

2 Visual memory for features, conjunctions, objects, and locations

Yuhong V. Jiang and Tal Makovski

University of Minnesota

Won Mok Shim

Massachusetts Institute of Technology

1. INTRODUCTION

In her Multiple-Entry, Modular Memory (MEM) model on human cognition, Marcia Johnson differentiated perceptual subsystems that interact directly with the external environment and reflective subsystems that operate in the absence of external input (Johnson, 1992). Visual memory is an example of processes that are situated at the border between these two. Short-term visual memory directly bridges visual perception with conceptual representation. It is abstracted from visual perception yet operates on perceptual input and retains many properties of visual objects including size, color, orientation, number, and spatial layout. Short-term visual memory can result from active encoding and retention of information in visual working memory (Phillips, 1974), or as a by-product of perceptual analysis of a previous trial event (Maljkovic & Nakayama, 1994, 1996). In either case, content previously stored in short-term memory may remain in long-term visual memory (Hollingworth, 2005), and both short-term and long-term visual memory can be used explicitly or implicitly to guide future visual processing (Brockmole & Henderson, 2006a, 2006b; Chun & Jiang, 1998; Downing, 2000; Vickery, King, & Jiang, 2005). The goal of this chapter is to provide a synthesis of visual memory for different visual attributes.

2. VISUAL WORKING MEMORY

When people view a briefly presented visual display, they first acquire a veridical, high-fidelity memory of the display, known as iconic memory (Averbach & Sperling, 1961; Neisser, 1967; Sperling, 1960). This memory is short-lived, typically lasting for less than half a second, and is easily erased by new visual input (Phillips, 1974). Iconic memory may be considered a lingering form of visual sensory processing, and it is useful for integrating input separated by very short intervals (Di Lollo, 1984; see also chapter 4, section 2.1). At longer delay intervals, visual information is stored in visual working memory (VWM). This

memory can last for several seconds and is more resistant to interference from new visual input (Phillips, 1974).

Visual working memory is important for many cognitive activities. When crossing a busy street, we must look left and right and remember what is on each side before deciding to cross. In team sports, players often need to be aware of the whereabouts of their team mates and opponents. Even in social interactions, we must encode who are around us to direct proper conversations to the right individual. Visual working memory was extensively studied both in neurophysiology and behavioral research. Neurophysiological studies have focused primarily on the domain specificity of the prefrontal cortex in spatial and nonspatial working-memory tasks. They are guided by the influential working-memory model of Baddeley and Hitch (1974; Baddeley, 1986), where working memory is divided into a central executive process and multiple slavery systems including the phonological loop, the visuospatial sketchpad, and the episodic buffer (Baddeley, 2000). In behavioral studies, VWM research has followed two traditions: the Baddeley tradition of using interference tasks to subdivide VWM into different domain-specific components (e.g., Logie, 1995), and a change detection tradition that links VWM with visual perception and visual attention. Chapter 1 extensively considered the domain specificity of VWM. Our review of VWM will primarily follow the change detection tradition.

2.1. Testing VWM

To probe VWM, researchers have devised two tasks that, by now, are operational definitions of VWM: the change detection task, and a delayed match-to-sample task. Figure 2.1 shows a schematic illustration of the tasks. In the change detection task (Rensink, 2002), a visual display is briefly presented for observers to remember. After a short interval of between one and several seconds, a test display is presented. The test display is either the same as the initial memory display or is changed in some manner. Observers are asked to decide whether a change is present or absent (Figure 2.1, left). To fulfill this task, observers must encode the initial display into VWM, keep it there during the retention interval, and compare it with the test display. By varying VWM load (i.e., the amount of information presented on the first display) and measuring change detection accuracy of different VWM loads, it is possible to estimate the capacity of VWM for various types of visual input, such as spatial locations and object features (Cowan, 2001; Pashler, 1988).

In addition to the change detection task, a delayed match-to-sample task is also frequently used to assess VWM (Figure 2.1, right). This task is used most often in nonhuman primate research (e.g., Davachi & Goldman-Rakic, 2001; Miller, Erickson, & Desimone, 1996). In this task, a sample—usually a single object or a single location—is presented, followed by a sequence of test stimuli. Subjects must decide whether each test stimulus matches the original sample. The delayed match-to-sample task is procedurally similar to the change detection task. However, presentation of successive test stimuli places a high demand on the main-

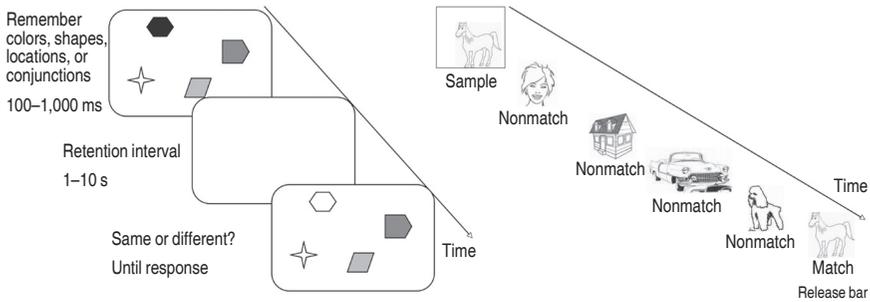


Figure 2.1. A schematic illustration of the change detection task (left) and delayed match-to-sample task (right). Each item is typically presented for 500 ms; interstimulus interval is usually 1 s.

tenance of the original sample's memory across filled-delay intervals of other stimuli and tasks. Adding new visual input and new cognitive tasks during the delay interval interferes significantly with the maintenance of sample memory (Fougnie & Marois, 2006; Makovski, Shim, & Jiang, 2006). As a result, filled-delays are usually avoided in human VWM tasks, and a change detection task with a blank retention interval has become the standard paradigm to test VWM (however, for challenges to this paradigm, see Hollingworth, 2003; Landman, Spekreijse, & Lamme, 2003; Makovski & Jiang, 2007; see also chapter 4).

2.2. Spatial versus object VWM

2.2.1. Neuroscience evidence

One of the most important questions in cognitive research is the division of labor for different cognitive processes. In vision, perception of object identity is considered separate from perception of object location or visually guided motor processing (Goodale & Milner, 1995; Sagi & Julesz, 1985; Ungerleider & Mishkin, 1982). In the primate brain, object vision and spatial vision (or visuomotor action) map roughly onto the occipitotemporal ventral stream and the occipitoparietal dorsal stream. The division is not absolute, with extensive crosstalk between brain regions in the ventral and dorsal streams (Felleman & Van Essen, 1991), but functions subserved by the two streams are characteristically different and can exist independently of each other.

Is the functional division between object and spatial processing confined to visual perception, or does it also extend to visual working memory? If yes, can we continue to identify a dorsal system for spatial VWM and a ventral system for object VWM? These are important questions because they pertain to the degree of domain specificity in high-level cognitive processes. The widely accepted model of working memory by Baddeley (1986) proposes that an important ele-

ment of working memory is the central executive, whose work is augmented by several slave systems. Because working memory is so closely related to central-executive processes such as attention (Awh & Jonides, 2001; see also chapter 1, section 2.3), its processes may be largely domain-general and applicable to memory for all kinds of materials. On the other hand, the existence of slave storage systems may result in some degree of domain specificity.

