Orienting Attention in Visual Working Memory Reduces Interference From Memory Probes

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Given a changing visual environment, and the limited capacity of visual working memory (VWM), the contents of VWM must be in constant flux. Using a change detection task, the authors show that VWM is subject to obligatory updating in the face of new information. Change detection performance is enhanced when the item that may change is retrospectively cued 1 s after memory encoding and 0.5 s before testing. The retro-cue benefit cannot be explained by memory decay or by a reduction in interference from other items held in VWM. Rather, orienting attention to a single memory item makes VWM more resistant to interference from the test probe. The authors conclude that the content of VWM is volatile unless it receives focused attention, and that the standard change detection task underestimates VWM capacity.

Keywords: visual working memory, visual attention, memory decay, memory interference, change detection

In a classic study, Sperling (1960) flashed an array of letters in three rows and four columns and asked his participants to recall the letters. He found that participants could report about four to five letters, even though they had a subjective impression that more letters were available immediately after display offset. Sperling then used a partial-report procedure in which participants were cued by an auditory beep to report a randomly selected row, signified by the pitch of the beep. If the beep was played right when the letters disappeared, participants usually could report nearly all the letters from the cued row, suggesting that they indeed had immediate access to a large number of letters. If the beep was played after a delay of 500 ms or so, reports for a given row reduced greatly, resulting in an estimate of about 1.5 letters per row. This study was instrumental to cognitive research. First, it revealed the presence of a high-capacity iconic memory (Neisser, 1967) that dissipates within half a second or so. After the memory dissipates, information is stored in visual or verbal short-term memory, which is relatively stable over time. Second, it showed that the testing procedure can significantly influence the estimation of memory capacity. Partial report is superior to whole report if memory degrades during the testing process. The degradation may arise from simple decay of information, as is the case in the original Sperling study, or it may arise from interference, as is the case in a later study in which a visual probe at the location of the original memory item induced backward masking (Averbach & Coriell, 1961).

Although Sperling’s (1960) study is now a classic in textbook materials, recent research on visual working memory (VWM) has reverted back to the use of whole-report procedures to probe memory capacity. VWM buffers visual information for a few seconds after its disappearance. It is used frequently in everyday visual tasks, such as crossing a busy street, speaking to a large audience, or playing in team sports. It is considered to be more robust than iconic memory. To measure the capacity of VWM, most studies use the standard change detection task (Rensink, 2002), in which an array of visual objects is first presented for memory encoding. After a retention interval of 1 s or so, a probe array of objects is shown, which may be either the same as the memory array or different in one object. Accuracy to report the presence or absence of a change at different memory loads is used to estimate VWM capacity (Pashler, 1988; Phillips, 1974). There are reasons why the whole-report procedure has been standard practice in VWM studies. First, revising the procedure into a partial-report procedure has not revealed a consistent advantage. For example, if a single test probe is shown, accuracy can sometimes be worse than when the whole-array probe is shown, perhaps because the single probe eliminates retrieval context (Jiang, Olson, & Chun, 2000). Second, adding a partial-report cue to the entire probe array, such as flagging out one of the test objects as the relevant comparison object, often leads to no improvement in comparison with the whole-array condition (Luck & Vogel, 1997). The partial-report procedure can sometimes be advantageous, particularly when the array is complex and the comparison process across the entire array is laborious (Hollingworth, 2003). Under
most VWM testing conditions in which individual items are presented, there is little evidence, from either recent VWM studies or the old Sperling (1960) and Averbach and Coriell (1961) studies, that VWM is subjected to the same kind of degradation observed in iconic memory (Phillips, 1974).

By now, most studies would characterize working memory, including VWM, as a robust form of memory whose content is accessible, even though the original input has disappeared and new input is delivered to the visual system (Miller, Erickson, & Desimone, 1996). This characterization has contributed to the proposed function of VWM as a bridge across temporal discontinuities and as a mechanism for mentally manipulating visual information after its disappearance (Courtney, Petit, Haxby, & Ungerleider, 1998). In light of these findings, it is perplexing that some recent studies have revealed a partial-report advantage (Griffin & Nobre, 2003; Landman, Spekreijse, & Lamme, 2003; Lepsien, Griffin, Devlin, & Nobre, 2005; Lepsien & Nobre, 2007; Makovski & Jiang, 2007). For example, Landman et al. (2003) presented a partial-report cue—a centrally presented arrow that pointed at the location of one of the eight memory items—and asked participants to judge whether the cued item matched a test probe that followed the partial-report cue. Unlike the cues used in earlier studies (Averbach & Coriell, 1961; Sperling, 1960), the partial-report cue was delivered long after the memory array had disappeared, so it could not have salvaged the cued item from iconic memory or from the transition between iconic memory and VWM (Vogel, Woodman, & Luck, 2006). This procedure was otherwise similar to the other partial-report procedures used in previous VWM studies, in which only a single memorized item needed to be compared with the test probe. However, with this procedure, Landman et al. found a significant benefit of the partial-report cue that was not observed in other VWM partial-report procedures. Similarly, Griffin and Nobre (2003) found that if observers were allowed to orient attention to a single item in VWM prior to the onset of the probe array, they performed better than if the orienting cue was absent. Figure 1 schematically illustrates the whole-report procedure and several partial-report procedures used in VWM studies.

