

Journal of Experimental Psychology: Human Perception and Performance

Location-Specific Effects of Attention During Visual Short-Term Memory Maintenance

Michi Matsukura, Joshua D. Cosman, Zachary J. J. Roper, Daniel B. Vatterott, and Shaun P. Vecera

Online First Publication, March 24, 2014. <http://dx.doi.org/10.1037/a0035685>

CITATION

Matsukura, M., Cosman, J. D., Roper, Z. J. J., Vatterott, D. B., & Vecera, S. P. (2014, March 24). Location-Specific Effects of Attention During Visual Short-Term Memory Maintenance. *Journal of Experimental Psychology: Human Perception and Performance*. Advance online publication. <http://dx.doi.org/10.1037/a0035685>

Location-Specific Effects of Attention During Visual Short-Term Memory Maintenance

Michi Matsukura
University of Iowa

Joshua D. Cosman
Vanderbilt University

Zachary J. J. Roper, Daniel B. Vatterott, and Shaun P. Vecera
University of Iowa

Recent neuroimaging studies suggest that early sensory areas such as area V1 are recruited to actively maintain a selected feature of the item held in visual short-term memory (VSTM). These findings raise the possibility that visual attention operates in similar manners across perceptual and memory representations to a certain extent, despite memory-level and perception-level selections are functionally dissociable. If VSTM operates by retaining “reasonable copies” of scenes constructed during sensory processing (Serences et al., 2009, p. 207, the sensory recruitment hypothesis), then it is possible that selective attention can be guided by both exogenous (peripheral) and endogenous (central) cues during VSTM maintenance. Yet, the results from the previous studies that examined this issue are inconsistent. In the present study, we investigated whether attention can be directed to a specific item’s location represented in VSTM with the exogenous cue in a well-controlled setting. The results from the four experiments suggest that, as observed with the endogenous cue, the exogenous cue can efficiently guide selective attention during VSTM maintenance. The finding is not only consistent with the sensory recruitment hypothesis but also validates the legitimacy of the exogenous cue use in past and future studies.

Keywords: visual attention, visual short-term/working memory, retention-interval cueing, exogenous cue, peripheral cue

Recent neuroimaging studies (e.g., Albers, Kok, Toni, Dijkerman, & de Lange, 2013; Christophel, Hebart, & Haynes, 2012; Ester, Anderson, Serences, & Awh, 2013; Harrison & Tong, 2009; Serences, Ester, Vogel, & Awh, 2009) suggest that early sensory areas, such as area V1 (primary visual cortex), are recruited to actively maintain a selected object feature in visual short-term memory

(VSTM).¹ Similarly, a work by Munneke, Belopolsky, and Theeuwes (2012) suggests that those early sensory areas are engaged as observers shifted their attention among multiple spatial locations represented in VSTM. These findings raise the possibility that visual attention operates in similar manners across observers’ perceptual and memory representations to a certain extent, even though selections within each of these representations are functionally dissociable (e.g., Hollingworth & Maxcey-Richard, 2013).

For instance, if memory representations in V1 are supported by the same neural mechanisms that encode the sensory information (i.e., the *sensory recruitment* hypothesis, e.g., Awh & Jonides, 2001; Serences et al., 2009), then it is possible that both exogenous (peripheral) and endogenous (central) cues can be utilized to control selective attention during VSTM maintenance. Despite different modes of orienting (e.g., Jonides, 1981; Posner & Cohen, 1984), the visual system can utilize both exogenous and endogenous cues to direct attention to a particular location during sensory processing (see Yantis, 2000, for a review). Yet, the results from the previous studies that investigated the exogenous cueing benefit during VSTM maintenance are inconsistent (Berryhill, Richmond, Shay, & Olson, 2012; Makovski & Jiang, 2007; Murray, Nobre, Clark, Carvo, & Stokes, 2013; Pertzov, Bays, Joseph, & Husain, 2013; Shimi, Nobre, Astle, & Scerif, in press; Sligte, Scholte, & Lamme, 2008). The goal of the present study was to examine whether attention can be directed

Michi Matsukura, Department of Psychology, University of Iowa; Joshua D. Cosman, Department of Psychology and Vanderbilt Vision Research Center, Vanderbilt University; Zachary J. J. Roper, Daniel B. Vatterott, and Shaun P. Vecera, Department of Psychology, University of Iowa.

This research was made possible in part by a National Science Foundation award (BCS 11–51209) to S.P.V. Portions of this research were presented at the 53rd Annual Meeting of the Psychonomic Society, Minneapolis, Minnesota, November 2012. We thank Kimberly Lane and Xin Yu for assistance with data collection, as well as Susanne Ferber and the two anonymous reviewers for their comments. M.M. conceptualized and designed the study. Programming, data collection and analyses were carried out by M.M. J.D.C., Z.J.J.R., and D.B.V. provided programming advice for selected experiments. M.M. wrote a draft of the manuscript, J.D.C., D.B.V., Z.J.J.R. and S.P.V. subsequently provided revision comments.