Studies on visual imagery have provided evidence that some degree of domain specificity is retained for internally generated visual representations. Brain-damaged patients with color perception deficits also have difficulty imagining the canonical color of everyday objects. They may be able to answer metaphorical questions about color, such as “what color is associated with envy?”, but not real-world questions about color, such as “what color is a peach?” (DeRenzi & Spinnler, 1967). In addition, patients with damage to the occipitotemporal lobe are able to imagine spatial locations such as the triads of states within the United States, but they have difficulty imagining object properties such as whether George Washington had a beard. Patients with damage to the occipitoparietal lobe often show the opposite deficits: an impairment at imagining spatial locations but no impairment at imagining object identities (Farah, 1988; Levine, Warach, & Farah, 1985). These studies suggest that, like perception, visual imagery may also be divided into ventral and dorsal streams (an issue considered at length in chapter 8, section 2.2). However, because these studies involve visual imagery rather than visual working memory, they may not directly inform us about the division of labor in VWM (but see chapter 1, sections 3 and 4). An important difference between visual imagery and VWM is that visual imagery is often derived from long-term memory and, as such, can be less veridical than the kind of memory formed from immediate perception (Olson & Jiang, 2004).

Neurophysiologists have approached the division of labor in VWM using the delayed match-to-sample task (Fuster, 1990). Their interest focuses on the function of the prefrontal cortex (PFC), which has extensive connections with both the parietal lobe and the temporal lobe (Goldman-Rakic, 1990). Empirical evidence on the functional division of the PFC has been mixed. On the basis of monkey neurophysiology data, Goldman-Rakic and colleagues propose that dorsolateral PFC underlies spatial VWM whereas ventrolateral PFC underlies object VWM—that is, the functional division in the prefrontal cortex parallels that in the posterior cortex (Wilson, Scalaidhe, & Goldman-Rakic, 1993).

However, the segregation of spatial and object VWM in dorsal and ventral lateral PFC has not been universally confirmed. Rao, Rainer, and Miller (1997) found that PFC neurons that carry memory for spatial properties of an object can also carry memory for nonspatial properties of that object. In their task, monkeys were trained to first remember the shape of a sample object. After a delay interval, an array of several test items was shown. Monkeys must localize the test item that matched the sample object and remember its location. After another delay interval, monkeys saccaded to the matched test location to obtain a reward. Rao et al. (1997) found that the same PFC neurons can be activated both during the first, object VWM delay and during the second, spatial VWM

delay. In addition, Rainer, Asaad, and Miller (1998) trained monkeys to remember both an object's identity and its location in a VWM task. They mapped out the receptive fields of PFC neurons and found that using traditional spatial VWM and object VWM tasks, the same neurons in PFC can convey both spatial and nonspatial information.

In light of the mixed results, an alternative theory is proposed to characterize PFC functional segregation. Petrides and colleagues argue that the PFC is not organized around the type of visual input (spatial or nonspatial), but around the type of cognitive processes necessitated by the VWM task (for a recent review, see Petrides, 2005). Specifically, merely maintaining something over time engages the dorsolateral PFC, but further manipulation and operation on that input (e.g., mentally rotating the object) engages the ventrolateral PFC. Whether PFC is divided along the content of VWM or along cognitive operations necessitated by a VWM task remains to be determined.

The same controversy exists in human functional neuroimaging studies on VWM. Using positron emission tomography (PET), Courtney, Ungerleider, Keil, and Haxby (1996) scanned normal subjects while they engaged in a spatial VWM task or an object VWM task. In these tasks, subjects had to remember either the location or identity of a single face among 23 gray squares. Courtney et al. (1996) found that the inferior frontal regions were more involved in object VWM tasks than spatial VWM tasks and that the superior frontal regions showed the reverse pattern. Dissociation between spatial and object VWM was also seen in other studies using functional magnetic resonance imaging (fMRI) (Courtney, Petit, Maisog, Ungerleider, & Haxby, 1998; McCarthy et al., 1996; Ungerleider, Courtney, & Haxby, 1998). These results, however, are not representative of all neuroimaging studies on human VWM, as many studies failed to find convincing dissociations between spatial VWM and nonspatial VWM tasks in the PFC (Dade, Zatorre, Evans, & Jones-Gotman, 2001; D'Esposito et al., 1998; Owen et al., 1998; Postle & D'Esposito, 1999).

The failure to cleanly separate spatial VWM and nonspatial VWM in the human brain does not necessarily mean that spatial VWM and object VWM must also be inseparable at the functional level. The mapping between cognitive functions and brain anatomy is that of many-to-many. Two processes can both activate the same brain regions yet still be separable at the functional level. Behavioral studies on VWM thus provide unique insight into the relationship between spatial VWM and object VWM.

2.2.2. Behavioral evidence

In this discussion, it is necessary to clarify two terms: "spatial" and "object". In human behavioral studies of spatial VWM, at least two types of spatial memory have been tested: memory for spatial locations of an array of objects, and memory for spatial locations of a single object or a sequence of dot locations. Some researchers consider the former—spatial locations of an array of objects—a form of object memory or pattern memory (Logie, 1995; Phillips, 1974), as subjects

seem to remember the entire pattern or spatial configuration of the array rather than individual item locations (Jiang, Olson, & Chun, 2000; Santa, 1977). In the following discussion we consider both types of spatial VWM.

The term “object” also requires clarification. By contrasting “spatial VWM” with “object VWM”, we do not intend to discuss whether VWM is space-based or object-based, an issue familiar to visual attention researchers (Scholl, 2001). Here, object VWM simply refers to VWM for properties of an object that are not its location. Object VWM would include such things as color, size, orientation, shape, and so on.

Empirically testing spatial VWM and object VWM is simple: show observers an array of items (or a sequence of items) and instruct them to remember locations or object identities and measure VWM performance. If the two types of VWM are not separable, then one might expect that: (1) both types of VWM are interfered with to similar degrees by various kinds of secondary tasks, and (2) VWM for spatial locations is contingent on VWM for object identities, such that a change in object identity from initial memory to later testing would impair memory retrieval of spatial locations, and vice versa. Conversely, dissociation of dual-task interference on spatial and object VWM tasks, and separable encoding of spatial location and object identity information would indicate a dissociation between the two. So, to what degree is spatial VWM separable from object VWM in behavior?

2.2.2.1. *Dual-task interference*

Studies using dual-task interference as a means to separate object and spatial memory are extensively reviewed in chapter 1 (see section 2), but the approach is worth briefly recapping here. In interference studies, spatial VWM is usually tested using the Corsi block task, in which an experimenter taps a sequence of blocks presented on the table and the observer then has to imitate that tapping sequence. Object VWM, in contrast, is usually tested with a pattern matrix. After being shown a grid of squares, some of which are filled in, observers are tasked to replicate what they have seen on a blank grid. Della Sala, Gray, Baddeley, Allamano, and Wilson (1999) found that adding additional spatial tasks such as following the sequence of pegs haptically interfered more with the Corsi task than the pattern matrix task, while adding visual tasks such as viewing irrelevant pictures during the delay interval interfered more with the pattern matrix task than with the Corsi task. Thus, the two types of spatial VWM—VWM for spatial sequence and VWM for a static pattern—can be separated (see also Klauer & Zhao, 2004).

Can spatial VWM for a static pattern be distinguished from object VWM for shapes? The answer seems to be “no”. A study that tested recall for static matrix patterns and recognition of Chinese characters found that both types of memory are insensitive to dynamic visual noise (Andrade, Kemps, Werniers, May, & Szmalec, 2002). In addition, both spatial VWM for an array of dots and nonspatial VWM for colors or scenes are significantly impaired by filled

delay tasks, including those of an auditory-choice reaction time task (Makovski et al., 2006).

Thus, the two types of spatial VWM are separable, but object VWM and spatial VWM for an array of items are not easily dissociated. The latter finding may seem surprising, given that the VWM capacity for remembering objects appears to be much lower than that for remembering locations of an array of items (Jiang et al., 2000; Rensink, 2000; Simons, 1996). However, the disparity in capacity may not be a good measure of different systems, given that it is much easier to chunk individual locations into a bigger pattern than to chunk features of multiple objects. One may still find greater capacity for array locations than identities even if the same system is used to remember these two types of stimuli. Woodman, Vogel, and Luck (2001) found results consistent with this proposal: visual search was unimpaired when observers held several colors or shapes in VWM, yet it was impaired when they held the locations of two sequentially presented dots in spatial VWM (Woodman & Luck, 2004).

