 76% by 12 (the number of letters in the display). Compared to whole reports of about 4.3 letters (when no cue is given), the partial report calculation gave a more accurate indication of the total number of letters actually available for report in iconic memory. Although Sperling introduced the partial report method as a way of calculating the information capacity of vSTM at ranges of between 0 and 1000 ms, this method is equally useful in providing a way to directly access the contents of vSTM at any given point in time. More specifically, it is well suited to the task of determining the extent to which specific visual properties have decayed at different time durations in vSTM.

Clark (1969) used the partial report method to explore the decay of color information in vSTM. She showed subjects a display of three rows of five circles that were randomly colored red, yellow, and green. In experiment one, a tone cued the observer to report the location of circles belonging to one color; for example, a high tone would cue the observer to report the location of all the red circles. Whole report trials were also included, where a fourth tone cued the observer to report the color of the circle at all of the fifteen locations. For both partial and whole reports, the tone occurred randomly at ISIs of 0 to 1250 ms. Using Sperling's (1960) calculation, she found that the partial report method yielded a report of about 20% more letters than the whole report, indicating that using the property of color was an efficient way of sampling from the vSTM representation. Interestingly, the partial report advantage did not lessen for ISIs ranging from 250 to 1250 ms, suggesting that after 250 ms, the color information necessary to sample a portion of the vSTM representation does not decay appreciably within this post-stimulus time.

Turvey and Kravetz (1970) investigated whether or not shape was an efficient selection criterion for sampling from vSTM at different durations, and in doing so, provided data about the decay of shape information. In their experiment, they showed observers a display of three rows of four letters for 100 ms. The letters chosen were R, O, and Z for their easy discriminability. After a delay of either 0, 500, or 1000 ms, a high, medium, or low tone sounded that cued observers to report the locations of a particular letter. They found that when shape was the selection criterion, partial report performance was superior to whole report at all ISIs, but the advantage lessened as the ISI increased. This result suggested that shape information decays in vSTM over delays of up to at least 1000 ms.

Other than these two studies, there is no other literature that directly addresses the issue of how size, color, and shape properties decay in vSTM. However, there are studies whose results can shed light on the issue, despite the fact that their main goal was not exploration of decay characterisics in vSTM. A study by Eriksen and Lappin (1967) using same/different judgments showed that shape information does *not* decay appreciably in vSTM at delays of up to 1000 ms. In their experiment, observers were shown a display of 4 irregular nine to sixteen-sided shapes for 125 ms. After a delay ranging from 0 to 1000 ms, they were shown a test display of one shape and asked if it was the same or different from the four shapes in the original display. On half of the trials the test shape was different from the original four, and on half of the trials it was the same as one of the original four. They found that accuracy to report whether or not a change had occurred remained stable at about 70% for ISIs of 50 to 1000ms. Hence, their results suggest that shape information does not decay appreciably in vSTM for delays of up to 1000 ms, a result that is in direct opposition to the Turvey and Kravetz study (1970).

One possible explanation that may account for this difference in results for the decay of shape information is that one study used a partial report method, and the other a same-different judgement task. Directly comparing results from partial report and judgement tasks is questionable because they require different kinds of memory report, namely, recall and recognition. It is an old and well-established fact that recognition memory is superior to recall memory (Myers, 1914), suggesting that recall and recognition are two different cognitive processes that may make different demands on vSTM. It may be the case that Eriksen and Lappin (1967) found no decay of shape information simply because the recognition memory report is easier than the recall memory report used by Turvey and Kravetz (1970). Because of these differences in methodology, it is not appropriate to directly compare results of the studies.

A study by Palmer (1988) used a slightly different methodology than the previous two, and yielded results indicating that shape information does *not* decay in vSTM at delays of up to 500 ms. He showed observers a study display of four lines of varying lengths for 50 ms. After a delay of either 120 or 500 ms, a tone sounded that cued the observer as to which of the four lines was to be compared against a single test stimulus line. The test stimulus would then appear, and observers were required to judge whether the test stimulus line was longer or shorter in length than the cued study display line. When they compared performance at delays of 120 and 500 ms, they found that there was no significant difference in the length difference needed in order to make an accurate judgement, suggesting that information about the size of a line does not decay significantly within this time. In a second experiment, rectangles of varying elongations were used as stimuli instead of lines. Observers were required to judge whether the test stimulus rectangle differed in horizontal or vertical elongation from the cued rectangle in the study display. Again, there was no significant difference between the elongation difference needed to make an accurate judgement at 120 ms and 500 ms delays. In sum, the Palmer results suggest that size and shape information does no*t* decay appreciably in vSTM between the delays of 120 and 500 ms.

Like the Eriksen and Lappin (1967) results, Palmer's (1988) result showing that shape information does not decay at delays of up to 500 ms is also in direct opposition to the Turvey and Kravetz (1970) study. Another possible explanation for this discrepancy stems from the fact that different numbers of objects were used in the test display for these experiments. For both Eriksen and Lappin's, and Palmer's study, there were four objects in the test display, whereas in Turvey and Kravetz's study, there were twelve. The number of objects in the test display is an important factor because it has been demonstrated that attention can hold on to, or process, about 4 or 5 objects at a time (Rensink, 2000a). Consequently, it may be that Eriksen and Lappin, and Palmer, did not find decay for shape information because attention had latched on to all four items, thereby effectively shielding them from decay.

Another reason why the results from the Turvey and Kravetz (1970), Eriksen and Lappin (1967), and Palmer (1988) studies cannot be compared directly is because letters, rectangles, and irregular polygons should not be considered as equivalently shape-like. That is, letters may require special verbal processing and storage in vSTM by virtue of their semantic nature. In contrast, while still associated with a semantic label, it may be that the representation of a rectangle is less dependent on verbal coding, and irregular polygons are not amenable to verbal coding at all.

Taken as a whole, these studies provide preliminary evidence for the proposal that visual properties have different patterns of decay in vSTM. The partial report studies suggest that color information does not decay at delays of 1000 ms, whereas shape information begins to decay at or before 500 ms. In contrast, the studies that required observers to make same/different judgments found that shape information does *not* decay at delays of 500 or 600 ms in vSTM. As for size information, the data thus far suggests that it does not decay at delays of up to 500 ms. As mentioned earlier, the inability to draw firm conclusions about the decay characteristics of different properties stems from the difficulty in comparing results across experiments that use different paradigms and stimuli. Another shortcoming of the current literature is that despite the fact it provides preliminary evidence that properties have different decay patterns, it is impossible to know how they decay in relation to one another without systematically comparing different properties within the same experimental framework.

Why Study the Decay Characteristics of Visual Properties?

Whether visual properties have different decay characteristics is an interesting idea to explore for several reasons. First of all, this becomes a salient issue when comparing results between different studies of vSTM because the properties of stimuli can vary greatly from study to study, from colored letters to black and white irregular shapes. If indeed the representation of one property were to decay more quickly than another, it would be erroneous to assume that all stimuli are represented with the same robustness in vSTM.

Secondly, finding unique decay characteristics for different visual properties provides a clue about how visual properties are stored in vSTM. Different patterns of decay for size, color, or shape suggest that visual properties are not necessarily stored in a unitary vSTM store. More specifically, unique decay patterns would provide preliminary support for the idea that there are independent, parallel short-term memory stores, each devoted to a particular attribute of the visual stimulus (eg. Magnussen, Greenlee, & Thomas, 1996).

Lastly, finding that visual properties have different decay characteristics may shed light on how different properties integrations come unbound in visual short-term memory. Currently, there is some evidence that the location of an object binds readily with the color or shape of an object (eg. Nissen, 1985; Isenberg, Nissen & Marchak, 1990). It may be the case that the integration strength of location with the size, color, or shape of an object depends on the specific property involved. For example, location may come unbound from one property more readily than the others.

Experimental Logic

Given that understanding the decay of properties in vSTM would shed light on these issues, further exploration of the topic is well justified. The purpose of the present experiment, then, is to systematically compare the decay of size, color, and shape information by sampling the contents of vSTM at different delay intervals using a partial report method. By measuring accuracy while varying the ISI and cue type, this method can provide a way of determining the decay of the contents of vSTM over time. More specifically, accuracy is an indicator of the extent to which representations have decayed in vSTM. When accuracy is high, it is assumed that vSTM representations must be sufficiently intact in order to support successful report of its contents. Conversely, when accuracy is low, it is assumed that vSTM representations must be decayed to the point where they are no longer supporting report. Consequently, it is assumed that as time elapses in VSTM, decreases in accuracy correspond to decay of the vSTM representation.

General Method

The following procedure was used for all of the three experiments described in this paper.

Participants

Each experiment was run on a different group of twelve male and female observers who ranged in age from 19 to 36 years old. Observers were right handed, had normal color vision, and normal or corrected-to-normal visual acuity. Observers were given either $10 or a course credit for approximately one hour of participation.

Procedure

Experiments were programmed using V-Scope software (Rensink and Enns, 1991) and presented on Imac computers viewed at a distance of 55 centimeters. Observers were shown a fixation cross at the center of the screen for 1000 ms, which signified that the stimulus display was about to appear. Immediately after the offset of the fixation cross, the stimulus display consisting of six items arranged in a radial array was shown for 200 ms. Each item in the display could be either large or small, red or blue, and a circle or a triangle. After an interstimulus interval (ISI) that ranged from 100 to 5700 ms (ranges differed for each experiment), a cue appeared at the center of the screen for 200 ms. The cue had a bar next to it that pointed to one of the six locations in the radial array. Three different cues were used, each requiring report of one of three properties: Si for size, Co for color, or Sh for shape. On each trial, observers were required to report the cued property of one of the six items by pressing the corresponding key on a keyboard labeled small, large, red, blue, circle or triangle. Cues were randomized so that observers did not know beforehand which object or property would be cued. Figure 1 shows the sequence of one trial.