Why does the partial-report cue enhance performance in Landman et al.’s (2003) procedure but not in other procedures? First, the memory retention interval is different. Although the interval between the initial memory display and the final test display is 1,600 ms in all conditions shown in Figure 1, the partial-report cue is delivered in the middle of that interval in Landman et al.’s procedure. If observers start using the cue right away, then the effective retention interval—that from memory display offset to the refreshing of the cued item—is shorter in Landman et al.’s procedure. If VWM decays during that time (the memory decay hypothesis), then performance in the whole-report procedure should be worse than that in the retro-cue procedure.

Second, the cuing procedure used in Landman et al.’s (2003) study may be particularly effective at directing focused attention to the critical item in VWM. The act of attending to the critical item reduces the relevant memory load. This can enhance performance.

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1 The timing of the partial-report cue delivery was 2–12 s in Lepsien et al. (2005).
for the following reasons. First, it may restrict the comparison between memory and probe to a single comparison (the simplified-comparison hypothesis) and eliminate the need to exhaustively compare every probe item with the corresponding memory item. Consequently, any change blindness originating from a comparison failure or decision noise is reduced (Hollingworth, 2003; Simons, Chabris, Schnur, & Levin, 2002). Second, multiple memory items may compete for memory resources and suppress each other’s representation (Bahcall & Kowler, 1999). Directing attention to a single memory item can release the interference from other memory items (interitem interference), enhancing memory performance of the critical item. Third, when attention is broadly distributed across multiple memory items, memory for these items may be labile and may be overwritten by the probe array. Focusing attention on a critical memory item solidifies its memory, making it more resistant to interference from the probe array (the probe interference hypothesis). These three sources of enhancement will be jointly referred to as the attentional enhancement hypothesis.

The current study focuses on the retro-cue advantage in measuring VWM. We are interested in this effect because if confirmed, it can potentially change the way VWM is conceptualized. It would suggest that the contents of VWM are not static but can degrade over time or with delivery of new stimuli. The following experiments are designed to test which of the hypotheses laid out above best account for the cuing benefit—henceforth referred to as the retro-cue benefit (Griffin & Nobre, 2003; Landman et al., 2003; Lepsien et al., 2005; Makovski & Jiang, 2007). It is important to note that the different hypotheses need not be mutually exclusive. It is possible that VWM is sensitive to decay, to the complexity of memory probe comparison, to interference from the other items in memory, and to interference from the probe. Our experiments are designed to test which combination of these hypotheses best accounts for the effect. Experiment 1 distinguishes between the decay and the broader attentional enhancement hypotheses. Experiments 2 and 3 will address the different forms of the attentional enhancement hypothesis.

Experiment 1

This experiment aims to test the memory decay hypothesis by eliminating differences in retention intervals across conditions. If the retro-cue benefit remains, then the decay hypothesis can be largely ruled out. Our experiment is unique in several respects. First, participants completed the task under articulatory suppression. On each trial they quickly rehearsed a prespecified word out loud to reduce verbal recoding (Baddeley, 1986). Second, we tried to equate the duration of memory retention by keeping constant the interval between the initial encoding and the memory refreshing. In the retro-cue condition, after an initial memory array and a blank retention interval of 1 s, a central arrow cue was presented for 100 ms, pointing to the location of a memory item that might later change. Assuming that participants started to refresh their VWM of the target item upon the onset of the cue, the effective memory retention interval would be 1,000 ms. The probe array was further delayed by 400 ms, such that the interstimulus interval (ISI) between memory and probe arrays was 1,500 ms. In the simultaneous-cue condition, after the initial memory array and a blank retention interval of 1 s, the probe array along with a central arrow cue was presented, pointing to the critical item that might change. The effective retention interval was also 1,000 ms, but the ISI between memory and probe arrays was 500 ms shorter than in the retro-cue condition, so any advantage in the retro-cue condition cannot be accounted for by differences in retention interval. Finally, in the no-cue condition, the trial sequence was the same as in the simultaneous-cue condition except that the central arrow was absent. Figure 2 illustrates a schematic trial sequence used in the three different conditions. Note that the no-cue condition was essentially a whole-report procedure, whereas the other two conditions were both partial-report procedures, with the retro-cue condition being similar to Landman et al.’s (2003) method.

Experiment 1 went beyond a simple replication of a retro-cue benefit. We also tested whether the effect was seen when the memory and probe arrays did not overlap in screen locations (Griffin & Nobre 2003; Lepsien et al., 2005). Specifically, items on the probe array might occupy the same screen locations as items on the memory display, or they might occupy locations that were 1.5 times expanded toward the periphery. As noted in the introduction, one explanation of the retro-cue benefit can be found in the probe interference account, which states that VWM is vulnerable to interference from subsequent visual input unless attention has already focused on the critical memory. This account does not specify whether or not interference from the probe array is screen based. If it is, expanding the probe array should reduce interference on VWM, and consequently the no-cue and simultaneous-cue performance should improve to match that of the retro-cue.

Finally, Experiment 1 tested both color VWM and shape VWM to ensure that the same pattern of results holds for different memory tasks. Because VWM for color is typically better than VWM for shape (Alvarez & Cavanagh, 2004; Eng, Chen, & Jiang, 2005), we used different memory loads for the two tasks (six colors and four shapes).