2.2.2.2. *Separable encoding of spatial and nonspatial properties*

Although interference studies fail to dissociate object VWM from spatial VWM for static patterns, there is strong evidence that the two types of information are not always coregistered in VWM. Remembering the identity of an object obligatorily puts the location of the object into VWM (Jiang, et al., 2000; Olson & Marshuetz, 2005; Tsal & Lamy, 2000), but remembering the locations of an array of items usually does not put the identities of these items in VWM (Jiang et al., 2000). These findings were obtained from change detection tasks that manipulated the consistency between test array properties and memory array properties (see Figure 2.2). When observers must perform a change detection task on object identities such as color or shape, their performance is significantly affected by whether the test array contains a change in item locations, even though location is a task-irrelevant dimension (Jiang et al., 2000). Interestingly, a change in location impairs performance only if the change has perturbed the relative configuration of element locations, but not if the change has resulted in no change in overall configuration (e.g., the change involves an expansion, contraction, or shifting of the original display). These results suggest that the spatial layout of an array of objects is obligatorily encoded, even when the task does not explicitly require location memory. The configuration, or spatial pattern, of an array of items allows VWM to use topographic representation of the display: identities are bound to locations, and locations are bound to an imaginary configuration. Finally, even with single-item arrays, the identity of the object seems to obligatorily encode the object's spatial location into VWM, which enables faster change detection at the object's location (Olson & Marshuetz, 2005).

The relationship between spatial and nonspatial encoding is asymmetric (Figure 2.2). When observers must remember dot locations for a change detection task, changing the shape or color of the array items has negligible effects on location change detection (Jiang et al., 2000). This finding suggests that nonspatial

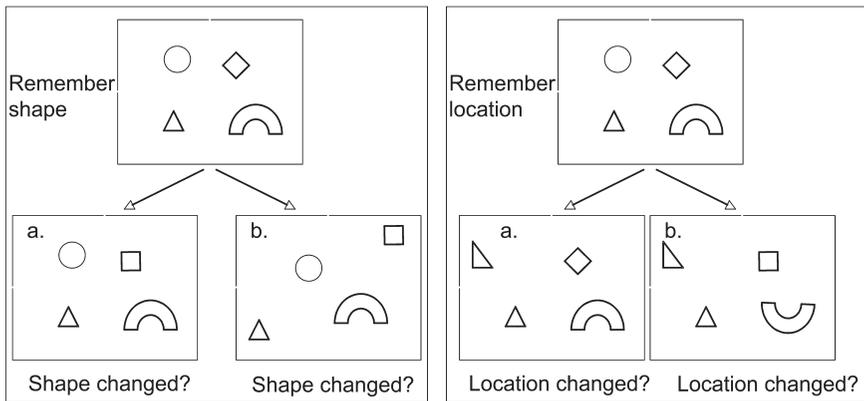


Figure 2.2. Effects of change in an irrelevant dimension on visual working-memory accuracy of a relevant dimension. Left: Detection of a shape change is easier if the locations of items do not change (a) than if they do (b). Right: Detection of a location change is unaffected by whether the items change shapes (b) or not (a).

properties are easily discarded during spatial VWM tasks, even when the change in nonspatial properties is highly salient. However, there is an exception to this independence, primarily in cases when items occupying the original memory array are elongated: memory for these items' center locations is significantly impaired if the individual items change orientation, which results in a change in the perceived grouping of elements (Delvenne & Bruyer, 2006; Jiang, Chun, & Olson, 2004).

Taken together, behavioral studies on the relationship between spatial VWM and object VWM have indicated their close relationship as well as possible dissociations. In spatial VWM, memory for an array of elements appears to be dissociable from memory for a single element or for a sequence of single-dot locations. Dual-task interference tasks reveal this dissociation, which possibly reflects two different mechanisms involved in registering space: a relational, object-based mechanism, and an environment-based or viewer-based mechanism. Interference studies have not reliably shown differences between spatial VWM for an array of items and object VWM for that array. In this case, remembering objects usually leads to memory for these objects' locations, but the reverse is typically not true. The complexity of the functional relationship between spatial VWM and object VWM may partly explain why neuroscientists have so far not succeeded at isolating the neural dissociation between the two.

2.3. The building blocks of VWM: Objects versus features

One of the most influential studies in VWM was the demonstration by Luck and Vogel (1997) that VWM was limited by the number of objects rather than the number of features per object. In their study, Luck and Vogel first tested VWM

for simple objects with a single feature, such as colored disks or tilted lines. They found that observers could remember about 4 different colors simultaneously, or about 4 different tilted lines simultaneously. They then tested observers on VWM of compound objects of multiple features, such as tilted lines of different colors. The results were clear: when color and orientation conjoined to form a single object, observers could remember about 4 of these compound objects, a total of 8 features. Indeed, there was no apparent limit to the number of features one could potentially remember, as long as they belong to a single object. Four compound objects containing four features each, including color, size, orientation, and the presence of a gap, could be easily remembered. These results were reminiscent of the object-based attention findings (Duncan, 1984; Egly, Driver, & Rafal, 1994; Lamy & Egeth, 2002), where visual attention operates upon all dimensions of a single object, allowing multiple features of a single object to be attended to simultaneously without any cost.

Although the equivalent performance between compound objects and single-dimension features has been used to argue for an object-based VWM account, this finding is also consistent with a feature-based VWM account that assumes separate storage limits for different dimensions. This alternative view, known as the multiple-pools of memory resources view, receives some support from studies on compound objects formed from a single dimension. Although Luck and Vogel (1997) reported that a compound object created by the juxtaposition of two colors was remembered as well as a simple object of just one color, this finding seemed specific to the highly saturated colors used in that study. Several groups found that color-color compound objects were as hard to remember as two simple color objects, finding no benefit for conjoining two features of the same dimension (Olson & Jiang, 2002; Wheeler & Treisman, 2002; Xu, 2002). However, the strongest version of the multiple-resources view—that conjoining features into objects plays no role in VWM—was also not supported by empirical data. When observers were presented with 4 colors and 4 orientations on a single display, they performed better if these features formed 4 colored-oriented bars than if they formed 8 objects, half of which were colored disks and half were tilted bars (Olson & Jiang, 2002). Thus, conjoining features of different dimensions into a single object enhanced VWM performance. Interestingly, observers tended to do better when a display contained simple feature objects that were heterogeneous, such as 4 colored disks and 4 tilted lines, than if the display contained simple feature objects that were homogeneous, such as 8 colored disks or 8 tilted lines. Thus, there is truth both to an object-based account and a multiple-pools of resource account of VWM (Olson & Jiang, 2002).

Why does the formation of a single object enhance VWM of multiple features? Is it simply because these features share the same location and thus are easier to remember? Lee and Chun (2001) directly contrasted the object-based account with a space-based account by using overlapping objects. Their results were consistent with the object-based account, finding no effects of the number of spatial locations on VWM performance. However, Xu (2006) provided the

most comprehensive data on this debate and found that spatial proximity as well as connectivity between parts (to form a single object) contribute to VWM performance.