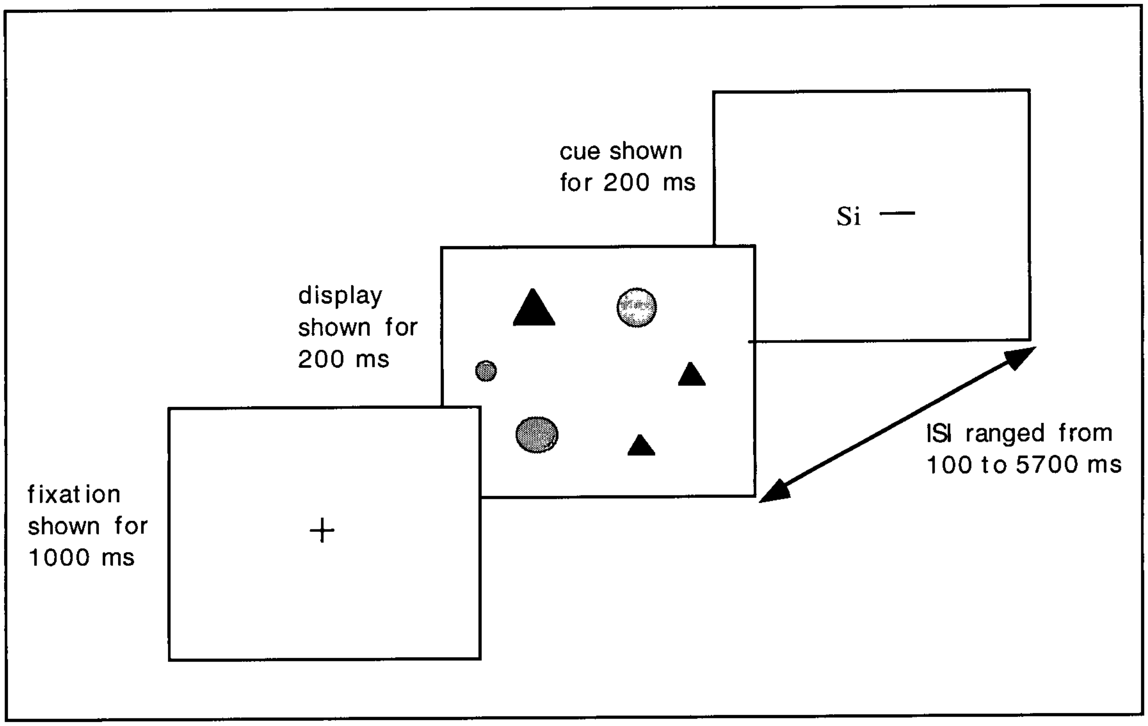

Figure 1. Sequence of stimulus events for one trial. On this trial, observers would press the key marked 'small' on the keyboard.

At the beginning of the session, observers were given 30 practice trials. During the practice trials, the subject was given feedback after each response; correct responses were followed by a plus sign, and incorrect responses were followed by a minus sign. After the practice trials, each observer was given 4 blocks of 72 trials. There was no feedback given in the non-practice trials. In the instructions given to participants, accuracy rather than a fast response time was emphasized.

Stimulus Specifications

The stimulus display consisting of six items in the radial arrangement subtended a visual angle of 9.5 x 8.5 degrees. The items were equally spaced apart, with an average distance of 2.4 degrees separating them.

By varying the three properties of size, color, and shape, a total of eight different objects were possible. Each of the eight objects appeared with equal probability over the course of the experiment. Stimulus displays were created with the constraint that each size, color and shape appeared three times in random locations within each display. For example, each display would have three large objects and three small objects, three red and three blue, and three triangles and three circles.

Large items subtended 1.7 x 1.7 degrees of visual angle, and small items 1.2 x 1.2 degrees, for a difference factor of 1.4. Red and blue items were created using the Pantone color system, and both colors had equal brightness and saturation ratings of 100%. Circles and triangles were the same height, as well as the same width when measured from the middle of the circle and the base of the triangle. The cues subtended 1.0 x 0.6 degrees, and the bar subtended 1.7 x 0.1 degrees.

General Results

In each of the three experiments, trials where errors were caused by misreading of the cue were removed before analyzing the data. This type of cue-related error could occur when, for example, the observer would give a size report when the cue indicated that a shape report was to be given. Trials with these types of errors were removed because they reflect faulty processing of the cue rather than a failure to accurately report from vSTM. Trials where keys other than the six marked ones were pressed were also removed. The total percentage of trials removed for both of these types of errors ranged from 1.4% to 2.4% across experiments.

The data from each experiment was analyzed using a repeated measures ANOVA, with five factors. The first factor was **interval**, or ISI, the amount of time that elapsed between the display offset and the cue onset. The second factor was the **report** the subject was required to make: size, color, or shape. The third, fourth and fifth factors corresponded to the properties of the object upon which the observer was required to report: whether it was small or large (the object's **size**), red or blue (the object's **color**), and a circle or a triangle (the object's **shape**). These last three factors were included to control for the possibility that the non-reported properties of an object had an effect on the accuracy for the property being reported. For example, it may have been the case that reporting the color of an object depended on whether the object was small or large. Post-hoc follow-ups were done using Fisher's Protected Least Significant Difference (PLSD) method.

Experiment 1

Method

Experiment 1 was designed to explore the decay of size, color and shape properties in the early phases of vSTM, namely, sensory storage and iconic memory. Hence, ISIs corresponding to both of these phases were used, namely, 100, 400, and 700 ms.

Results

Accuracy for each report at the three intervals is shown in Figure 2. Table 1 in Appendix A shows the corresponding means and standard errors. Significant main effects were found for the interval factor, $F(2,22) = 14.75$, $p < .0001$ and the report factor, $F(2,22) = 6.27$, $p < .01$. The interaction of primary interest between interval and report was also significant, $F(4,44) = 5.44$, $p < .001$, making qualifying statements for the main effects necessary. Accuracy for color reports dropped significantly across the three intervals, $F(2,22) = 14.94$, $p < .0001$, with accuracy at the 100 ms interval differing from the 400 and 700 ms intervals with $p < .01$, and $p < .0001$, respectively, as well as the 400 ms interval differing from the 700 ms interval, $p < .05$. In contrast, accuracy for size reports did not change across intervals, $F(2,22) = 1.42$, $p > .25$. Accuracy for shape reports differed significantly across intervals, $F(2,22) = 8.44$, $p < .01$, with the 100 ms interval being more accurate than the 400 and 700 ms intervals, $p < .001$ and $p < .01$.

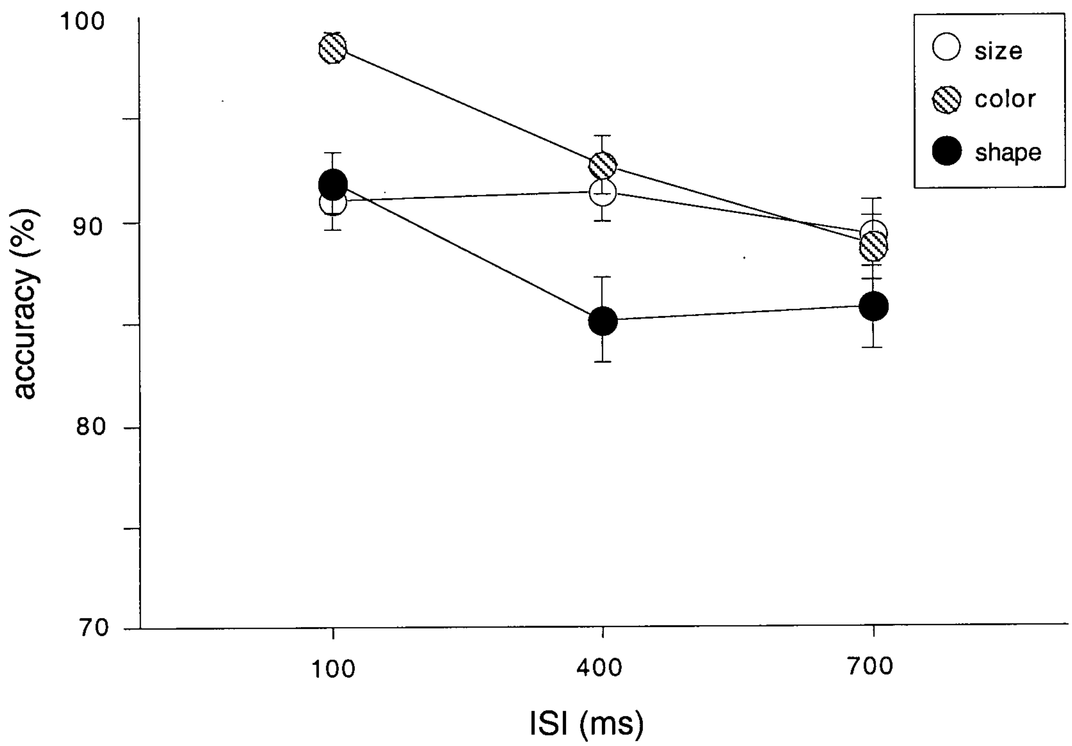

Figure 2. Accuracy rates for size, color, and shape reports at the three ISIs (Experiment1). Chance performance is at 50% and bars represent standard error.

The interaction between interval and report can also be interpreted at the level of each interval. At 100 ms, accuracy for the three reports differed significantly, $F(2,22) = 8.74$, $p < .01$. Accuracy for color reports was significantly better than for size, $p < .001$, and shape, $p < .01$. At 400 ms, the accuracy for the three reports also differed significantly, $F(2,22) = 12.39$, $p < .001$, but in this case, accuracy for the shape report was significantly worse than size, $p < .001$, and color, $p < .0001$. At 700 ms, there was no significant difference in accuracy between the three reports, $F(2,22) = 1.25$, $p > .30$.