Method

Participants. Participants tested in this study were volunteers from Harvard University and its community. They provided informed consent and received one course credit or $10/hr. All participants had normal or corrected-to-normal visual acuity and normal color vision. They ranged from 18 to 31 years old. There were 18 participants in Experiment 1.

Equipment. Participants were tested individually in a room with normal interior lighting. They sat approximately 57 cm away from a 19" computer monitor. The experiment was programmed with psychophysical toolbox software (Brainard, 1997; Pelli, 1997) implemented in MATLAB, which can be accessed at the following website: http://www.mathworks.com.

Materials and trial sequence. On each trial, six unique color disks (diameter = 1.31") and four unique novel shapes (1.31") were placed equidistantly on an imaginary circle (radius = 4.92") centered at fixation. The background of the display was black. The number of items was selected to exceed the conventional VWM capacity (Alvarez & Cavanagh, 2004; Luck & Vogel, 1997). Colors were selected randomly from nine different colors, and

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2 Following Griffin and Nobre’s (2003) terminology, we used “retro-cue” to capture the retrospective nature of the cue in bringing to mind information that has disappeared. This term is sometimes contrasted with “pre-cue,” which precedes memory encoding (Makovski & Jiang, 2007).
shapes were selected from 10 novel shapes (Shuman & Kanwisher, 2004). The memory display was presented for 300 ms and followed by a blank retention interval of 1,000 ms. In the retro-cue condition, a central white arrow (1.44° in length) was presented for 100 ms, followed by a blank interval of 400 ms, before the presentation of the probe array. In the simultaneous-cue condition, after the 1,000-ms blank interval, the central arrow was presented simultaneously with the probe array for 100 ms, after which only the probe array remained. The probe array contained six colors or four shapes placed equidistantly on an imaginary circle whose radius was either the same as the memory array (overlapped conditions) or 1.5 times greater than the memory array (expanded conditions, shown here). Participants were told to remember the initial memory array and judge whether items on the probe array were the same as or different from items on the memory array. On simultaneous-cue and retro-cue trials, only the item cued by the central arrow could change.

In all conditions, participants were told to determine whether the probe array was identical to the memory array or whether one of the items had changed color (in the color blocks) or shape (in the shape blocks) by pressing the S key for “same” and the D key for “different.” They were told that when the central arrow cue was presented, it was always 100% valid, in that items not cued would never change. Participants were also informed that if a change occurred to the cued item, which happened 50% of time, it would be a new color (or shape) not presented on the memory array. Participants were free to move their eyes.

Design. In both the color and shape tasks, we used a $3 \times 2 \times 2$ design with cue condition (retro-cue, simultaneous cue, or no cue), spatial relation (overlapped or expanded), and item change (present or absent) manipulated orthogonally. There were 240 trials in color VWM and 240 trials in shape VWM. Half of the participants completed the color task first, while the other half completed the shape task first. Trials within the color (or shape) task were randomly intermixed in presentation order. Unlike accuracy, speed of response was not emphasized.

Articulatory suppression. To minimize verbal recoding, participants were required to rehearse out loud a three-letter word as quickly as they could throughout a block of trials. The word they had to rehearse was specified at the beginning of each block of 48 trials.

Data analysis. In this experiment and subsequent ones, we calculated the percentage of correct responses, $d’$, and $A’$ (Grier, 1971; MacMillan & Creelman, 2004). Because statistical results were the same for all indices, we report only the percentage of correct presses. $A’$ results and mean reaction time (RT) for correct responses for all three Experiments are listed in Tables A1, A2, and A3 the Appendix.

Results

Figure 3 plots the mean accuracy for the color and shape tasks separately. In both tasks, even when articulatory suppression was used and the effective interval between encoding and retrieval was comparable across conditions, accuracy in the retro-cue condition was still significantly higher than that in the simultaneous-cue and no-cue conditions, replicating Landman et al.’s (2003) results.

A repeated measures analysis of variance (ANOVA) on cue condition (retro-cue, simultaneous cue, or no cue) and spatial relation (overlapped vs. expanded) revealed a significant main effect of cue condition in accuracy: for color VWM, $F(2, 34) = 19.87, p < .001$, and for shape VWM, $F(2, 34) = 8.63, p < .001$. 

![Figure 2](image-url)
The retro-cue condition was significantly more accurate than the simultaneous-cue condition: in color VWM, \( F(1, 17) = 11.18, p < .004 \), and in shape VWM, \( F(1, 17) = 9.13, p < .006 \). Similarly, the retro-cue condition was significantly more accurate than the no-cue condition: in color VWM, \( F(1, 17) = 43.78, p < .001 \), and in shape VWM, \( F(1, 17) = 11.84, p < .001 \). The presentation of a cue simultaneously with the test display also conveyed a significant advantage in comparison with no-cue trials in color VWM, \( F(1, 17) = 7.81, p < .02 \), but not in shape VWM, \( F(1, 17) < 1 \). This advantage may be related to simplified memory comparison: With a cue, participants only needed to make one comparison; without a cue, they needed to make multiple comparisons (Hollingworth, 2003). This advantage was more significant for color VWM than for shape VWM, perhaps because we used different set sizes for color and shape tasks (i.e., without a cue, participants may need to make six comparisons in color VWM and only four comparisons in shape VWM).