Although more features are remembered when they form compound objects than when they are multiple, single-feature objects (Luck & Vogel, 1997), these data do not provide direct evidence that the proper conjunction between different features is entirely resource-independent. In most studies on object- versus feature-based VWM discussed above, a change-present trial usually consists of replacing an old property with a new property not shown on the initial memory array. Thus, a red vertical line may change into a blue vertical line, with none of the initial memory items being blue. To correctly perform the task, observers only need to remember which features are present; correct conjunction between red and vertical and their spatial locations is not strictly required. To test whether features-conjunction in VWM comes for free, Wheeler and Treisman (2002) compared two types of change trials: a change involving a new feature value not presented on the initial memory array, and a change involving an old feature value presented at a location occupied by a different object. They found that performance was worse on the latter type of “feature-swapping” trials, suggesting that memory for proper conjunction of features was imperfect. In addition, whether multiple features of a single object are stored in VWM depends on task requirements. In visually guided motor tasks such as picking up a blue block and placing it at a designated location, observers usually acquire one relevant feature at a time, rather than storing all features of an object simultaneously (Droll & Hayhoe, 2007; Droll, Hayhoe, Triesch, & Sullivan, 2005).

The imperfect memory for conjunction, however, does not necessarily mean that VWM for feature conjunction demands more attention than VWM for single features. Gajewski and Brockmole (2006) asked observers to remember color and shape of several objects. During the retention interval, attention was directed to a subset of the objects with an exogenous cue. Recall performance was enhanced for the cued positions. Interestingly, the uncued objects were also remembered as an integrated whole, as participants often recalled both features or neither of the two features of an object. In interference studies, Johnson, Hollingworth, and Luck (2008) found that a secondary task presented during the filled-delay interval interfered with feature VWM to the same degree as it did with conjunction VWM (see also Allen, Baddeley, & Hitch, 2006). These results are understandable given that feature–location conjunction appears to be obligatory (Jiang et al., 2000; Olson & Marshuetz, 2005). Thus, conjunction is an important element for VWM for feature–location binding as well as for multiple-feature conjunctions.

2.4. VWM capacity limit

Much of VWM research has been devoted to characterizing its capacity limit. Two separate questions on this issue have been raised (Figure 2.3 [in color plate section]). First, is the capacity limit of VWM influenced by the complexity

of visual features? That is, do complex features fill up the VWM space more quickly than do simple features? Second, should this limit be thought of as limited in the number of slots, or should it be conceptualized as limited in resolution in a slot-less space? Much progress has been made to answer these questions, but no clear conclusions have been reached.

2.4.1. Does feature complexity matter?

Is the number of items one can hold in VWM fixed for different visual attributes, or is it variable, such that VWM can hold more simple objects (e.g., colors) than complex objects? The empirical data are clear: complexity matters in change detection tasks. For example, Alvarez and Cavanagh (2004) showed that when observers must remember several colors for a color change-detection task, they can remember about 4 colors. But when they must remember several random polygons for a shape change-detection task, they can only remember about 2 polygons. These results have led Alvarez and Cavanagh to propose a “flexible-slot” model of VWM, where the number of slots in VWM varies with object complexity. Complex attributes such as random polygons, cubes of different lightness shadings, and unfamiliar faces fill up VWM space more quickly than do simple attributes such as colors.

To provide an independent index of complexity, Alvarez and Cavanagh (2004) calculated the “informational load” of each object by measuring the slope of visual search RT as a function of the number of elements on a display. Thus, colors have low informational load because searching for a color among other colors results in a shallow slope. Unfamiliar faces have high informational load because searching for an unfamiliar face among other unfamiliar faces results in a steep slope. These empirical data are highly replicable (Curby & Gauthier, 2007; Eng, Chen, & Jiang, 2005; Olsson & Poom, 2005), but their interpretation is far from straightforward.

Do these data uniquely support the flexible-slot model? Advocates for the fixed-slot model have quickly pointed out that there may indeed be a fixed number of slots in VWM, but one complex shape can occupy more than one fixed slot (Zhang & Luck, 2003). A random polygon, for example, has definable parts and may take up two or more slots. Regardless of whether one adopts the “flexible-slots” or the “fixed-slots” view, what seems clear is that complexity of an object matters. But why does complexity matter? Is it because complex objects are truly harder to remember in VWM, or is it because the change from one complex object to another complex object results in a smaller change signal?

Unfortunately, this question is not easily answered. The informational load used to index complexity is essentially a similarity measure: faces are considered more complex than colors because the unfamiliar faces are more similar to one another than simple colors are to one another, as reflected by less efficient visual search for faces among faces than for colors among colors (Duncan & Humphreys, 1989). However, because faces always change into other faces and

colors always change into other colors, not only are items on the memory display more “complex” for face trials, but the memory items are also more similar to a changed test item on those trials. In other words, to detect a face changing into another face, observers are operating on the detection of a relatively small change signal. It is only logical that performance on face change trials will be lower than that on color change trials, even if the number of VWM slots for faces is equivalent to that for colors (or even if the resolution for faces is comparable to that for colors). (For additional discussion of the impact of visual similarity on memory and how such effects have been used to test assumptions regarding the contents and capacity of VWM, see chapter 1, section 5.1.)

Because the “complexity” measure used in preceding studies directly affects the size of the change signal, reduced performance for remembering complex items can be accounted for at the output change detection stage, without considering any influence of complexity on intrinsic memory capacity. Indeed, in a recent study, Awh, Barton, and Vogel (2007) made a simple manipulation: they changed polygons into Chinese characters or vice versa and found that performance on between-category change trials was much better than performance on within-category change trials. These results underscore the inadequacy of disregarding output limitations in change detection. That similarity at the output-comparison stage matters, however, does not refute the possibility that complexity at the memory-input stage could also matter. The latter must be tested while controlling for the size of change signal for different visual attributes. This work remains to be done.

2.4.2. *Neuroimaging evidence for VWM of locations, simple features, and complex features*

Recent neuroimaging studies on human VWM have shown that the posterior parietal cortex correlates with increasing VWM load (Linden et al., 2003; Todd & Marois, 2004). Its activation increases as the number of colors to be remembered increases from 1 to about 4. As the capacity of VWM is reached, parietal activity also asymptotes, showing no further increase as memory load increases from 4 to 7 (Todd & Marois, 2004). But what aspects of the VWM task is the posterior parietal cortex (PPC) reflecting? Is it the number of locations (or objects) that must be monitored? Is it memory for identities? Or is it both spatial monitoring and VWM for object identities?

If PPC is involved primarily in monitoring space (or objects; Culham, Cavanagh, & Kanwisher, 2001; Jovicich et al., 2001), then its activity should be sensitive to the number of items in VWM but not to the complexity of these items. Thus, PPC activation should be comparable when observers must remember colors (a simple attribute) and shapes (a complex attribute). Alternatively, if PPC is involved primarily in memorizing the identity of objects, then its activation should be modulated by the aspect of the object that is relevant to the memory task. Remembering colors exerts a lower load on VWM than remembering shapes (Alvarez & Cavanagh, 2004), so PPC activity should be

lower for remembering 1 color than remembering 1 shape. Furthermore, given that it takes about 4 colors to fill up VWM space and about 2 shapes to fill up VWM space, PPC activity should reach asymptote when memory load exceeds 4 colors or 2 shapes. Figure 2.4 [in color plate section] shows different predictions of the two models.

Empirical evidence has provided some support for both models (Song & Jiang, 2006). When observers are presented with colored polygons and must remember either color or shape on separate trial blocks, PPC activity was higher for remembering one shape than for remembering one color, suggesting that PPC was sensitive to what must be remembered. However, activity in PPC increased when the number of memory objects increased and asymptoted at 4 objects for both the color task and the shape task, even though behavioral capacity reached asymptote at 4 for color and only 2 for shape. Thus, the asymptote of PPC activity was sensitive only to the number of objects and not to their identity. PPC appears to be involved both in monitoring spatial locations (or individual objects) and in memory of specific object attributes.