Significant main effects were also found for the factors of size, $F(1,11) = 5.13$, $p < .05$, and color, $F(1,11) = 9.49$, $p < .01$. However, two three-way interactions were found that require qualification of these main effects. The first three-way interaction is report by size by color, $F(2,22) = 4.51$, $p < .05$. This interaction was broken down at each level of each variable to yield the following:

i. When broken down by report, the size by color interaction is significant when the report is shape $F(1,11) = 6.49$, $p < .05$. Further simplified, when the report is shape and the object is large, accuracy is better for blue objects than red ones, $F(1,11) = 11.87$, $p < .01$.

ii. When broken down by size, the report by color interaction is significant when the object to be reported upon is large $(F,22) = 4.08$, $p < .05$. Further simplified, when the object is large and red, there is a significant difference in the accuracy for reports, $F(2,22) = 7.06$, $p < .01$. Specifically, when the object is large and red, report for color is better than report for size, $p < .05$, and shape, $p < .001$. In addition, when the object is large, and the report to be made is size, accuracy for blue objects is better than for red ones, $F(1,11) = 4.95$, $p < .05$.

iii. When broken down by color, the report by size interaction is significant when the object to be reported upon is blue, $F(2,22) = 5.99$, $p < .01$. Further simplified, when the object is blue and small, there is a significant difference in the accuracy between reports, $F(2,22) = 9.12$, $p < .001$. Specifically, when the object is blue and small, report for shape is worse than for color, $p < .01$, and size, $p < .001$. In addition, when the object is blue, and the report to be made is size, accuracy for small objects is better than for large objects, $F(1,11) = 12.85$, $p < .01$.

The second three-way interaction found was interval by size by shape, $F(2,22) = 8.76$, $p < .01$. This interaction was broken down at each level of each variable to yield the following results:

i. When broken down by interval, the size by shape interaction was significant only at the interval of 700 ms, $F(1,11) = 7.83$, $p < .05$. Further simplified, this interaction can be reduced to three statements about the 700 ms interval. First, when the object to be reported upon was a circle, accuracy was better for small objects than large ones, $F(1,11) = 6.20$, $p < .05$. Secondly, when the object was a triangle, accuracy was better for large objects than small ones, $F(1,11)$, $= 5.15$, $p < .05$. Lastly, accuracy for circles was better than for triangles when the object was small, $F(1,11) = 4.93$, $p < .05$.

ii. When broken down by size, the interval by shape interaction was significant when the object to be reported upon was large, $F(2,22) = 6.58$, $p < .01$. Further simplified, when the object was a large circle, accuracy was better at the 100 ms than the 700 ms interval, $F(2,22) = 5.70$, $p < .01$.

iii. When broken down by shape, the interval by report interaction was significant when the object to be reported upon was a triangle, $F(2,22) = 5.93$, $p < .01$. Further simplified, when the object was a triangle and it was small, there was a significant difference in the accuracy at different intervals, $F(2,22) = 18.03$, $p < .0001$. Specifically, when the object was a small triangle, accuracy was better at the 100 ms interval than the 400 ms, $p < .01$, and 700 ms intervals, $p < .0001$. Accuracy was also better for small triangles at the 400 ms interval than the 700 ms interval, $p < .05$. In addition, when the object was a triangle, and the interval was 100 ms, accuracy was better for small objects than large, $F(1,11) = 5.03, p < .05$.

Discussion

The results of main interest from Experiment 1 demonstrate that the size, color, and shape properties of an object show different patterns of decay in vSTM for durations of up to 700 ms. Color information decays steadily from 100 to 700 ms, whereas size information shows a very different pattern and does not decay at all. Shape information shows yet another pattern and decays significantly from 100 to 400 ms, and then remains intact up to 700 ms. This preliminary evidence of unique decay characteristics for different visual properties has implications for how the visual properties of objects are stored in vSTM. It suggests that not all of the visual properties of the object are represented in vSTM with equal robustness. More specifically, there may be independent and parallel stores associated with different visual properties, with unique decay characteristics for each store contributing to the strength of the property in the object representation. The nature of how the visual properties of objects are stored in vSTM will be returned to in the general discussion.

Another way the data was approached was by comparing the accuracy of size, color and shape reports at different ISIs. At the 100 ms ISI, accuracy for color reports was significantly better than accuracy for size and shape reports. However, the better accuracy for color reports could be explained by differences in cue processing. A control experiment was run that measured the processing time associated with each cue. Observers were required to press a key on the keyboard marked 'size' when they saw the

Si cue, 'color' when they saw the Co cue, and 'shape' when they saw the Sh cue as quickly as possible. Observers were, on average, 40 ms slower to process the size cue than the color cue, and 75 ms slower to process the shape cue than the color cue. This could conceivably be because the size cue 'Si' and the shape cue 'Sh' are more similar to each other and more difficult to differentiate than the color cue 'Co'. At a delay interval of only 100 ms, the extra 40 or 75 ms it takes to process the size and shape cue may be long enough for the representation of size and shape properties to decay significantly, resulting in poorer performance for these reports. Consequently, the better accuracy for color reports at 100 ms can be attributed to the relatively faster processing of the color cue. Note however, that the difference in processing times for cues should not make a difference at longer ISIs; for example, when the delay to receive the cue has already been 700 ms or more, an extra 40 ms to process the cue is likely to be trivial.

When accuracy of the different reports was compared at the 400 ms ISI, size and color were not significantly different from each other, but both were significantly better than the shape report. Again, at a delay of 400 ms, it is unlikely that this result is caused by the differences in cue processing time. As support for this assertion, take size and color reports: even though there is a 40 ms difference in the time it takes to process their respective cues, accuracy between them is not significantly different. It is therefore unlikely that the large difference between accuracy for shape and size reports is due to the 35 ms difference it takes to process their respective cues. It is more likely that the differences in accuracy at 400 ms are due to the different patterns of decay for these properties. By 700 ms, the accuracy for all three reports did not differ significantly, suggesting that at this point, each property is represented in an equally strong manner in visual working memory.

It is difficult to explain the results of the three-way interactions and perhaps the most parsimonious explanation of them is a statistical one: when many factors are included in an analysis, the probability of finding significant interactions that, in fact, may simply be due to chance increases. For the most part, the seemingly random results are most logically explained this way; however, from a select number of the seemingly chaotic three-way interactions, there is a pattern that emerges. The pattern suggests that in specific cases, the accuracy associated with blue objects is higher than that of red objects. There are two interactions for which better accuracy for blue objects than red is found: when the object is large and the report required is shape, and when the object is large and the report required is size. Note that there are no significant interactions showing accuracy to be better for red objects than blue.

It is not immediately evident why the color of an object at this level of specificity would affect the accuracy of reporting its size or shape; however, it is possible that the difference in accuracy between blue and red objects may be related to the fact that there is a separate visual processing stream for blue objects (short wavelength properties), and red and green objects (medium and long wavelength properties). More specifically, it is believed that the short wavelength system is phylogenetically newer and was evolved for the purpose of color vision, whereas the middle and long wavelength system is older with the primary purpose of analyzing motion, form and depth (Mollon, Estevez & Cavonius, 1990). Based on this theory, it is possible that objects processed by the short wavelength system receive special color processing, resulting in better accuracy for blue than red objects.

Experiment 2

Methods

Experiment 1 found that size, color and shape information have different patterns of decay in vSTM. By an ISI of 700 ms, corresponding to the start of the visual working memory phase, the accuracy for each of these properties was not significantly different, suggesting that the representations for each were equally strong at this point. Experiment 2 extends the ISI to 100, 700, 1300 and 1900 ms to explore the pattern of further decay of these different properties at even longer intervals of visual working memory.

Results

Accuracy for each report at the four intervals is shown in Figure 3. Table 2 in Appendix A shows the corresponding means and standard errors. Significant main effects were found for the interval factor, $F\ (3,33) = 10.96$, $p < .0001$ and the report factor, $F\ (2,22) = 5.05$, $p < .05$. The interaction of primary interest between interval and report was also significant, $F\ (6,66) = 2.74$, $p < .05$, making qualifying statements for these main effects necessary. Accuracy for color differed significantly across the four intervals, $F\ (3,33) = 4.41$, $p < .01$. At 100 ms, accuracy was significantly better than at the 700, 1300, and 1900 ms intervals by $p < .01$, $p < .05$, and $p < .01$, respectively. In contrast, accuracy for size did not vary over the four intervals $F\ (3,33) = .52$, $p > .50$. Accuracy for shape differed significantly across the four intervals, F (3,33) = 6.50, $p < .001$, showing a pattern similar to that of color reports. Accuracy at the interval of 100 ms was significantly better than at the 700, 1300 and 1900 ms intervals by $p < .05$, $p < .01$, and $p < .001$, respectively. However, accuracy at the interval of 700 ms also approached being significantly better than accuracy at the 1900 ms, $p < .08$.

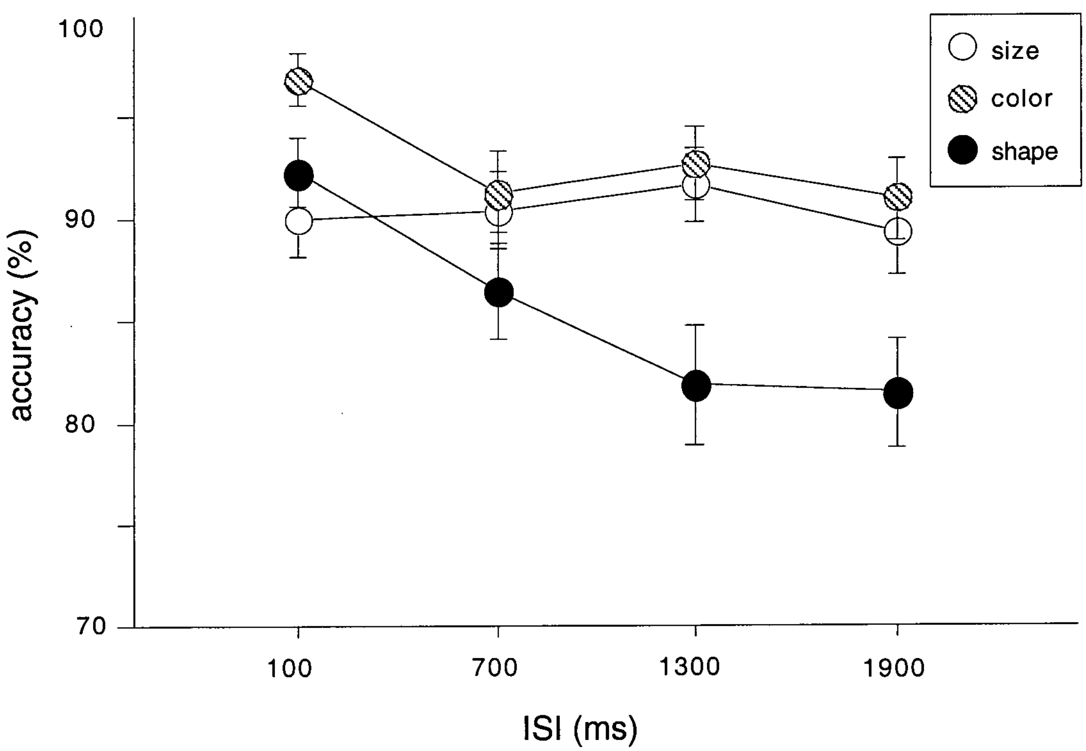

Figure 3. Accuracy rates for size, color, and shape reports at the four ISIs (Experiment 2).