The above analyses combined data across overlapped and expanded test conditions. Was there any difference between overlapping and expanded test displays? The ANOVA test showed that there was not: The main effect of the memory–test spatial relationship was not significant in either color VWM, \( F(1, 17) = 1.66, p > .20 \), or shape VWM, \( F < 1 \). Neither did this factor interact with cue conditions: for color VWM, \( F(2, 34) = 1.34, p > .25 \), and for shape VWM, \( F < 1 \). Simple \( t \) tests showed that the advantage of a retro-cue over a simultaneous cue and no cue held for color VWM as well as for shape VWM, both when the probe array overlapped with the memory array, \( t(17) > 2.71, ps < .02 \), and when the probe array was expanded and spatially not overlapping with the memory array, \( t(17) > 2.21, ps < .05 \).

The retro-cue not only enhanced accuracy but also sped up RT (see the Appendix for RT data). Even though the task instruction emphasized accuracy and not RT, participants were faster making a same–different judgment when the cue was presented before the probe array than when it was presented simultaneously with the probe array. This facilitation was seen for both the overlapped displays and the expanded displays. The facilitation was on the order of 150 ms (retro-cue vs. simultaneous cue) and has also been seen in other studies (Griffin & Nobre, 2003; Makovski & Jiang, 2007). Because results from RT are generally consistent with those from accuracy (or \( A' \)), we will no longer present RT in later experiments.

Discussion

Experiment 1 showed that performance in a VWM task, as measured by change detection, differed significantly for different testing procedures. In comparison with a whole-report procedure in which participants matched an entire probe array with their memory, a partial-report procedure can lead to better performance, but only under certain conditions. When the cue that narrowed the whole report into a partial report was delivered simultaneously with the probe array, it did not consistently facilitate performance. But when the cue preceded the probe array by 500 ms, it enhanced performance in comparison with the whole-report procedure. These results held whether the memory array and the probe array overlapped in screen locations or did not overlap, suggesting that the potential interference from the probe array is not screen or viewer based.

The findings from Experiment 1 departed from many previous studies on the partial-report procedure, primarily in the timing of the partial-report cue. In classic studies on iconic memory, the partial-report cue was delivered immediately after the offset of the memory display, allowing participants to extract information from iconic memory (Averbach & Coriell, 1961; Becker, Pashler, & Anstis, 2000; Sperling, 1960). In more recent studies on the consolidation of information into VWM, Vogel et al. (2006) also used a cue that trailed the memory display by less than 500 ms, salvaging iconic memory or enhancing the transition between iconic memory and VWM. In contrast, in Experiment 1 the cue was delivered 1,000 ms after the initial memory encoding, when iconic memory had decayed (Dilollo, 1980).

The retro-cue advantage shown in Experiment 1 cannot be accounted for by a simple memory decay hypothesis. We equated the interval between encoding and the refreshing of VWM across different conditions. Indeed, the ISI between the memory and

Figure 3. Results from Experiment 1. A retro-cue significantly enhanced performance both when the probe array and memory array overlapped in location and when they did not overlap. The error bars show standard errors of the means.
probe displays was longer in the retro-cue condition than in the other conditions, so one could not explain the retro-cue benefit as reflecting less decay of VWM in the retro-cue condition than in the other conditions.

**Experiment 2**

Why does focusing attention on the critical memory item enhance VWM performance? There are several possibilities. The simplest possibility is that cuing simplified the memory probe comparison process. Instead of a comparison of each probe item with each memory item at the corresponding locations, cuing simplified the process to a single comparison. The simplified comparison reduces decision noise inherent to an exhaustive comparison task and reduces the kind of change blindness from a failure to compare (Hollingworth, 2003; Simons et al., 2002). Earlier studies had used the simultaneous-cue condition to try to rule out the simplified-comparison hypothesis. However, there are several reasons why participants may have not effectively used the simultaneous cue. First, the cue is less salient when presented concurrently with the probe array, so comparison across the whole array may have already started before the cue was used. Second, the presentation of the entire probe array provides a retrieval context that may have encouraged participants to do a whole-array comparison rather than a single-item comparison (Jiang et al., 2000).

To test whether attentional cue enhances performance by simplifying the comparison process, in Experiment 2 we simplified the comparison process in all conditions by eliminating irrelevant items on the probe display. Figure 4 shows four conditions tested in this experiment. In all conditions the probe display contained a single test object. Participants' task was to determine whether this object was the same as or different from the memory object shown previously in the same location. Because only a single comparison needs to be made, the simplified-comparison account predicted that the retro-cue should no longer enhance performance.

**Method**

**Participants.** Fifteen new participants from the same general subject pool as that described for Experiment 1 completed Experiment 2.

**Materials.** Similar to Experiment 1, we tested color VWM and shape VWM, but this time we randomly intermixed color and shape trials to further remove strategic differences between the two tasks. Memory load was six for color VWM and four for shape VWM. The initial memory display was presented for 1,000 ms to ensure adequate encoding time (Eng et al., 2005).

**Design and procedure.** In both color and shape VWM tasks, we orthogonally manipulated whether or not there was a retro-cue presented 500 ms before the probe display (retro-cue vs. no retro-cue) and whether or not there was a central arrow cue presented simultaneously with the probe display (simultaneous cue vs. no simultaneous cue). With this design we can separate the effects of a retro-cue preceding the probe display from the effects of a simultaneous cue presented concurrently with the probe display.