The coding of spatial properties and object attributes can be separated to some degree to different parts of the posterior parietal cortex (Xu & Chun, 2006). Activation in the inferior segment of the intraparietal sulcus correlated with the number of objects regardless of object complexity, whereas activity in the superior segment of the intraparietal sulcus and the lateral occipital complex was modulated by complexity. Xu and Chun suggest that the inferior intraparietal sulcus represents the number of locations occupied by objects while the superior intraparietal sulcus and the lateral occipital complex encode the total amount of visual information.

2.4.3. *How is VWM limited: storage slots, resolution, or central executive?*

Why is VWM limited? At least two possibilities exist. First, VWM may be limited because central-executive limits prevent us from encoding more items into VWM. Second, VWM is limited in terms of the amount of information one can store. This storage limit can be revealed in one of two ways: as limited slots or limited resolution. When the storage information is capped at some level, adding more items can overflow in a limited-slot model, or it can result in each item being stored with low fidelity (in a limited-resolution model). These possibilities are not mutually exclusive, although different researchers have emphasized different aspects of the capacity limit.

2.4.3.1. Is VWM limited in storage space or in resolution?

Although no serious researcher would deny that resolution must be limited in VWM, many have endorsed a somewhat different conception of VWM's capacity limit—namely, that of limited slots in a metaphorical storage locker. There are historical reasons why slot models are so heavily preferred over the alterna-

tive conception of a “resolution limit”. Visual WM studies were preceded by many years of research on verbal WM, and the capacity limit of verbal WM was conceptualized in slot models: there are 7 plus or minus 2 chunks in verbal WM (Miller, 1956), with this magical number being modulated by an individual’s articulatory speed and the phonological word-length effect (Baddeley, 1986). Naturally, when researchers approach visual WM, the first question to ask is: how many slots does VWM contain?

The answer can sometimes be surprising. Using the change detection task, Pashler (1988) suggested that the capacity of VWM for upright letters was approximately four. He also found that the capacity was not significantly influenced by familiarity: upright letters did not result in a higher capacity than inverted letters. That the capacity of VWM was somewhat insensitive to familiarity was also confirmed in other studies using unnameable stimuli (Chen, Eng, & Jiang, 2006). As more studies were conducted, the magical number four started to emerge as the approximate capacity limit for a wide range of visual stimuli, including colors, line orientations, letters, and compound objects created by conjunction of colors and orientations (Cowan, 2001; Irwin & Andrews, 1996; Luck & Vogel, 1997). The magical number four is very attractive to researchers seeking for parsimony across cognitive domains. “Four” is also the upper limit of independent objects that one can individuate simultaneously (Pylyshyn & Storm, 1988), and “four” is the transition between a small, exact number system and a large, approximate number system in animals, human infants, and adults (Dehaene, 1997). Indeed, the fact that this number concerns coherent objects rather than features making up those objects strengthens the link between VWM and other cognitive processes. It is probably no coincidence that objects seem to be the operating units for selective attention, enumeration, multiple-object tracking, and VWM.

However, the model of VWM as limited in four slots is challenged on two grounds. First, “four” fails to characterize the capacity limit for many properties of objects. Complex attributes, such as the shapes of random polygons or faces of unfamiliar individuals, have a much lower capacity limit than simple properties such as color (Alvarez & Cavanagh, 2004; Olsson & Poom, 2005). This challenge, although significant, does not fundamentally shake the conception of VWM as limited in slots. It places constraints on how the slots are used up by different visual attributes, something researchers are currently debating (see section 1.4.1). The more damaging challenge to slot models is the idea that VWM is an amorphous space limited not by the number of slots but by how veridical the representation is (Wilken & Ma, 2004).

Data discussed so far—that change detection declines as the number of items to be remembered increases—can be explained by both the limited-slot view and the limited-resolution view, as long as the latter assumes that resolution declines with increasing memory load. Thus, memory for a red color may be relatively veridical at lower set sizes, such that a correct change detection can be made when red turns into purple. But as load increases, memory for the red color may be less veridical, such that it fails to detect the red turning into purple, but

the memory may be good enough to detect the red turning into green, a more dramatic change.

There are two major differences between the limited-slot and limited-resolution views: the source of performance limitation, and the fate of overflowing input. According to the limited-slot view, only four (or some other number of) objects can be encoded in VWM. Performance is thus limited by memory input load, and items overflowing the limited slots will not be retained in VWM. At high load, a random subset will be encoded in VWM and the rest will not be encoded. If the memorized subset is later tested, then performance should be perfect. But if the other subset is tested, then observers must make a random guess. This is essentially the assumption in Pashler's method of VWM capacity calculation (Pashler, 1988). The limited-resolution view makes very different assumptions about the source of performance limitation. In this view, all items are encoded in VWM to some degree, no matter how many are to be remembered. Memory load changes the veridicality of VWM. With a lower load, each item is represented with high fidelity, allowing a small change between the memory and the test stimuli to be detected. With a higher load, each item is represented with poorer fidelity, so correct detection requires a much bigger change signal between the memory and the test stimuli. The main source of performance limitation thus lies both at the level of memory input load (the higher the load, the lower the fidelity), and at the level of change detection output (the smaller the change signal, the lower the performance). In this view, there are no "overflowing" items: all items are retained in VWM to some degree. In addition, the decline in resolution across memory load is a gradual process. There is no cut-off of four, for example, below which the resolution is perfect and above which the resolution is very poor.

The limited-resolution view receives strong support from studies that systematically varied both memory load and size of the change signal between the original memory element and the testing stimulus (Jiang, Shim, & Makovski, 2008; Wilken & Ma, 2004). Consistent with the limited-resolution view, it takes a larger change signal for performance to reach a constant threshold as memory load increases. There is no evidence for a cut-off at four or another number for remembering color, orientation, spatial frequency, or face identity. If we use the standard method to calculate capacity (Pashler, 1988), we would get very different estimates of the capacity depending on the size of the change signal. The limited-slot view must either revise its assumptions or allow the number of slots to be resizable depending on testing conditions.

Despite greater empirical support for the limited-resolution view, what still dominates VWM researchers' conception is the limited-slot view. Stronger advocates and additional empirical data may be needed to reverse this trend.

2.4.3.2. *Is VWM limited in storage or in central-executive control?*

So far we have considered VWM as limited in storage capacity, either in terms of the number of slots or in terms of resolution. However, recent event-related <ok as added to define ERP?>

brain potential (ERP) studies by Vogel and colleagues have provided a new perspective, according to which the VWM capacity limitation is closely related to central-executive limits.

In Vogel's studies, colors or tilted lines served as memory items in a change detection task. These items were evenly displayed in the left and right hemifields, of which only one hemifield contained relevant memory items. At the beginning of each trial a cue signaled the relevant side for observers to remember. A sustained negative ERP signal during the change detection retention interval was found, and it was contralateral to the remembered hemifield. The ERP signal increased as VWM load increased and reached plateau when VWM capacity limit was reached. The increase in amplitude from 2 to 4 correlated with individual observers' memory capacity (Vogel & Machizawa, 2004), allowing Vogel and colleagues to use this ERP signal to probe VWM capacity limit.