The interaction between interval and report can also be interpreted at the level of each interval. At the 100 ms interval, the accuracy of the three reports differed significantly, F (2,22) = 5.15, $p < .01$. More specifically, report for color was significantly better than report for size, $p < .01$, and report for shape, $p < .05$. At the 700 ms interval, there was no significant difference in accuracy between reports, F (2,22) 1.29, $p > .25$. At the 1300 ms interval, there was a significant difference in accuracy between the three reports, $F(2,22) = 4.79$, $p < .05$. Report for color was better than report for shape, $p < .01$, and report for size was also better than report for shape, $p < .05$. At the 1900 ms interval, there was the same pattern of significant differences in accuracy between the three reports, $F(2,22) = 5.25$, $p < .05$, with accuracy for color report being better than accuracy for shape report, $p < .01$, and size report also being better than shape report, $p < .05$.

In addition to these results that are of main interest to the paper, several two and three-way interactions were found. The first significant two-way interaction found was report by size, $F(2,22) = 5.83$, $p < .01$. Simplified at the level of report, accuracy was significantly better for large objects than small objects when the report was shape, $F(1,11) = 21.85$, $p < .001$. Simplified at the level of size, accuracy for reports differed significantly when the object to be reported upon was small, $F(2,22) = 10.85$, $p < .001$. Specifically, when the object was small, accuracy for reporting the size of the object was better than for reporting the shape of the object, $p < .0006$, and accuracy for reporting color was also better than accuracy for reporting shape, $p < .001$. The second two-way interaction found was color by shape, $F(1,11) = 5.63$, $p < .05$. When broken down by shape, accuracy for objects that were circles was better for blue circles than red circles, $F(1,11) = 9.64$, $p < .01$.

The first three-way interaction found was interval by report by color, $F(6,66) = 2.26$, $p < .05$. This interaction was broken down at each level of each variable to yield the following:

i. When broken down by interval, the report by color interaction was significant at the 1300 ms interval, $F(2,22) = 4.61$, $p < .05$. Further simplified, when the interval was 1300 ms and the report to be given was shape, accuracy was better for blue objects than red ones, $F(1,11) = 5.89$, $p < .05$. In addition, when the interval was 1300 ms, and the object was red, there was a significant difference between accuracy for reports, $F(1,11) = 5.11$, $p < .05$. Specifically, accuracy for reporting the size of a red object was better than for reporting the shape of it, $p < .01$, and accuracy for reporting the color of a red object was also better than for reporting the shape of it, $p < .05$. When the interval was 1300 ms and the object was blue, there was also a significant difference between reports, $F(1,11) = 3.58$, $p < .05$. Specifically, accuracy for reporting the color of a blue object was better than for reporting the size of it, $p < .05$, and for reporting the shape of it, $p < .05$.

ii. When broken down by color, the interval by report interaction was significant when the color of the object to be reported upon was red, $F(6,66) = 3.13$, $p < .01$. Further simplified, when the object was red and the report given was shape, there was a significant difference between accuracy at different intervals, $F(3,33) = 5.31$, $p < .01$. Accuracy was better at the 100ms than the 1300 ms, $p < .001$, and the 1900 ms intervals, $p < .01$. Accuracy was also better at the 700 ms interval than the 1300 ms interval, $p < .02$. When the object was red and the interval was 1300 ms, accuracy between reports differed significantly, $F(2,22) = 5.11$, $p < .05$. Specifically, report for the size of the object was better than report for the shape of the object, $p < .01$, and report for the color of an object was better than report for the shape of the object, $p < .05$. When the object was red and the interval was 1900 ms, report for the color of the object was better than report for the shape of the object, $F(2,22) = 4.62$, $p < .05$.

iii. When broken down by report, the interval by color interaction was not significant at any of the levels of report.

The second three-way interaction found was report by size by color, $F(2,22) = 9.62$, $p < .001$. This interaction was broken down at each level of each variable to yield the following:

i. When broken down by report, the size by color interaction was significant when the report to be made was shape, $F(2,22) = 3.96$, $p < .05$. Further simplified, when the report was shape, and the object was blue, accuracy was better for large than small objects, $F(1,11) = 97.43$, $p < .0001$. In addition, when the report was shape and the object was large, accuracy was better for blue objects than for red objects, $F(1,11) = 10.42$, $p < 01$.

ii. When broken down by size, the report by color interaction was significant when the object to be reported upon was large, $F(2,22) = 5.48$, $p < .01$. Further simplified, when the object was large and blue, there was a difference in accuracy between the three reports, $F(2,22) = 4.08$, $p < .05$. Specifically, accuracy for color reports was better than for size, $p < .05$, and accuracy for shape reports was also better than for size, $p < .05$. When the objected to reported upon was large, and the report required was shape, accuracy was better for blue objects than for red objects, $F(1,11)$, $p < .01$.

iii. When broken down by color, the report by size interaction was significant when the color of the object to be reported upon was blue, $F(2,22) = 15.51$, p

$< .0001$. Further simplified, when the object to be reported upon was blue and small, there was a difference in accuracy between the reports, $F(2,22) = 15.87$, $p < .0001$. Specifically, accuracy for size was better than for shape, $p < .0001$, and accuracy for color was also better than for that of shape, $p < .0001$. When the object to be reported upon was blue and large, there was a difference in accuracy between reports, $F(2,22) = 4.08$, $p < .05$. Specifically, report for color was better than report for size, $p < .05$, and report for shape was also better than report for size, $p < .05$.

Discussion

The results of main interest from experiment two provide further evidence that the size, color, and shape properties of an object have different decay characteristics in vSTM for durations lasting up to 1900 ms. Perhaps the most surprising result from this experiment was that shape information does not appear to decay at all for durations of up to 1900 ms in vSTM. This is quite remarkable, given that color and shape information undergo significant decay at the same durations. This immunity to decay suggests that information about the size of an object is stored differently in vSTM than color and shape are, leading to the proposition that perhaps a separate stream of visual processing supports vSTM for size information. As mentioned in the discussion of Experiment 1, this is an issue that will be returned to in the general discussion.

The representation of both color and shape information decays significantly between delays of 100 and 700 ms. This is not surprising, given that 100 ms delays correspond to a highly detailed sensory memory, and 700 ms delays correspond to the end of iconic memory; it is expected that the amount of information that can be maintained between these two intervals would decrease. Of interest, however, is how the pattern of decay for color and shape information diverges at this point. From delays of 700 to 1900 ms, information about the color of the object does not decay; in contrast, shape information continues to gradually decay until 1300 ms, at which point it stabilizes and shows no more decay for up to 1900 ms.

The finding that the properties of size, color, and shape have unique patterns of decay in vSTM at durations of up to 1900 ms also has implications for how different properties are integrated to form object representations in vSTM. At this point, it should be noted that observers were required to maintain a fourth visual property in vSTM: the location of the object. In order to make a correct report, the integration of location with each of the properties of size, color, and shape was necessary. For this reason, the strength of the location-property binding, based on the amount of time that has elapsed in vSTM, may have affected accuracy to report the different properties of objects. This issue will be further discussed in the general discussion.

The data was also approached by comparing the accuracy of size, color and shape reports at different ISIs. For the 100 ms ISI, the results were similar to those in Experiment 1, in that color reports were significantly better than shape reports. They differed in that size reports were also better than shape reports though. At delays of 700 ms, there was no difference in accuracy for size, color, and shape reports, a result that is also in agreement with the findings of Experiment 1. Note that it cannot be said that by this ISI, the three properties have decayed to the same level, because size information has not decayed at all. It appears more precise to say that at delays of 700 ms in vSTM, there was no difference in the strength of the representation for the three different properties. At delays of 1300 and 1900 ms, the accuracy for different reports again diverged. At both of these intervals, reports for the size and color of objects were better than reports for the shape of them. The relatively poorer performance for reporting the shape of an object at these ISIs was attributable to the fact that size and color information did not decay appreciably after 700 ms, whereas shape information did.

The results from the two-way interactions yield two interesting patterns of results. The color by shape interaction indicated that accuracy is better for blue objects than red when the object to be reported upon is a circle. This is one of the same patterns that emerged from the interactions in experiment one: that in some cases, the accuracy for blue objects is better than accuracy for red objects. The second two-way interaction, report by size, indicated that reporting the shape of an object is more difficult when the object is small than when it is large. Along a similar vein, it was found that when objects are small, reports for size and color are more accurate than reports for shape. Figure 4 illustrates this interaction, with means and standard errors shown in Table 3 of Appendix A.