*Figure 4.* Trial sequences of the four conditions tested in Experiment 2. The memory array contained six colors or four shapes. Participants decided whether the single test item was the same as or different from the memory item at that location. On cue trials, the cued item was always later probed. The top two rows show the no simultaneous-cue conditions. The bottom two rows show the simultaneous-cue conditions.
Figure 4 shows a schematic illustration of the four conditions. The design was otherwise similar to Experiment 1’s overlapped conditions, except that the probe display contained only a single probe object that always coincided with the location of the critical memory item. Participants were asked to press the $S$ key if the probe object was the same as the memory object at that location before or to press the $D$ key if it was not the same.

Each participant completed 320 experimental trials, divided randomly and evenly into different conditions: 2 tasks (color or shape) × 2 retro-cues (present vs. absent) × 2 simultaneous cues (present vs. absent) × 2 item changes (present vs. absent) × 20 cases. Articulatory suppression was used to reduce verbal recoding.

Results

Figure 5 shows the mean percentage of correct responses separately for color and shape VWM tasks. An ANOVA for task, retro-cue, and simultaneous cue revealed a significant main effect of retro-cue, with higher accuracy when a retro-cue was presented 500 ms before the probe array than when it was absent, $F(1, 14) = 18.29, p < .01$. No other main effects or interactions were significant, $ps > .30$. Follow-up tests showed that performance was enhanced by the presence of a retro-cue for both color VWM, $F(1, 14) = 5.84, p < .03$, and shape VWM, $F(1, 14) = 16.80, p < .01$. The presentation of a central arrow cue simultaneously with the probe array did not alter performance, $p > .25$ for color VWM and $p > .35$ for shape VWM.

Discussion

Experiment 2 showed that VWM performance was better when the critical item was retrospectively cued. This advantage was seen even when the probe display contained a single probe item, which only required a single memory probe comparison. Direct comparisons across Experiments 1 and 2 revealed no interaction between retro-cue (retro-cue vs. no cue) and experiment (whole-probe array vs. single-probe array), $F < 1$. Given that the single probe already simplified the comparison process, it should have enhanced performance whether or not it was preceded by a retro-cue. Nonetheless, we still found an attentional cuing effect, suggesting that simplified comparison cannot fully account for the advantage of attentional cuing.

Experiment 3

Why does attentional cuing enhance VWM performance, and why is this enhancement restricted to retro-cuing? One critical difference between retro-cuing and simultaneous cuing or single-probe cuing is the timing of attentional allocation. With retro-cuing, attention is already directed to the critical memory before the presentation of the probe display. In contrast, it takes time for attention to move to the cued item when the cue is concurrent with the probe. Even when the cue is the single probe itself, it takes at least 100 ms for attention to move to the cued location (Posner, 1980). The sensitivity of memory performance to the timing of the cue suggests that VWM of multiple items is susceptible to degradation and that the degradation is reduced only when focused attention is delivered without much delay.

What is the source of memory degradation? There are at least two possibilities. First, VWM may be degraded because multiple items in VWM may interfere with one another. This interitem interference may result from the suppression of nearby memory items (Bahcall & Kowler, 1999) or from incorrect binding of different memory attributes to their proper locations (Treisman & Zhang, 2006). Interitem degradation is removed when attention is cued to the critical item, resulting in enhanced performance. Second, VWM can be degraded by the presentation of the probe stimulus, which may interfere with VWM of multiple items (probe interference). As new visual input, the probe may overwrite or degrade the representation of memory items (Simons, 2000). It may also disrupt the rehearsal of memory information, leading to reduced memory performance. Focused attention on the critical memory can reduce probe interference by consolidating the critical memory into a durable format.

So what is the primary source of memory degradation that is reduced by attentional cuing? We test this question by manipulating memory load from one to six items. Both interitem interference and probe task interference accounts predict that the retro-cue should not enhance performance when memory load is one, as attention has already been focused on the single memory item.
However, the two accounts differ in their prediction about the cuing benefit as a function of memory load. Because interitem competition is more dramatic for higher memory load, release from interitem interference should be greater at higher loads. In turn, attentional cuing should be greater at higher loads. In contrast, if attentional cuing acts by reducing probe interference, the size of the interference should be determined by the probe stimulus, which is constant across all memory loads. The cuing benefit should not scale with memory load.

To contrast these hypotheses, in Experiment 3 we varied memory load from one to six. Because VWM load is affected not only by set size but also by item complexity (Alvarez & Cavanagh, 2004; Eng et al., 2005), we tested shape (a complex property) as well as color (a simple property).

Method

Participants. Twelve participants from the same general subject pool as that described for Experiment 1 completed Experiment 3.

Design and procedure. We manipulated three factors orthogonally: the type of stimulus tested (color or shape), the number of items on the memory display (from one to six, presented equidistantly along the circumference of an imaginary circle), and the timing of the cue (retro-cue or simultaneous cue). In the retro-cue condition, after an initial memory array (1,000 ms) and a blank retention interval (1,000 ms), the retro-cue was presented for 100 ms, followed by a blank lag of 400 ms, before the presentation of a test item. In the simultaneous-cue condition, the cue was presented simultaneously with the test item. Figure 6 (left) shows a schematic illustration of the trial sequence.