This neurophysiological marker was used further to examine differences between groups of individuals who have high or low VWM capacity (Vogel, McCollough, & Machizawa, 2005). The relevant memory items (which varied in number as 2 or 4) were either presented alone, or intermixed with 2 irrelevant items that were distinguished from the relevant items by color (red vs. blue) or by locations (different visual quadrants). When the relevant memory items were presented without distractors, both low and high VWM capacity groups showed higher ERP signal as memory load increased from 2 to 4. Surprisingly, when the relevant memory items must be extracted from 2 other distractors, the ERP signal in the high-memory-capacity group reflected the number of relevant memory items, but the ERP signal in the low-memory-capacity group reflected the total number of items. These results show that high-capacity individuals are also efficient at filtering out unwanted information, but low-capacity individuals fail to protect VWM from being filled up with unwanted information. These results suggest that the capacity of VWM is closely related to an individual's ability to exclude irrelevant items from current tasks, an arguably important element of central-executive control. Vogel and colleagues' findings fit well with the Baddeley's working-memory model, where the central-executive process is important for VWM. Consistent with these findings, recent studies that added filled-delay tasks during change detection showed that amodal, central attention is a necessary component of change detection (Makovski et al., 2006). Models of VWM capacity that focus exclusively on storage limit are thus unlikely to be adequate.

To summarize, behavioral and cognitive neuroscience research in the past decade has significantly enhanced our understanding of factors that influence performance in a short-term change-detection task. However, this research has not unambiguously resolved several fundamental questions about VWM capacity, including whether VWM is limited by storage slots or by resolution, whether its storage space is limited by the complexity of to-be-remembered visual attributes, and whether the "magical number four" plays any role in VWM capacity limitation.

3. SHORT-TERM VERSUS LONG-TERM VISUAL MEMORY

Human memory is historically divided into short-term and long-term stores which are considered somewhat separable, at least when memory for verbal materials is considered (Atkinson & Shiffrin, 1968). Evidence for the separation includes (1) different effects on the serial position curve, (2) different types of encoding (phonological vs. semantic) (3) capacity (limited versus unlimited) (Miller, 1956; Nickerson & Adams, 1979), and (4) dissociation in neural correlates, where the hippocampus is considered critical for transforming short-term memory (STM) into long-term memory (LTM) (Scoville & Milner, 1957).

There is some evidence that visual STM and visual LTM may also be separable. Short-term memory for visual materials is highly limited in capacity, but long-term memory for visual stimuli has no clear capacity limit. After viewing 600 photographs of scenes and events, each for 2 s, subjects recognized 92% of images when tested one day later, and 63% of images when tested one year later (Nickerson, 1965; see also additional discussion in chapter 4, section 2.3). Such dramatic differences in capacity are vividly depicted in the titles of two widely cited articles, “Learning 10,000 Pictures” (Standing, 1973), and “The Magical Number 4 in Short-term Memory” (Cowan, 2001). However, increasing evidence has shown that the separation between visual STM and visual LTM may not be the most natural way to carve out visual memory systems.

The enormous capacity difference between visual STM and LTM may lead us to expect that if we can rely on visual LTM for a short-term change-detection task, performance would improve. Thus, if we have already acquired familiarity with a visual display, change detection on that display can be supported by visual LTM and STM. Such “dual coding” may help alleviate the degree of failure to detect changes. This proposal, however, has not stood the test of several studies. Wolfe, Oliva, Butcher, and Arsenio (2002) and Oliva, Wolfe, & Arsenio (2004) found that change detection failed to improve on displays repeated for hundreds of trials, as long as the object that might change varied from one trial to another. Thus, the ability to detect a change in your own living-room is probably not better than detecting a change in someone else’s living-room. Similarly, Olson and Jiang (2004) found that repeating the same exact memory display 30 times failed to improve change detection on those trials, even though subjects were able to recognize the repeated displays at the end of the experiment, suggesting that they acquired visual LTM for the displays. The only case in which visual LTM seemed to facilitate change detection was when the target that might change was always the same one on a repeated display. In this case, visual LTM informed observers which locations or objects were more important, allowing attention to be preferentially directed to that item (Olson, Jiang, & Moore, 2005).

The availability of visual LTM for scenes (Oliva et al., 2004), novel objects (Wolfe et al., 2002), and spatial locations (Olson & Jiang, 2004) does not contribute further to a short-term change-detection task. The dramatic, previously observed capacity difference between visual LTM and visual STM perhaps reflects not so much the qualitative differences between the two stores as differ-

ences in the visual system's efficiency at encoding details versus encoding gist. Previous short-term tasks usually required people to detect minute differences between two similar images, while long-term tasks usually required people to differentiate qualitatively different images. When placed within the same testing context where the size of the change signal is controlled for, dual-coding of an image in both visual LTM and visual STM does not provide any advantage over coding of the image only in visual STM. This is not to deny a role of past experience in current processing. As will be reviewed in subsequent sections, experience modifies the allocation of spatial attention (Chun & Jiang, 1998; Olson et al., 2005). To the degree that important regions in past experience coincide with the target region in the current task, visual LTM can enhance performance by prioritizing the retention of that region in visual STM. But it does not, in itself, contain any further information that cannot be extracted online. The 10,000 pictures remembered in visual LTM (Standing, 1973) are simply not held at the same level of precision as the 4 images remembered in visual STM (Cowan, 2001).

Undeniably, there is more information available in visual LTM than what can be currently accessed. This kind of "capacity difference", however, does not constitute a qualitative difference between memory systems. Both visual STM and LTM can support detection of changes to visual details and semantic gist (Brockmole & Henderson, 2005; Hollingworth, 2005), and both rely on similar brain regions (Ranganath & Blumenfeld, 2005). Even medial temporal lobe-damaged patients, traditionally considered normal with short-term memory, have difficulty retaining information in visual STM (Olson, Page, Moore, Chatterjee, & Verfaellie, 2006). Together, these studies suggest that it is time to seek an alternative taxonomy for human visual memory, one that separates memory for gist versus details rather than memory in the long-term versus short-term.

4. EFFECTS OF VISUAL MEMORY ON SEARCH

Although we do not usually think of visual search as a memory task, several lines of research suggest that memory is accumulated from visual search tasks and is used to affect future search processes. Examples of memory influence on search include trial-sequence effects, contextual cueing, the preview effect, online search memory, and guidance from visual working memory. These different paradigms likely result from different mechanisms. We consider them separately here.

4.1. Trial-sequence effects

It has been known for decades that visual perception is strongly influenced by trial-sequence effects. For example, if the current trial's target happens to be the same as the preceding trial's target, response is facilitated, showing positive priming (Schacter & Buckner, 1998). Conversely, if the current trial's target

happens to be the same as the preceding trial's distractor, response is delayed, showing negative priming (Neill, 1977; Tipper, 1985). These priming effects are usually stronger in the short-term and without intermittent trials. Additionally, they may be difficult to detect after 30 s or so, perhaps because new memory is formed from the intermittent trials, rendering the old memory less useful. However, intertrial priming effects can last for days or years and can survive the interference from hundreds of intermittent trials (DeSchepper & Treisman, 1996).

An example of an intertrial sequence effect is the “priming-of-popout”, initially described by Maljkovic and Nakayama (1994, 1996; see also Kristjánsson & Nakayama, 2003). Maljkovic and Nakayama used a popout search task where subjects reported the shape of a red item among green items, or vice versa. The target on a given trial can either be red or green, so it was defined by a singleton rather than by particular feature values. Nonetheless, if the target was red on trial N and happened to be red again on trial $N + 1$, performance was faster than if the target color on trial $N + 1$ did not match that of trial N . This kind of priming occurred not only for target color but also for target location, even when neither was the target-defining feature. By varying the lag between repetitions, Maljkovic and Nakayama (1994) found that the priming effect decayed over time but was observable for up to 30 s. Interestingly, observers were generally unaware of the intertrial priming effect shown in this paradigm, distinguishing this kind of memory from visual working memory. The cross-trial priming effect has been extended to conjunction search tasks (Geyer, Muller, & Krummenacher, 2006; Kristjánsson, Wang, & Nakayama, 2002) and reflects both bottom-up and top-down biases toward repeated target properties (Hillstrom, 2000).