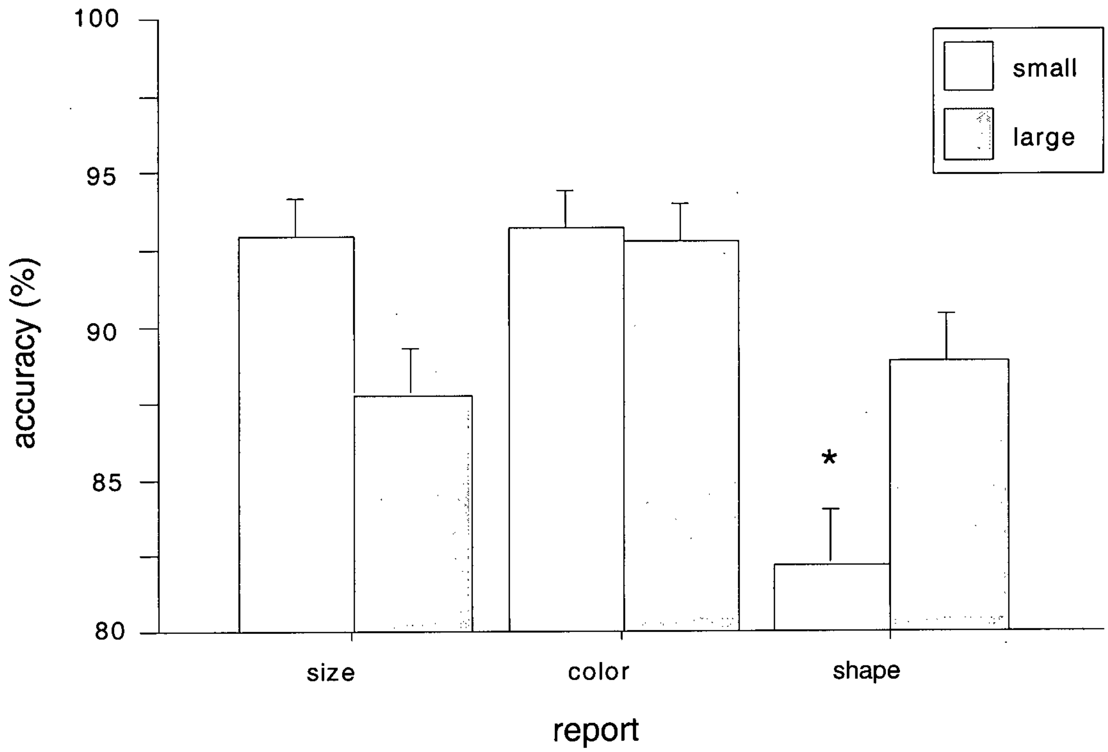

Figure 4. Accuracy rates for size, color, and shape reports when the objects are small and large (Experiment 2).

What this result suggests is that when the object is small, observers have difficulty differentiating between a triangle and a circle. The possibility that it would be difficult for observers to differentiate between a circle and a triangle was addressed in a control study run prior to the experiments. In the control study, eight observers were shown just one object in the center of the screen, followed by one cue that required the observer to report the size, color, or shape of the object. Reaction times and accuracy to report whether the object was a circle or a triangle did not differ depending on whether the object was small or large, $F(5,35) = 1.05$, $p > .40$. From this result, it was decided that the objects were not so small as to impair the differentiation between circles and triangles. Nevertheless, the significant size by report interaction was still found in Experiment 2, and it raises the possibility that shape information does not, in fact, decay more rapidly than size and color, rather, the decline in accuracy is due to difficulty in differentiating between a small circle and a small triangle.

In order to address this concern, the data was reanalyzed with only large objects included. A graph of the interval by report interaction is shown in Figure 5, with the corresponding means and standard errors shown in Table 4 of Appendix A.

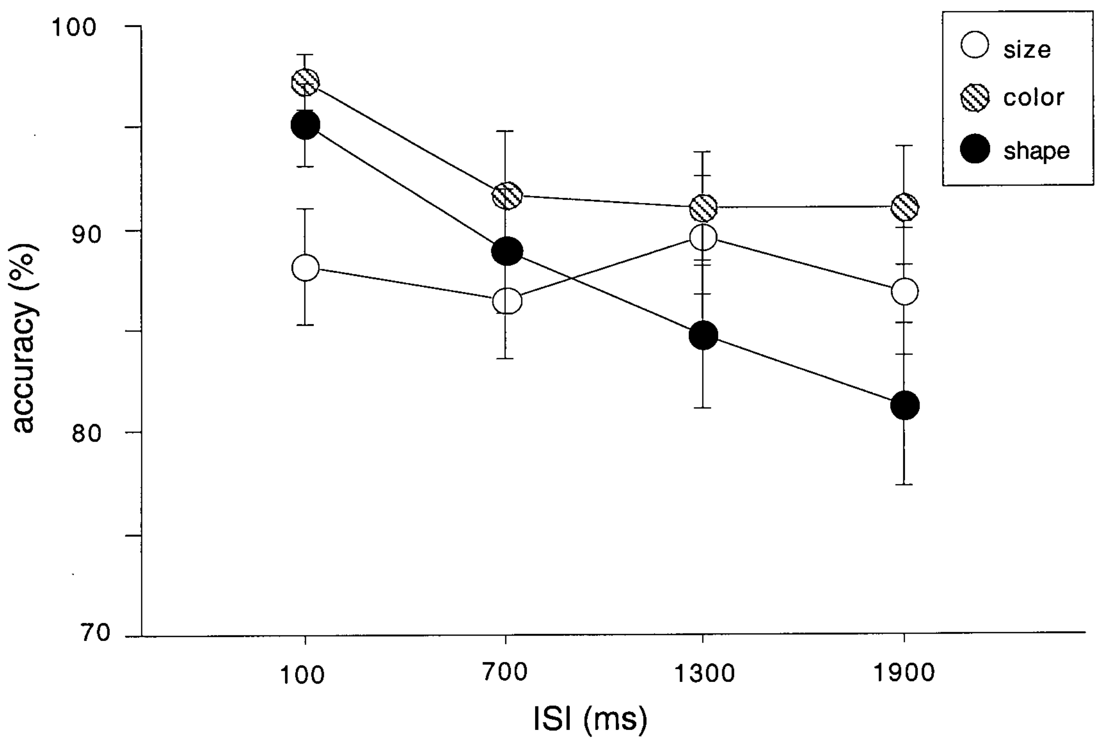

Figure 5. Accuracy rates for size, color, and shape reports at the four ISIs with small objects removed (Experiment 2).

Although the overall accuracy to report all properties improved when small objects were removed from the analysis, the accuracy to report shape information still showed a similar pattern of response to when the small objects were included. For the shape report, although accuracy for the 100 ms and 700 ms ISIs was not significant, $p > .15$, accuracy at the 100 ms interval was significantly better than accuracy at the 1300 ms, $p < .05$, and

1900 ms intervals, $p < .01$. More importantly, the accuracy at 700 ms approached being significantly better than accuracy at 1900 ms, $p < .11$, showing that shape information has continued to decay at ISIs beyond 700 ms, in contrast to color information. Hence, even when small objects are removed from the analysis, the decay of shape information still shows a pattern that is different from that of color and size.

Experiment 3

Method

Experiment 2 found that size, color and shape properties show a different pattern of decay in vSTM at delay durations of up to 1900 ms. Interestingly, accuracy for size and color did not drop at all after 700 ms, suggesting that information for both size and color properties does not decay appreciably at a duration of up to 1900 ms in vSTM. Experiment 3 sought to find the point in vSTM at which these properties begin to decay by extending the ISI even further. Phillips (1974) found that vSTM for patterns of light remained fairly robust for durations of up to 3 seconds, whereas Vogel et al. (2001) found that at ISIs of up to 4900 ms, there is little decay in the visual working memory representation for colored squares. For this reason, experiment 3 explores the contents of vSTM at even longer ISIs than these of 100, 1900, 3800 and 5700 ms.

Results

Accuracy for each report at the four intervals is shown in Figure 6. Table 5 in Appendix A shows the corresponding means and standard errors. Significant main effects were found for the interval factor, $F(3,33) = 19.22$, $p < .0001$ and the report factor, $F(2,22) = 3.65$, $p < .05$. The interaction of primary interest between interval and report was also significant, $F(6,66) = 2.71$, $p < .05$, making qualifying statements for these main effects necessary. Accuracy for color differed significantly across the four intervals, $F(3,33) = 7.67$, $p < .001$. At 100 ms, accuracy was significantly better than at the 1900, 3800, and 5700 ms intervals by $p < .001$, $p < .001$, and $p < .001$, respectively. Accuracy for size also varied across the four intervals, $F(3,33) = 7.90$, $p < .001$, although the pattern was slightly different from that of color. Accuracy at 100 ms was no different from accuracy at 1900 ms, $p > .25$, but better than accuracy at 3800, $p < .01$, and 5700, $p < .0001$. For the size report, accuracy was also better at the 1900 ms interval as compared to the 5700 ms one, $p < .01$. Accuracy for shape also differed significantly across the four intervals, $F(3,33) = 13.47$, $p < .0001$, showing yet a different pattern. Accuracy at the interval of 100 ms was significantly better than at the 3800 and 5700 ms intervals by $p < .0001$ and $p < .0001$, respectively. Accuracy at the interval of 1900 ms was also significantly better than accuracy at the 3800 ms, $p < .001$, and the 5700 ms intervals, $p < .001$.

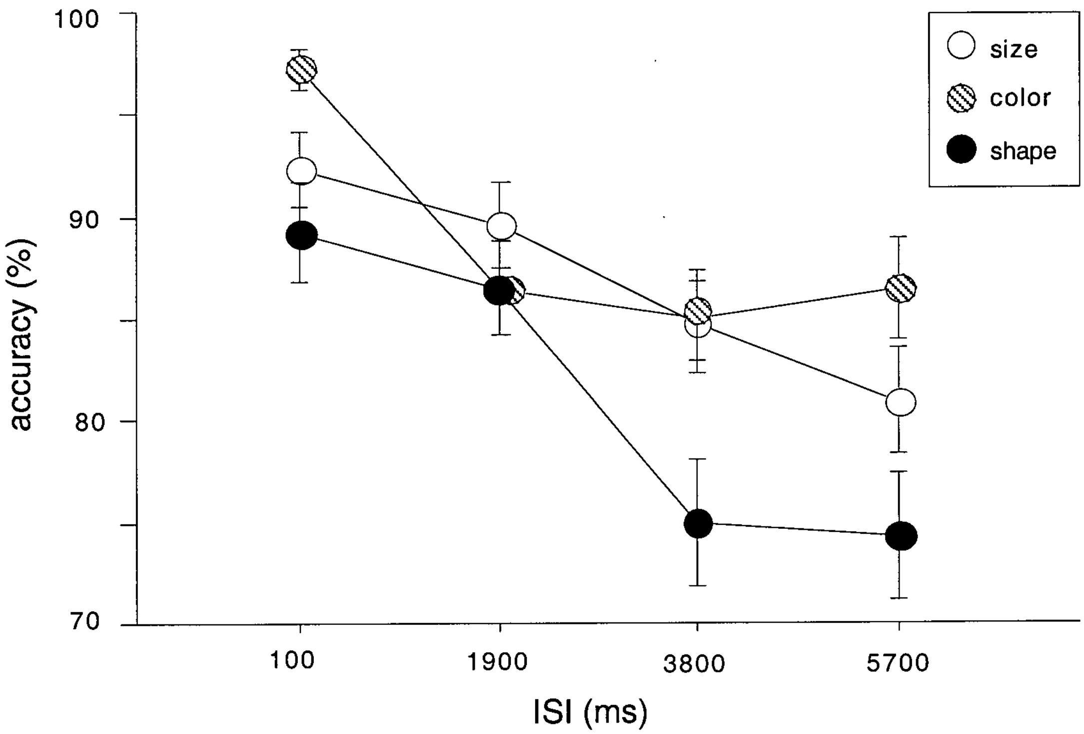

Figure 6. Accuracy rates for size, color, and shape reports at the four ISIs (Experiment 3).