Each participant completed 1,248 experimental trials (divided into 26 blocks of 48 trials each), carried out in two 1-hr sessions. The trials were randomly and evenly divided into different conditions. Participants completed the experiment under articulatory suppression. In all other respects the experiment was identical to Experiment 2.

Results

Figure 6 (right) shows mean accuracy for color and shape tasks at different memory loads. An ANOVA confirmed that overall accuracy was higher in the color task than in the shape task, higher at lower memory loads, and higher with a retro-cue, all ps < .01. The interaction between stimulus type and memory set size was significant, $F(5, 55) = 11.51, p < .01$, driven by ceiling performance at a memory load of one for both color and shape VWM but lower performance for shape than color at higher memory load. The benefit provided by a retro-cue interacted marginally with memory load, $F(5, 55) = 2.21, p = .07$. The other interactions were not significant, ps > .25.

Follow-up tests showed that the retro-cue enhanced performance at all memory loads (ps < .05) except for Load 1 ($p > .70$). The retro-cue enhanced performance even when there were only two items in the memory array, $p < .02$ (Lepsien et al., 2005). Most important, when a memory load of one was removed from the analysis, the interaction between retro-cue and memory load was not significant, $F < 1$. Is this lack of interaction due to insufficient statistical power? Apparently not: When comparing the cue effect between Set Size 1 and Set Size 2, a significant interaction was found, $F(1, 11) = 4.80, p < .05$, with an observed power of 0.61. However, when comparing Load 2 with any other load, including Load 4 (twice that of Load 2) and Load 6 (the most extreme value), no interaction was detected ($F$s < 1). This suggests that any load effect from Load 2 or a higher load must be substantially smaller than that from Load 1 to Load 2. Moreover, individual data analysis revealed that the interaction between load (Loads 2 to 6) and cue was not significant in 11 of the 12 participants. Finally, we tested the linear contrast interaction of load and cue; that too was insignificant, $F < 1$. In other words, the

![Figure 6](image-url)

*Figure 6. Left: Trial sequences of the two conditions tested in Experiment 3. The memory display contained from one to six colors or shapes. Right: Results from Experiment 3; error bars represent ±1 SE of the retro-cue benefit (retro-cue minus simultaneous cue). The retro-cue benefit was seen at all memory loads greater than 1 and was not greater for a higher memory load or for shapes than colors. Simu = simultaneous.*
retro-cue benefit did not scale with memory load, even though the attentional advantage conveyed by the release of interitem competition and suppression should be greater at higher memory load. These results held when the dependent measure was log transformed for accuracy (Schweickert, 1985).

Finally, we calculated memory capacity on the basis of Cowan’s $K$ measure (Cowan, 2001), where $K$ is an index of the estimated number of items participants held in VWM at different memory load. The equation for calculating $K$ was as follows: $K = \text{memory load} \times (\text{hit} + \text{correct rejection} - 1)$. The estimated color VWM capacity was 2.7 in the simultaneous-cue condition and 3.5 in the retro-cue condition. The estimated shape VWM capacity was 1.8 in the simultaneous-cue condition and 2.5 in the retro-cue condition. By this measure, the estimated capacity is 25%–28% lower if one uses the simultaneous-cue procedure rather than the retro-cue procedure.

Discussion

In Experiment 3, we compared the size of the retro-cue benefit across different memory set sizes and for color and shape VWM. We found no evidence that the retro-cue benefit increased at higher memory loads. A significant retro-cue advantage was seen when memory load exceeded one, but it did not change for Set Sizes 2 to 6. These results were inconsistent with the idea that attentional cuing enhanced VWM representation by releasing interitem interference. The inter-item interference view is also inconsistent with findings from a recent study (Makovski & Jiang, 2007), which found no retro-cue benefit when attention was retro-cued to two of the six memory items. Even though this condition also involved a reduction in memory load and interitem interference, it did not improve performance. Similarly, Sperling (1960) did not find a retro-cue benefit when attention was cued to a row of items (rather than to a single item) after a delay of 500 ms. Together, these results show that the key factor for producing a retro-cue benefit is not the reduction of memory load per se, but a fundamental change of VWM property when attention is focused on a single memory item. These results are better explained by the probe interference hypothesis, according to which focused attention increased the robustness of VWM to interference from probe displays. At Memory Load 1, attention had already been focused on the critical item, leading to a robust form of memory. Further refreshing of its memory provided no additional benefit. When attentional load was greater than one, attention was initially distributed among multiple memory items. Memory for these items is not fully consolidated in the absence of focused attention. This memory can be degraded by new visual input. The retro-cue focused attention on the critical item, allowing its memory to be more resistant to probe interference.