4.2. Contextual cueing

Humans process a visual display more quickly the second time it is presented. This kind of repetition effect has been systematically explored in a paradigm dubbed “contextual cueing” by Chun and Jiang (1998). Observers were asked to perform a standard visual search task for a letter T among Ls. Unknown to them, some of the search trials repeated occasionally in the experiment, such that over the course of an hour, observers had seen several hundred novel displays and a few repeated displays. Because the repetition was not immediate and was dispersed among many nonrepeating trials, observers typically were unaware of the repetition and could not recognize the repeated displays (Chun & Jiang, 1998, 2003). Even so, visual search speed on repeated displays became progressively faster than on nonrepeated displays (Figure 2.5). This facilitation was not simply due to learning of potential target locations (Miller, 1988), as Chun and Jiang controlled for the repetition of target locations for repeating and nonrepeating trials (i.e., the target locations were repeated on nonrepeating trials but the distractor locations were not). It was also not due to motor priming (Nissen & Bullemer, 1987), as the identity of the target was randomly assigned so the repeated displays were not associated with repeated motor responses. In addi-

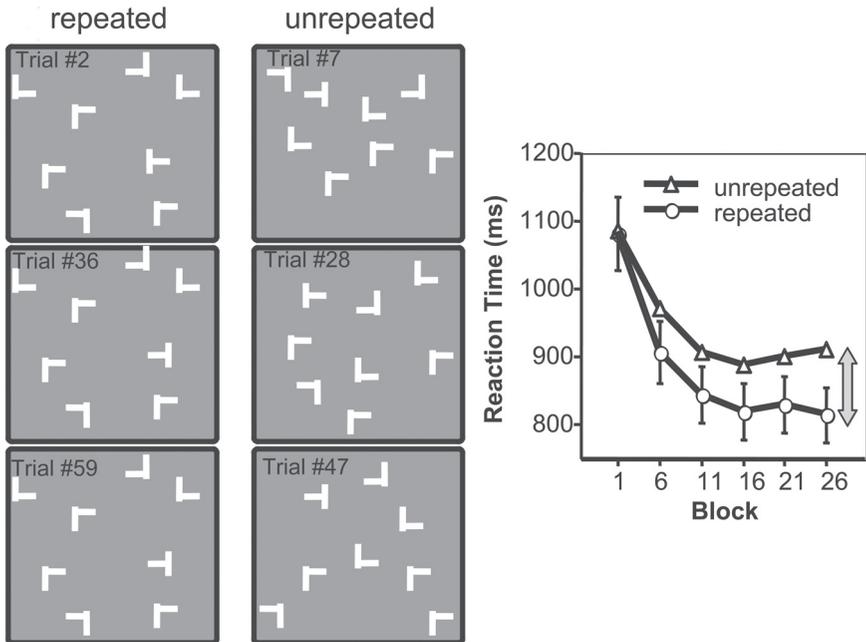


Figure 2.5. A schematic illustration of the contextual cueing paradigm and typical experimental results.

tion, the facilitation was not produced by perceptual familiarity with the entire configuration of a repeated trial, as the benefit was eliminated if all locations were repeated but the target's location was randomly swapped with distractors' locations (Chun & Jiang, 1998; Jiang, King, Shim, & Vickery, 2006; Wolfe, Klempe, & Dahlen, 2000). The improvement in RT observed in this paradigm thus reflects an implicit, associative learning mechanism, where the display configuration is associatively learned with the target location. When a repetition is detected, visual attention can be quickly directed to the associated target location, allowing search to be completed on the basis of "instance" memory (Logan, 1988). The benefit has been known as "contextual cueing", as if the search context surrounding the target is cuing attention toward the target's location (but see Kunar, Flusberg, Horowitz, & Wolfe, 2007, reviewed next).

What makes contextual cueing so intriguing as a form of visual memory is that although its content lacks semantic gist, it is very powerful and has high capacity. Because all displays are created essentially by random placement of T and Ls on the screen, they are visually similar and cannot be distinguished by semantic gist. Indeed, putting a natural scene in the background, such that the target location is consistently paired with a particular scene, usually results in explicit learning of the association (Brockmole & Henderson, 2006a; Jiang et al.,

2006). In the absence of semantic gist, learning is usually implicit and operates on completely abstract and homogeneous visual displays. It is thus surprising to see how robust contextual cueing is to various kinds of stressors. Observers have no difficulty learning 60 repeated displays among 1,800 novel displays, spread over 5 different search sessions, and learning from one day did not result in proactive or retroactive interference on learning from another day (Jiang, Song, & Rigas, 2005). Once acquired, memory for repeated displays lasts for at least 1 week, in that search remained faster on previously learned displays than on new ones (Chun & Jiang, 2003; Jiang et al., 2005). Simultaneously loading VWM up with colors, locations, or potential search targets does not at all impair learning (Vickery, Sussman, & Jiang, 2006). Even selectively tuning attention away from repeated elements does not eliminate learning (Jiang & Leung, 2005; Rausei, Makovski, & Jiang, 2007). Finally, learning transferred to displays that did not exactly match the original trained displays (Brady & Chun, 2007; Jiang & Wagner, 2004; Olson & Chun, 2001), and in some cases, a repetition of just 3 locations was sufficient for transfer (Song & Jiang, 2005). Contextual cueing is such a powerful effect that, at this point, conditions that lead to no learning (Jiang & Chun, 2001; Ono, Jiang, & Kawahara, 2005) seem more informative than conditions that result in learning!

The exact mechanism that leads to facilitation of search speed, however, remains controversial. The dominant view is an attentional guidance view, according to which repeated context guides attention to the target location. This memory-based search can be faster than the default, perception-based serial search. A simple prediction from the attentional guidance view is that contextual cueing should be stronger for visual search involving a larger number of elements, because the memory-based search will likely win more often if the default, serial search takes longer (as is the case on large set-size displays). However, repeated attempts to find an increase in cueing effect for larger set sizes have failed (Kunar et al., 2007). This led Kunar et al. to propose an alternative account, according to which search itself always proceeds via the default, perception-based serial search, even on repeated displays. Once the target is located, however, observers are faster at making a response on repeated trials, perhaps because they are more confident that the target is in that position.

Although the lack of modulation by set size is perplexing, it is not as damaging to the attentional guidance view as one might think. The prediction that cueing should be greater at higher set sizes rests on several assumptions, some of which are known to be false. One assumption is that the resultant memory trace is as strong on high set-size displays as on low set-size displays. But this may not be true. Indeed, Hodsoll and Humphreys (2005) found that contextual cueing was weaker for set size 20 than for set size 10, suggesting that the memory trace may be weaker at higher set sizes, perhaps because different displays become less distinctive as set size increases. In addition, many studies have shown that learning in the search task is local and that observers seem to rely on the nearest items to help search. If observers always learn to associate with the target the nearest four items (Brady & Chun, 2007; Olson & Chun, 2001), then learning will not

be modulated by how many other elements are on the display. The idea that contextual cueing reflects only response-stage learning is also inconsistent with eye-tracking studies. Using real-world scenes as the learning context, Brockmole and Henderson (2006b) found that fewer eye movements were required to find the target on repeated displays, with direct orienting of gaze to the target once learning is complete. Thus, repeated search context can guide attention, at least when the context involves real-world scenes.

Regardless of whether one endorses the attentional guidance view or a response bias view, it is clear that research on visual context learning has gone beyond demonstrating that humans are capable of various types of statistical learning under various conditions.