The interval by report interaction can also be approached by determining significance across intervals rather than across report. At the 100 ms interval, the three reports differed significantly, $F(2,22) = 5.25$, $p < .01$. More specifically, report for color was better than report for size, $p < .06$, and report for shape, $p < .01$. At the interval of 1900 ms, there was no significant difference between the accuracy of reports, $F(2,22) = .47$, $p > .60$. At the interval of 3800 ms, there was a significant difference between the accuracy of different reports, $F(2,22) = 3.63$, $p < .05$. Specifically, report for size and color were both better than report for shape, both with $p < .05$. At the interval of 5700 ms, there again was a difference in the accuracy of different reports, $F(2,22) = 4.59$, with accuracy for color being better than accuracy for shape, $p < .01$.

Two other main effects were found for size, $F(1,11) = 5.25$, $p < .05$, and color, $F(1,11) = 7.57$, $p < .05$. However, two two-way interactions were found that require qualification of these main effects. The first significant two-way interaction found was report by color, $F(2,22) = 7.83$, $p < .01$. Further simplified, there was a significant difference between report accuracies when the object to be reported upon was red, $F(2,22) = 8.04$, $p < .01$. More specifically, when the object was red, size and color reports were better than report for shape, with $p < .01$, and $p < .01$, respectively. In addition, when the report to be made was shape, accuracy for blue objects was better than accuracy for red ones, $p < .01$.

The second significant two-way interactions was size by shape, $F(1,11) = 4.91$, $p < .05$. Further simplified, when the object to be reported upon was a triangle, accuracy was better when the object was small than when it was large, $F(1,11) = p < .01$.

Discussion

The results of main interest from Experiment 3 demonstrate that the color property of an object decays differently than the size and shape properties at durations of vSTM lasting up to 5700 ms. The most striking result in this experiment was that at delays of 1900 ms and longer in vSTM, color information appeared to undergo little if no appreciable decay. Shape and size information, in contrast, began to significantly decay only at intervals longer than 1900 ms. For the size report, this result was consistent with the findings of Experiment 1 and 2. For the shape report, it was surprising that there was no significant difference in accuracy between the 100 ms and 1900 ms intervals. The results from Experiments 1 and 2 showed that shape information begins to decay significantly from as early as around 400 ms. In way of explanation, it is possible that the relatively improved accuracy of the shape report at the 1900 ms interval in Experiment 3 was due to the overall increased difficulty of the task at these longer ISIs. Performance at a certain level of the independent variable sometimes depends on its relative difficulty in comparison to the other levels of the independent variable. For example, in Experiment 3, when 1900 ms was one of the shorter, easier intervals tested, accuracy for shape was better on it (86.5%) than in Experiment 2, when 1900 ms was the most difficult interval tested (81.4%). It seems as if observers undergo a shift in mental effort so that they do reasonably well on 'easier' levels of the task, regardless of the overall difficulty level of the task

Looking at the data for reports across intervals, the results show that at intervals of 100 ms, report for the color of an object was better than the size or shape of the object. This was identical to the result from Experiment 1, and very similar to the result of Experiment 2. At 1900 ms, there was no significant difference between reports. This was an unexpected result as well, given that in Experiment 2, accuracy for shape was worse than that of color and size at this delay ISI. Again, this aberrant data point can be explained by task demands. At the interval of 3800 ms, color and size reports were more accurate than that of shape. At the interval of 5700 ms, the accuracy for color was better than accuracy for shape. Again, the advantage for reporting the color of objects over the size and shape of objects at long ISIs comes from the fact that after delays of 1900 ms, color information does not appear to decay, whereas shape and size information do.

It is interesting to note that despite the delay duration being nearly six seconds long, accuracy rates are still at 75%, even for the most inaccurate report of the three, shape. Given that the amount of information that can be held in vSTM at delays of this duration are associated with the amount of information that can be held by attention, a baseline rate of 75% corroborates nicely with an attentional capacity limits of about 3 items found at delays of about 200 ms (Rensink, 2000a). How the experimental paradigm used in this study can further explore the role of attention in maintaining vSTM representations is an issue that will be returned to in the general discussion.

General Discussion

The results from each of these three studies demonstrate that the properties of size, color, and shape decay at different rates in vSTM. By combining the data from the three experiments, a story emerges about how these properties decay in vSTM between the durations of 100 and 5700 ms. Figure 7 shows graphs of the three experiments side by side.

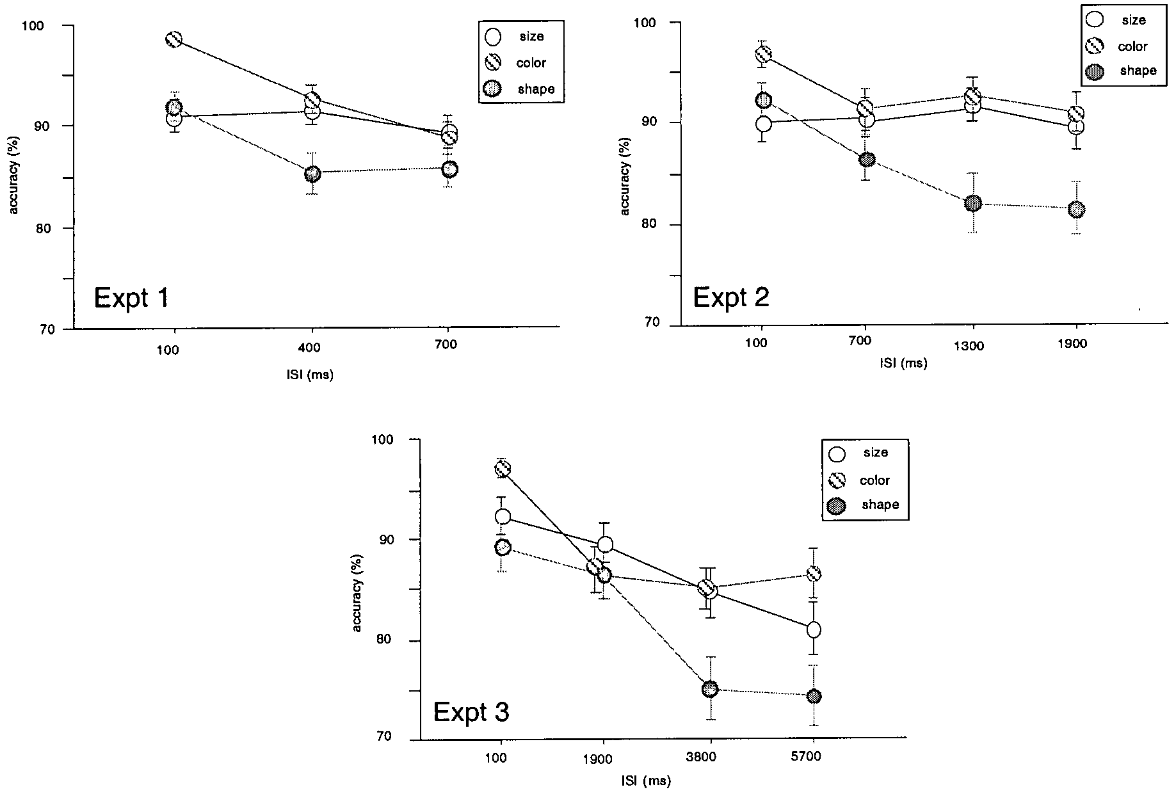

Figure 7. Accuracy rates for size, color, and shape reports at the respective ISIs (Experiments 1, 2, and 3).

After the offset of the visual stimulus, the information about the color of an object is well-maintained in sensory storage, after which it decays significantly until 700 ms, a duration that corresponds to the end of iconic memory. At this point, the representation of color information appears to arrive at a stable level where it does not decay any further. Information about the size of an object shows a very different pattern of decay: it does not decay appreciably between the durations of 100 and 1900 ms. However, at 1900 ms, information about size begins to decay and continues to decay.

The pattern of decay for the shape information of an object is somewhat less clear-cut, but with exception to one aberrant data point in Experiment 3, the results show that it begins to decay at durations of 400 ms or sooner. Interestingly, however, information about the shape of an object ceases to decay at the longest two intervals of each experiment. In experiment one, there was no significant difference in accuracy between the 400 ms and 700 ms intervals; in experiment two, there was no significant difference between the 1300 and 1900 ms intervals; and in experiment three, there was no significant difference between the 3800 and 5700 ms intervals. This pattern of results suggests that, unlike color and size information, the decay of information for the shape property of an object may be dependent on task demands

Parallel Independent Stores in vSTM

There are several ways in which the significance of these findings can be discussed. First and foremost, the presence of different decay rates for different visual properties says something interesting about how the different properties may be stored in vSTM. Unique decay rates for size, color, and shape information suggest that not all of the visual properties of an object are represented in vSTM with equal robustness. Take a large red triangle, for example, at a duration of 3800 ms. At this point, the redness of the object has not decayed and is still well represented, but the information about the 'triangleness' and 'largeness' of the object have decayed significantly. At this point then, the color, size and shape properties of the object are no longer equally represented; the representation has become one of a red 'blob', with undefined shape and size properties.