General Discussion

VWM is usually considered a robust form of visual memory that does not quickly decay (Makovski & Jiang, 2007; Phillips, 1974; Vogel, Woodman, & Luck, 2001) and can be maintained across changes in eye position (Irwin, 1992; Phillips, 1974) or across presentation of new visual input (Miller et al., 1996). However, recent studies using the retro-cue paradigm have challenged this view (Griffin & Nobre, 2003; Landman et al., 2003; Lepsien et al., 2005; Makovski & Jiang, 2007). Retrospectively cuing attention to one of the memory items long after iconic memory has decayed and transmission to VWM has completed can enhance VWM performance. The current study clarifies the nature of the retro-cue benefit by testing the memory decay and the attentional enhancement hypotheses. We have shown that the retro-cue benefit is not due to memory decay, as it is observed even when the interval between memory encoding and refreshing is longer in the retro-cue condition than in the other conditions. Performance is enhanced by attentional cuing, and this enhancement cannot be simply explained by reducing decision noise during the comparison process: The use of a single test probe reduced the number of comparisons to one without removing the retro-cue benefit. We believe that the effect reflects an interaction between attention and VWM, in which focused attention enhances the durability of VWM. Our experiments further rule out the possibility that attention simply made VWM more resistant to interference from concurrent memory load, as the attentional enhancement effect does not increase with heavier memory load, which would have produced greater interitem interference. Instead, we believe that the effect reflects a change in the durability of VWM to probe interference as a function of attentional allocation. Previous studies that use rapid serial visual presentation have shown that the consolidation of information into VWM relies significantly on attention. Without focused attention, memory for a perceived stimulus is highly vulnerable to interference from subsequent input (Chun & Potter, 1995). Orienting attention to a single item in VWM consolidates the memory and reduces the interference produced by the probe task. This orienting effect is accompanied by a cost to VWM of the uncued items. Griffin and Nobre (2003) found that after attention has been cued to one of the memory items, participants’ memory of the other, uncued items is poor.

These results have significant theoretical and methodological implications. At the theoretical level, they suggest a modification to the dominant view of VWM as a robust form of visual memory. VWM is typically considered a window into cognitive control, as successful maintenance and retrieval of information online depends significantly on central executive processes (Baddeley, 2003; Makovski, Shim, & Jiang, 2006; Vogel, Woodman, & Luck, 2003).

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3 Performance in the no-cue (or simultaneous-cue) condition was lower than that seen in other studies (Luck & Vogel, 1997), most likely because the costs used in this study were less saturated and distinctive in comparison with those used in other studies. However, as noted by a reviewer, one might argue that the low performance was driven by intermixing different cue trials, which might have led to the adoption of strategies detrimental to the no-cue (or simultaneous-cue) condition. To rule out this possibility, we tested 7 observers in an experiment in which the retro-cue and simultaneous-cue conditions were either randomly mixed in presentation order or tested in separate blocks. If participants adopted strategies detrimental to the no-cue (or simultaneous-cue) condition in the mixed design, then the cue effect should be eliminated in the blocked design, and performance in the no-cue (or simultaneous-cue) condition should be better in the blocked than the mixed conditions. This, however, was not what we found. Accuracy in the mixed design was comparable to accuracy in the blocked design in both the no-cue conditions (64.6% vs. 65.4%, respectively) and the retro-cue conditions (73.2% vs. 74.6%, respectively). The main effect of cue was significant, $p < .01$, but the main effect of blocking type (mixed or blocked) or their interaction was not significant.
This view of VWM as a reflection of top-down control has dominated the conception of VWM, buttressed in part by the observation that VWM does not quickly decay and that it can be maintained across interruptions. However, several studies in VWM have already shown that VWM is also sensitive to bottom-up input. For example, VWM shows a dramatic recency effect, in which the trailing array is much better retained than the preceding arrays (Broadbent & Broadbent, 1981; Brockmole, Wang, & Irwin, 2002; Jiang & Kamar, 2004; Phillips & Christie, 1977; Song & Jiang, 2006a). In neurophysiology, Miller and colleagues have shown that, whereas cells in the prefrontal cortex can maintain their selectivity over filled delays, cells in the inferior temporal cortex do not maintain their memory selectivity over filled delays (Miller & Desimone, 1994; Miller et al., 1996). In human functional brain imaging, although the prefrontal and posterior parietal cortices show VWM-related activity for various types of input (Song & Jiang, 2006b; Todd & Marois, 2004; Xu & Chun, 2006), the inferior temporal cortex is selective to specific stimulus type. For example, the fusiform face area shows VWM activity for faces but not for scenes during the retention interval (Druzhgal & D’Esposito, 2003). These studies suggest that the access to VWM may be guarded both by top-down control and by bottom-up inputs. This view of VWM can be partly mapped onto Baddeley (1986) and Logie’s (1995) models of working memory, in which the central executive works in tandem with “subsidiary systems.” The subsidiary systems, such as the visual–spatial sketchpad, may be sensitive to obligatory updating by new input. Although the current study does not fundamentally change the Baddeley or Logie model of VWM, it has highlighted the need to consider bottom-up influences, such as obligatory updating of VWM, and this is something that has largely been neglected in existing VWM models.

At the methodological level, this study shows that the estimation of VWM capacity can depend significantly on the testing procedure. The standard change detection task uses a whole-report procedure and can underestimate VWM capacity by 25%. The retro-cue procedure, in which the critical memory item is retro-spectively cued prior to probe presentation, can be considered a better procedure, especially if one’s interest is to characterize the upper capacity limit. Indeed, even the retro-cue procedure used here may have underestimated VWM capacity. Although the retro-cue did not overlap with the memory items in spatial locations, it may have produced some interference, as interference from new input is not screen or viewer based (Experiment 1). This interference must be less than that produced by the probe; otherwise, the interference by the cue would have swamped any advantage of attentional cuing. The lower interference by the retro-cue than by the probe item may originate from differences in spatial location (central vs. peripheral; far away from vs. near the initial memory item) or differences in similarity to VWM contents.