Research on this topic, however, faces significant challenges. Despite the robustness of contextual cueing to many stressors, researchers have not yet sorted out all factors that modulate the size of the learning. As a result, one cannot always predict whether contextual cueing will be reliably found in a given situation. Indeed, contextual cueing is sometimes not found even, though a priori one may expect a learning effect. For example, Junge, Scholl, and Chun (2007) found that contextual cueing was absent if observers first searched through all nonrepeating displays and then were introduced to some repeating displays. It was as if the initial phase of no-repetition tuned the system out of a repetition detection mode. Lleras and Von Muhlenen (2004) found that cueing was seen only when observers were told to adopt a more passive strategy for search; if observers were told to devote an active effort to find the target, contextual cueing was not found. Hodson and Humphreys (2005) obtained a very weak contextual cueing effect when the display contained 20 elements, even though there was no a priori reason why cueing would not occur there. The quirks of visual implicit learning remain to be fully sorted out.

4.3. Preview effect

Watson and Humphreys (1997) systematically explored a preview effect in visual search first reported by Kahneman, Treisman, and Burkell (1983). Instead of presenting all items simultaneously for observers to search, Watson and Humphreys (1997) presented a subset of the distractor first for about 1 second before adding the remaining distractors and the target. They found that previewing the distractors and keeping them on the search display resulted in efficient rejection of the previewed items. The preview effect was initially given the term of “visual marking,” reflecting the hypothesis that previewed items were “marked” or inhibited from future search.

The inhibition account was challenged by alternative views that placed more emphasis on the new, rather than the previewed, items (Donk & Theeuwes, 2001b, 2003; Jiang, Chun, & Marks, 2002). Donk and Theeuwes (2001b), for example, proposed that the preview effect simply reflected capture of attention by the abrupt onset of the newly added items. They showed that if the new items were isoluminant with the background and thus providing no abrupt onset,

then the preview effect was much reduced or eliminated. However, more recent research by Humphreys and colleagues provide strong evidence for the existence of an active inhibition process for the previewed items (Braithwaite, Hulleman, Watson, & Humphreys, 2006; Braithwaite, Humphreys, Watson, & Hulleman, 2005; Kunar & Humphreys, 2006; Kunar, Humphreys, Smith, & Hulleman, 2003). It is fair to say that both inhibition and attentional capture contribute to the preview effect initially reported by Watson and Humphreys (1997) and Kahneman et al. (1983).

To be able to eliminate the previewed items from search, some kind of visual memory must be involved because the previewed items and new distractors are indistinguishable at the time when all items are presented. There are several candidates for this memory, including visual memory for the locations of the previewed items, visual memory for the locations of the new items, and visual memory for different temporal onsets of the two groups. A systematic exploration on this topic showed that the memory needed for the preview effect came primarily from the latter two sources, where observers held in visual memory the locations of the new items and the differential temporal onset between the two groups (Jiang & Wang, 2004). Inhibition of the old group and abrupt onset of the new group may contribute to the representation of different temporal groups and are thus part of visual memory used for the preview effect.

4.4. Online search memory

In many visual search tasks, serial (or partially serial) allocation of attention is needed. In this process, attention moves from one location to another or from one cluster to another. An online search memory about already visited locations is important, as an efficient serial search avoids visiting the same location multiple times. Several studies have provided evidence for the existence of a within-trial, online search memory. They compared visual search through unchanging displays and changing displays on which the target and distractors are relocated randomly every 100 ms or so. Despite earlier observations suggesting the opposite (Horowitz & Wolfe, 1998), later studies show that search is significantly disrupted in the relocation condition (Gibson, Li, Skow, Brown, & Cooke, 2000; Kristjánsson, 2000; Takeda, 2004), suggesting that previously visited locations are retained in memory for that search trial.

This kind of online search memory is quite durable but is not robust against disruption. If a search trial is interrupted by a blank interval before search is complete, observers can resume their search after the interval without any difficulty. Thus, performance on a continuous trial without blank interruption is comparable to performance on a paused trial with many blank interruptions (Shen & Jiang, 2006), even when the blank interval lasted for 6 s or more. The online search memory is also robust against interference from passively viewing additional visual displays. However, filling in the blank interval with other spatial tasks, such as additional search on a new display or an additional visual working-memory task, significantly disrupted the search memory accumulated

before the interruption. The online search memory may reflect both inhibition of return to already visited locations (Klein, 1988), and observers' deliberate intention not to revisit already searched locations.

4.5. Attentional guidance by contents in VWM

Although visual working memory and visual attention are characterized by two different terms, they are intimately related processes (see, e.g., Olivers, Meijer, & Theeuwes, 2006). Holding additional information in verbal or visual working memory significantly interferes with visual search performance (de Fockert, Rees, Frith, & Lavie, 2001; Woodman & Luck, 2004). In addition, the content of spatial and nonspatial working memory directly interacts with the allocation of attention to corresponding locations and features. For example, Awh, Jonides, and Reuter-Lorenz (1998) showed that shape discrimination of the target was facilitated when a target happened to land at a location held in VWM. Downing (2000) found that when observers held an object shape in VWM and subsequently performed a discrimination task on two other items, one of which matched the shape in VWM, discrimination was faster on the matched object than on the novel object. The content of VWM can facilitate not only overall response speed, but also the slope of the RT–set-size function. For example, Soto, Heinke, Humphreys and Blanco (2005) found that search efficiency was enhanced when the target was surrounded by an item matching what was currently in VWM (for a similar effect in a popout search task, see also Soto, Humphreys, & Heinke, 2006). Items that were recently viewed but not actively stored in VWM did not influence subsequent visual search, suggesting that active use of VWM was the primary source for facilitation of search.

The guidance of visual search by the content of VWM is consistent with several models of visual search, such as the Feature Integration Theory (Treisman, 1988), the Guided Model (Wolfe, 1994), and the Biased Competition Model (Desimone & Duncan, 1995). Visual working memory serves to exert top-down bias on the weighting of relevant target properties, facilitating visual search for those properties (Vickery et al., 2005).

The content of VWM, however, does not automatically bias visual search toward items matching VWM's content. If an item in VWM was never the target of search, search was not biased toward that item (Woodman & Luck, 2007). An active attentional set at using VWM content for search seems a necessary condition for their interaction, suggesting that the cognitive system is flexible at using VWM in current search.

<does this read correctly, or is something missing?>

5. CONCLUDING REMARKS

In an influential paper, O'Regan (1992) argued that visual memory never needs to be developed to an exquisite level because the external visual world is a proxy for internal representation. If we need to know what object is where, we can sim-

ply open our eyes and look! Indeed, studies by Hayhoe and colleagues (e.g., Ballard, Hayhoe, & Pelz, 1995; Droll & Hayhoe, 2007; Droll et al., 2005; Triesch, Ballard, Hayhoe, & Sullivan, 2003) showed that observers prefer to look back at an object they looked at previously to extract additional perceptual properties about it rather than pushing all properties into VWM once and for all. Certainly, visual memory lacks the kind of details and richness provided by visual perception, and this lack of richness contributes to the surprisingly inefficient coding of detailed changes across cuts of visual scenes or social interactions (Levin & Simons, 1997; Simons & Chabris, 1999; Simons & Rensink, 2005). While we agree that visual memory cannot be used to substitute for visual perception, we have reviewed evidence that visual perception is constantly aided by visual memory, and visual memory is constantly accumulated from visual perception. Visual memory allows us to maintain spatiotemporal continuity in this constantly changing environment. It enables us to visualize without actually seeing, and it helps us see things we already experienced more efficiently.

6. ACKNOWLEDGMENTS

The authors were supported by funding from NIH MH071788, NSF 0733764, and ARO 46926-LS. We thank Kristine Liu for comments and suggestions. Correspondence should be sent to Yuhong Jiang, 75 East River Road, S251 Elliott Hall, Minneapolis, MN 55455. Email: jiang166@umn.edu.

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