The proposal that the color information of an object can be strongly represented in vSTM while the shape and size information are not provides preliminary support for the idea that there are independent, parallel short-term memory stores, each devoted to a particular attribute of the visual stimulus (eg. Magnussen, Greenlee, & Thomas, 1996). A study by Magnussen et al. (1996) provided evidence for parallel, independent vSTM systems for spatial frequency and contrast information. The experiment was a forced-choice discrimination task where subjects were required to report which of two visual displays, separated by ISIs ranging from 1 to 10 seconds, had higher spatial frequency or contrast. In the first experimental condition, observers knew beforehand which property would be cued for report, which meant that the observer only had to maintain that one property in vSTM. They found that ability to discriminate differences in spatial frequency did not vary across ISIs of up to 10 seconds, whereas ability to discriminate differences in contrast became worse as the ISI increased This suggested that spatial frequency information does not decay in vSTM up to durations of 10 seconds, whereas contrast information does.

In the second experimental condition, the observer did not know at the start of the trial which of the two properties would be cued for report. This required the observer to maintain both properties in vSTM. Even though this manipulation doubled the processing load, the performance to discriminate differences in spatial frequency and contrast was identical to performance in the first condition. That the performance did not deteriorate when the processing load was doubled can be interpreted as support for the idea that separate stores maintain spatial frequency and contrast information. However, more importantly, finding identical performance for single report and dual-report conditions ruled out the possibility that poor performance for contrast information in the dual-report condition was due to a unitary memory store that devoted less resources to contrast information than it did to spatial frequency information. This could not be the case, because contrast information showed the same significant decay when it was the only property required for report. Overall, given that performance did not change when the processing load was doubled, and that spatial frequency and contrast information showed different decay rates, Magnussen et al. concluded that this was strong evidence for independent and parallel vSTM stores for spatial frequency and contrast information.

Based on Magnussen et al.'s experimental logic, the present experiment would have yielded stronger evidence of independent stores for size, color, and shape information had a single-report condition been run that required observers to maintain only one of the three properties in vSTM. Had the decay rates for these single-report conditions been identical to the decay rates from the present experiment, it would have ruled out the possibility that the faster decay of shape was due to a general purpose vSTM mechanism that devoted its resources to color and size, and indeed attributable to an independent vSTM store for shape information.

Nevertheless, the presence of unique decay rates for size, color, and shape information provides preliminary evidence for the hypothesis that there are independent vSTM stores for different visual properties. This is particularly true for size information, because its representation at a 100 ms delay does not differ significantly from how it is represented at a 1900 ms delay. This absence of decay for size information from its high-fidelity sensory representation sets it apart from the properties of color and shape, for which the representations decay significantly after the sensory storage phase.

A different way to frame Magnussen et al's (1996) hypothesis that there are independent and parallel vSTM stores for different properties is to say that there are different vSTM stores for properties that are processed within the scope of attention, and outside the scope of attention. More specifically, perhaps it is the case that spatial frequency information can be handled by a high-capacity non-attentional stream of processing, whereas contrast is handled by a capacity-limited attentional stream of processing. The distinction that attentional and non-attentional streams of visual processing handle different properties provides a framework in which the different patterns of decay for size, color and shape can still be explained in terms of independent and parallel vSTM stores. For example, it is possible that color and shape information, handled by an attentional processing stream, require transfer from sensory storage to a more durable vSTM storage system, which results in a loss of information. In contrast, size information, handled by a non-attentional processing stream, does not likewise undergo this procedure.

The idea that some visual properties can be processed outside the scope of attention is a popular one, being essential to Milner and Goodale's (1998) two visual systems theory, as well as Rensink's (2000b) theory of triadic architecture. In both of these theories, size is a good candidate for a property that is processed outside the scope of attention. In the two visual systems theory, visual information processed outside the scope of attention is used to guide motor movements such as grasping, a task for which gauging the size of objects is crucial. In the triadic architecture theory, visual information processed outside the scope of attention is used to form a general 'layout' of the scene that helps to guide attention, another task for which the size of objects affects their spatial arrangement (ie. whether they are near or far from one another). Furthermore, empirical evidence from studies of inattentional blindness has found that the perception of motion, color, location, and numerosity can also be accomplished by non-attentional streams of processing (Mack & Rock, 1998). In contrast, the inattentional blindness studies also found that perception of shape information requires attention (Mack & Rock, 1998).

In summary then, it is hypothesized that the absence of decay for size information at durations of 1900 ms is attributable to size being maintained by a high-capacity non-attentional processing stream in vSTM. In contrast, the significant decay in shape information seen at durations of 400 ms and beyond reflect that this information is being maintained by a limited-capacity attentional processing stream in vSTM. Whether attentional or non-attentional streams of processing would maintain color information is unclear: Mack and Rock (1998) find that it can be processed outside the scope of attention, yet it follows a pattern of decay more similar to shape than size.

The Disintegration of Visual Properties in vSTM

The presence of unique decay rates for different visual properties also has implications for how properties integrations come unbound in vSTM. A discussion about the integration of object properties must make note of the fact that in this experiment, observers were required to maintain a fourth visual property in vSTM: the location of the object. (Recall that the cues indicated the location of the object to be reported upon with a bar). Because the location of the object needed to be maintained in vSTM, the integration of location with each of the properties of size, color, and shape was necessary to make a correct report. Take again the example of a large red triangle at a duration of 3800 ms in vSTM. The red property of the object is still intact, whereas the 'triangle' and 'large' information have decayed significantly. An observer would experience such a vSTM object representation as 'something red at that location'. At this point, it is plausible that the color and location of the object are tightly integrated, resulting in high accuracy for reporting the color of the object. In contrast, the integration of the shape and location of the object, or the size and location of the object, may have become weak, resulting in poor accuracy for reporting the size or shape of the object. These explanations suggest that how strongly different properties are integrated, based on the amount of time that has elapsed in vSTM, affects accuracy to report the different properties of objects.

There is evidence that properties such as color, shape, and orientation each bind readily with location, but not with each other, leading to the suggestion that location is the 'master' property with which all other properties are bound (eg. Nissen, 1985). For example, Nissen (1985) demonstrated that the location and color features of an object are integrated and represented in a single map. In the first of her series of experiments, observers performed a partial report task where a stimulus display of four objects of different colors and shapes were presented, immediately followed by a simultaneous mask and cue that appeared for 1500 ms. The cue could either be a location word: top, bottom, right, or left, which cued the observer to report the color at that location, or a color word: red, green, blue, or black, which cued the observer to report the location of that color. She found that accuracy to report the color of an object was equal to the accuracy to report the location of an object, leading her to conclude that the information about color and location was integrated and represented in a single 'map'. The same principle was demonstrated when report was for the shape and location of the objects, leading to the same conclusion that the information about shape and location was integrated in a single map.

A stronger test of the hypothesis that there is a different map for representing each location – property integration was done by Isenberg, Nissen & Marchak (1990). In their experiment, observers were shown a display of four colored bars of four different orientations located on the four corners of an imaginary square, followed by a simultaneous mask and cue, with the cue pointing to one of the four locations. Observers were required to report both the color and orientation of the object indicated by the cue. They found that reports for color were significantly better than those for orientation, and that when the ISI was increased, accuracy to report color dropped, whereas accuracy to report orientation remained the same. In essence, their manipulations demonstrated that there was no relationship in the pattern of accuracy shown between report for color and report for orientation. This supported the multiple maps theory, in that there are separate maps for spatial layout of color, and spatial layout of orientation.

The results of these studies suggest that location is readily integrated with the properties of color, shape, and orientation. Given that location appears to be a master ‘hub’ that links the integration of different properties, it will be assumed that size also readily integrates with location. With regard to the present study then, the possibility arises that the different patterns of decay for size, color, and shape reflect different rates of disintegration of the location-property representation, rather than different patterns of decay for the properties themselves. In other words, it may be the case that shape-location integrations come unbound more readily than do the size-location integrations, and that the color-location integration remains tightly bound for the longest period of time. This difference in the relative strengths of integration would result in better localization of color than shape and size at longer ISIs, and corresponding better accuracy rates. In order to test whether it is the representation of the property itself that is decaying or the property-location representation, a paradigm would have to be used that does not require the maintenance of location information in vSTM.

For example, suppose an observer were shown a display of four different black shapes: a circle, a square, a triangle, and a diamond, and then after a certain delay shown another display where one of the shapes has changed: a star, a square, a triangle, and a diamond. If the observer is required to simply report whether or not a change has occurred between the two displays, then binding the location of the object with the object itself is not necessary. Rather, the task can be performed by just remembering what shapes were in the first display, regardless of their locations. A decrease in accuracy to detect whether a shape had changed would then reflect a decay in the representation of shape information, independent of the shape-location integration. The same logic could be carried out to determine whether or not the decay characteristics for size and color observed in the present study were attributable to different rates of disintegration with location information.

The Role of Attention in Integrating Object Properties

If indeed it is the case that the increasing difficulty to report the size and shape properties of an object at long ISIs is because these properties have come unbound from location information, what might account for this phenomenon? To answer this question, three points about the role of attention and the representation of objects in vSTM must be introduced. The first point is that attention is believed to serve an integrative function; one of the most widely cited accounts comes from Treisman and Gelade's (1980) feature integration theory. It states that the visual properties of an object are represented in separate maps, and focused attention binds these different properties from a specific location into the unified object that we experience. The second point is that attention is limited in the amount of information that it can simultaneously hold and maintain in vSTM at once (eg. see Cowan, 2000 for a review). Third, there is some evidence showing that different properties have different information loads. A study by Alvarez and Cavanagh (in review) gave preliminary evidence for the notion that objects have different information loads based on which visual properties make up the object. In order to determine the information load of an object, they used a visual search task with the following logic: the slower the processing speed, the greater the information load of the object. They found that the search rate for colored squares was nearly eight times faster than the search rate for random polygons, suggesting that shape has a higher information-processing load than does color.