The benefit of a retro-cue observed here is much less than that seen in Landman et al.’s (2003) original study. Even with the retro-cue procedure, we did not find evidence for a high-capacity system. Two differences between our methods and those of Landman et al. (2003) could explain the disparity in results. First, the Landman et al. study tested memory for orientation, while we tested memory for color and shape. Strategies such as grouping oriented lines to form a configuration may be more successful than similar strategies for color memory or shape memory. Second, there were only two possible orientations tested in the Landman et al. study, and these two orientations were easily distinguished (they were horizontal and vertical). In contrast, our experiment tested a total of 9 colors and 10 shapes, which were probably more similar. Given that the veridicality of VWM representation may be graded, the ease of distinguishing items in memory can affect memory capacity (Alvarez & Cavanagh, 2004; Eng et al., 2005; Olsson & Poom, 2005). Thus, it is perhaps not meaningful to talk about a magic number for VWM capacity; that number may be highly variable, depending on the feature values selected to test VWM (Jiang, Shim, & Makovski, 2007; Wilken & Ma, 2004).

Our study complements previous research by showing that visual attention significantly influences VWM. Information that is selectively attended during encoding of the prechange display gains access to VWM (Griffin & Nobre, 2003; Lepsien et al., 2005; Rensink, Oregan, & Clark, 1997; Schmidt, Vogel, Woodman, & Luck, 2002). After VWM encoding, attention is continuously needed to maintain information in VWM. VWM is severely impaired if a secondary task is conducted during the delay interval (Fougnie & Marois, 2006; Makovski et al., 2006). This interference largely arises from amodal, central attention, because an attended auditory secondary task impairs VWM, but a passively viewed visual stimulus barely affects VWM (Makovski et al., 2006). What our study has added to the understanding of attention and VWM is that attention also modulates the durability of VWM. Memory consolidation is thus not just a matter of time (Vogel et al., 2006) but also an act of selective attention. If attention is distributed across multiple items, such that several items are simultaneously retained in VWM, then memory for these items is vulnerable to interference from the test display. But the distribution of attention can change such that one of the memorized items becomes selectively attended, in which case memory for that item becomes more robust (Makovski & Jiang, 2007). Thus, focusing attention retrospectively on a single item in VWM can solidify that memory. Whether this act of attention qualitatively changes the format of VWM is an interesting question to test in the future.

References


(Appendix follows)
### Table A1
**Experiment 1**

<table>
<thead>
<tr>
<th>Measure</th>
<th>Color VWM</th>
<th></th>
<th></th>
<th>Shape VWM</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Expanded</td>
<td>Overlapped</td>
<td>Expanded</td>
<td>Overlapped</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No cue</td>
<td>0.63</td>
<td>0.70</td>
<td>0.70</td>
<td>0.70</td>
<td>0.73</td>
<td>0.70</td>
</tr>
<tr>
<td>Simu cue</td>
<td>0.70</td>
<td>0.77</td>
<td>0.70</td>
<td>0.70</td>
<td>0.73</td>
<td>0.72</td>
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<tr>
<td>Retro-cue</td>
<td>0.77</td>
<td>0.86</td>
<td>0.70</td>
<td>0.78</td>
<td>0.73</td>
<td>0.72</td>
</tr>
</tbody>
</table>

**RT**

| No cue   | 967 | 924 | 768 | 936 | 886 | 777 | 1038 | 965 | 805 | 948 | 909 | 770 |

**Note.** VWM = visual working memory; Simu = Simultaneous.

### Table A2
**Experiment 2**

<table>
<thead>
<tr>
<th>Measure</th>
<th>Color VWM</th>
<th></th>
<th></th>
<th>Shape VWM</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Simu cue absent</td>
<td>Simu cue present</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No cue</td>
<td>0.82</td>
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<td>0.86</td>
<td>0.78</td>
<td>0.86</td>
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<tr>
<td>Retro-cue</td>
<td>0.73</td>
<td>0.70</td>
<td>0.70</td>
<td>0.78</td>
<td>0.75</td>
<td>0.72</td>
</tr>
</tbody>
</table>

**RT**

| No cue | 963 | 740 | 956 | 974 | 965 | 948 |

**Note.** VWM = visual working memory; Simu = Simultaneous.

### Table A3
**Experiment 3**

<table>
<thead>
<tr>
<th>Measure and condition</th>
<th>Color VWM by load</th>
<th></th>
<th></th>
<th>Shape VWM by load</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>A'</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Simu cue</td>
<td>0.97</td>
<td>0.96</td>
<td>0.91</td>
<td>0.91</td>
<td>0.86</td>
<td>0.83</td>
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<tr>
<td>Retro-cue</td>
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<td>0.97</td>
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<td>0.93</td>
<td>0.90</td>
<td>0.88</td>
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<tr>
<td>RT</td>
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<td>887</td>
<td>887</td>
<td>945</td>
<td>924</td>
</tr>
<tr>
<td>Retro-cue</td>
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<td>697</td>
<td>742</td>
<td>731</td>
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</table>

**Note.** VWM = visual working memory; Simu = Simultaneous.