From these three points, the proposition emerges that after the iconic phase, visual properties with high information loads strain the capacity of attention and begin to slip out of its hold, consequently coming unbound from the integrated object representation. In relation to the present experiment, it is possible that at around 400 ms, shape information is the first property to come unbound from the object representation, as it carries the highest information load and places the greatest strain on attention. When this happens, the connection between the shape information and location information of the object is severed, and the shape information appears to decay as the shape can no longer be localized. The same process occurs at delays of 1900 ms with size information. Lastly, because color information has the smallest information load, attention is able to hold together the color-location integration of the object representation for durations of at least 5700 ms.

Future Directions

There are several avenues of potential study that could follow the present study. First of all, it would be interesting to pursue the idea that different properties have inherently different information loads. The present experiments could be manipulated in order to assess whether size, color, and shape had different information loads by making the objects in the stimulus display homogenous for the two non-reported properties, and requiring only one report in each of three different conditions. For example, in a color condition, a stimulus array of six different colored circles of the same size would be shown. After a delay, one circle would appear and the observer would report whether it was the same or a different color. For the shape condition, the objects in the stimulus display would be of six different shapes, all of the same color and size. For the size condition, the objects in the stimulus display would be of six different sizes, all of the same color and shape. The logic goes that the higher the report accuracy, the smaller the information load of that property, with the converse also being true. That is, if the property of color has a smaller information load than shape, then the accuracy for observers to maintain six colors in vSTM would be better than the accuracy to hold six shapes in vSTM. Establishing inherently different information loads for different properties would lend credence to the notion that the different patterns of decay observed for different properties is related to attentional capacity.

The second potential area of study is related to the first in that it involves further exploring the role that attention plays in maintaining object representations in vSTM. In experiment three, we saw that at the longest ISIs of 5700 ms, accuracy was at 75% for shape, the poorest of the three reports. Given that the amount of information that can be maintained in vSTM is associated with the amount of information that can be held by attention (eg. Cowan, 2000), a baseline rate of 75% corroborates nicely with an attentional capacity of about three items at ISIs of longer than 200 ms (Rensink, 2000b). Calculating a capacity measure of three items in the present experiments is based on the following logic: when the number of objects held by attention equals three, the total accuracy is 3/6 (the percentage of the time the items are seen)+ 3/6 x .50 (the percentage of the time that the items are not seen, but that the observers will guess correctly, given that there are only two response options), which equals 75%. It would be interesting to see whether or not the same capacity estimate would be found if the number of objects in the stimulus display was increased to ten instead of six. Theoretically, the capacity of attention should remain the same, and not vary based on the amount of items in the display. In essence then, results from this manipulation would have implications for whether or not the transfer of information from sensory storage to more durable vSTM storage, presumably through the effort of attention, is affected by the initial amount of information in the display.

Lastly, it would be interesting to explore whether vSTM representations can be maintained outside of the observer's awareness, yet still contribute to correct responses. This idea came from the observation that several observers remarked on how surprised they were by their accuracy rates; they expected to have done more poorly because they felt that they had guessed on many of the trials. The hypothesis that representations unavailable to conscious awareness affect conscious report could be tested by having observers give a confidence rating that indicated how sure they were of their response after each trial. That is, if accuracy rates remained stable across ISIs and confidence ratings dropped, it would demonstrate that accuracy was being supported by a representation that was not available to conscious awareness. For example, if an observer were correct 90% of the time when reporting color at an ISI of 700 ms and had full confidence, and was also correct 90% of the time at an ISI of 5700 ms but had zero confidence, then it could be concluded that a representation of color information that is outside of awareness was contributing to accuracy at the 5700 ms ISI. That information unavailable to conscious awareness influences conscious report is not a new phenomenon; perception without awareness has been repeatedly demonstrated in the literature (eg. see Merikle, 1998 for a review). However, finding different influences on conscious report from different properties would be a valuable contribution. For example, if it were the case that accuracy for reporting size information was more independent of confidence ratings than reporting color information, this would suggest that size information was more closely associated with non-conscious streams of visual processing than color information.

References

Averbach, E. & Sperling, G. (1960). Short-term storage of information in vision. In C. Cherry (Ed.), Information Theory. London: Butterworth.

Averbach, E. & Coriell, A. S. (1961). Short-term memory in vision. Bell Systems Technical Journal, 40, 309-328.

Bentley, M. I. (1899). The memory image and its qualitative fidelity. American Journal of Psychology, Oct. v. 11(1), 1-48.

Clark, S. E. (1969). Retrieval of Color Information from Preperceptual Memory. Journal of Experimental Psychology, 82 (2), 263-266.

Cowan, N.(2000). The magical number 4 in short-term memory: A reconsideration of mental storage capacity. Behavioral and Brain Sciences, 24, 87-185.

Eriksen, C. W. & Lappin, J. S. (1967). Selective Attention and Very Short-Term Recognition Memory for Nonsense Forms. Journal of Experimental Psychology, 73 (3), 358-364.

Isenberg, L., Nissen, M. J., & Marchak, L. C. (1990). Attentional Processing and the Independence of Color and Orientation. Journal of Experimental Psychology: Human Perception and Performance, Nov. v 16 (4), 869-878.

Jevons, W. S. (1871). The Power of Numerical Discrimination. Nature, 3, 281 – 282.

Mack, A. & Rock, I. (1998). Inattentional Blindness. Massachusetts: MIT Press.

Magnussen, S., Greenlee, M. W., & Thomas, J. P. (1996). Parallel Processing in Visual Short-Term Memory. Journal of Experimental Psychology: Human Perception and Performance, Feb. v 22 (1), 202-212.

Merikle, P. M. (1998). Psychological Investigations of Unconscious Perception. Journal of Consciousness Studies, 5 (1), 5-18.

Milner, A. D., & Goodale, M. A. (1995). The visual brain in action. Oxford: Oxford University Press.

Mollon, J. D., Estevez, O. & Cavonius, C. R. (1990). The two subsystems of colour vision and their roles in wavelength discrimination. In C. Blakemore (ed.), Vision: Coding and Efficiency, 119-131. Cambridge: Cambridge University Press.

Myers, G. C. (1914). A comparative study of recognition and recall. Psychological Review, Nov. v. 21(6), 442-456.

Neisser, U. (1966). Cognitive psychology. New York: Meredith Publishing Company.

Nissen, M. J. (1985). Accessing Features and Objects: Is Location Special? In M. I. Posner & O. S. M. Marin (Eds.), Attention and Performance XI (pp. 205-219). Hillsdale, N. J.: Erlbaum.

Palmer, J. (1988). Very short-term visual memory for size and shape. Perception & Psychophysics, 43, 278-286.

Phillips, W. A. (1974). On the distinction between sensory storage and short-term visual memory. Perception & Psychophysics, 16 (2), 283-290.

Rensink, R. A. (2000a). Visual Search for Change: A Probe into the Nature of Attentional Processing. In G. W. Humphreys & D. J. Simons (Eds.), Visual Cognition: Special Issue, Change Blindness and Visual Memory, 345-376. UK: Psychology Press Ltd.

Rensink, R. A. (2000b). Seeing, sensing and scrutinizing. Vision research, 40, 1469-1487.

Sperling, G. (1960). The Information Available in Brief Visual Presentations. Psychological Monographs: General and Applied, 74 (11), Whole No. 498.

Treisman, A.M., & Gelade, G. (1980). A feature-integration theory of attention. Cognitive Psychology, 12, 97-136.

Turvey, M. T. & Kravetz, S. (1970). Retrieval from iconic memory with shape as the selection criteria. Perception & Psychophysics, 8 (3), 171-172.

Vogel, E. K., Woodman, G. F., & Luck, S. J. (2001). Storage of Features, Conjunctions, and Objects in Visual Working Memory. Journal of Experimental Psychology: Human Perception and Performance, 27 (1), 92-114.

Wundt, W. (1899). A criticism of tachistoscopic experiments. Philosophische Studien, 15, 287 – 317.

Appendix A

Table 1

Means (%) and standard errors for reports at each interval (Experiment 1)

	Interval					
	100 ms		400 ms		700 ms	
Report	mean	se	mean	se	mean	se
Size	91.0	1.5	91.4	1.3	89.4	1.7
Color	98.6	0.5	92.7	1.5	88.7	1.6
Shape	91.9	1.5	85.3	2.1	85.8	2.0

Table 2

Means (%) and standard errors for reports at each interval (Experiment 2)

	Interval							
	100 ms		700 ms		1300 ms		1900 ms	
Report	mean	se	mean	se	mean	se	mean	se
Size	89.9	1.9	90.5	1.9	91.7	1.8	89.4	2.0
Color	96.9	1.3	91.3	2.0	92.7	1.9	91.0	1.9
Shape	92.4	1.7	86.5	2.3	81.9	2.9	81.4	2.7

Table 3

Means (%) and standard errors for reports when objects are small and large (Experiment 2)

	Object Size			
	Small		Large	
Report	mean	se	mean	se
Size	93.0	1.1	87.8	1.5
Color	93.2	1.2	92.7	1.3
Shape	82.2	1.9	88.9	1.6

Table 4

Means (%) and standard errors for reports at each interval with reports for small objects removed (Experiment 2)

	Interval							
	100 ms		700 ms		1300 ms		1900 ms	
Report	mean	se	mean	se	mean	se	mean	se
Size	88.2	2.9	86.5	3.0	89.6	2.8	86.8	3.1
Color	97.2	1.3	91.7	3.1	91.0	2.8	91.0	2.9
Shape	95.1	2.0	88.9	3.0	84.7	3.7	81.3	4.0

Table 5

Means (%) and standard errors for reports at each interval (Experiment 3)

	Interval							
	100 ms		1900 ms		3800 ms		5700 ms	
Report	mean	se	mean	se	mean	se	mean	se
Size	92.4	.019	89.6	.020	84.7	.025	80.9	.026
Color	97.2	.009	86.5	.023	84.9	.020	86.5	.025
Shape	89.2	.023	86.5	.024	75.0	.031	74.3	.031