Correspondence concerning this article should be addressed to Michi Matsukura, Department of Psychology, 11 Seashore Hall E, University of Iowa, IA City, IA 52242. E-mail: michi-matsukura@uiowa.edu

¹ We consider VSTM and visual working memory (VWM) as the same set of processes.

to a specific item's location represented in VSTM with the exogenous cue.

Of course, by hypothesizing that the exogenous (peripheral) cue can be used to control selective attention during VSTM maintenance, we do not mean that the cue appearing at the exact same perceptual location with the cued item represented in VSTM (e.g., Figure 1) unpredictably draws an observer's attention on the account of its abruptness or saliency. In fact, every attention-directing cue used in the present study was presented long after iconic images of to-be-remembered items had faded away, and a single test item appeared, again, long after an icon of the cue had disappeared (beyond the iconic memory range; Irwin & Yeomans, 1986; Sperling, 1960). Moreover, every valid cue correctly predicted the to-be-tested item's location (50% cue validity), and the observers were instructed to take advantage of the information provided by this cue. Indeed, such a cue is likely to control selective attention in a goal-directed fashion (Shimi et al., in press). Accordingly, in the present study, the term "exogenous/peripheral" is used to denote a specific location that the cue appears during VSTM retention (in relation to the endogenous/central cue), but not to suggest that such a cue unpredictably attracts the observer's attention by virtue of its abruptness or saliency (as observed during sensory processing, with the cue validity below 50%, e.g., Jonides, 1981). We will return to this issue in General Discussion.

The Retention-Interval Cueing Effects

Since Griffin and Nobre (2003) reported that attention can select a visual item already stored in VSTM (even after iconic images of to-be-remembered items faded away, but see Averbach & Coriell, 1961; Sperling, 1960), a number of studies replicated the retention-interval cueing effects (e.g., Astle, Summerfield, Griffin, & Nobre, 2012; Berryhill et al., 2012; Hollingworth & Maxcey-Richard, 2013; Makovski, 2012; Makovski & Jiang, 2007; Makovski, Sussman, & Jiang, 2008; Matsukura & Hollingworth, 2011; Matsukura, Luck, & Vecera, 2007; Munneke et al., 2012; Murray et al., 2013; Rerko & Oberauer, 2013; Shimi et al., in press; Tanoue & Berryhill, 2012; Williams & Woodman, 2012; see Maxcey-Richard & Hollingworth, 2013, for use of the auditory cue; see Hollingworth & Hwang, 2013; Pertzov et al., 2013; Williams, Hong, Kang, Carlisle, & Woodman, 2013, for replications with nonbinary, continuous measures; see Landman, Sperkrijse, & Lamme, 2003; Pinto, Sligte, Shapiro, & Lamme, 2013; Sligte et al., 2008, for replications with all validly cued trials).²

Both retention-interval cueing benefit and cost are measured by presenting an attention-directing cue during the delay of a change-detection trial (similar to Figure 1, see Luck & Vogel, 1997; Vogel, Woodman, & Luck, 2001, for the original change-detection paradigm without any cueing manipulation). In a typical color change-detection task used in the area of retention-interval cueing research, observers are shown a memory array that contains a set of colors and a subsequent test array that contains a single test probe, separated by a brief delay interval. During this delay period, a cue appearing at 500 ms or longer after the memory array offset (i.e., beyond the iconic memory range) either correctly or incorrectly predicts the to-be-tested item's location for a certain percentage of trials. The observers' task is to report whether a single test probe had the same or different color from the item presented at the corresponding location in the memory array. For the cueing ben-

efit, the observers typically recognize validly cued items more accurately compared to neutrally cued items. For the cueing cost, the observers tend to recognize invalidly cued items less accurately compared to neutrally cued items.

Given there is no perceptual representation for attention to enhance or encode into VSTM at the time of the cue presentation, Matsukura et al. (2007) subsequently demonstrated that the retention-interval cueing effects are generated by a selective attention mechanism that protects the cued item from memory-related degradation processes, such as passive decay, possible interference by other uncued items stored in VSTM, or some other kind of degradation (see Astle et al., 2012; Griffin & Nobre, 2003; Pertzov et al., 2013, for similar interpretations with the cueing cost). This protection account was originally contrasted with the prioritization account, which suggests that the role of attention during VSTM maintenance is to merely facilitate the comparison process that occurs when memory is tested (see Landman et al., 2003, for the results consistent with this account). That is, when attention is directed to a particular item in VSTM, the cued item is given the priority to be compared with the test probe first, before this comparison moves onto other uncued items.

While other studies proposed that orienting attention to an item maintained in VSTM makes the cued representation more resistant to perceptual interference generated by the test probe presentation (e.g., Landman et al., 2003; Makovski & Jiang, 2007; Makovski et al., 2008; see Murray et al., 2013, for a similar interpretation of the cued item's representation, p.552), the results from a recent electrophysiological study (Williams & Woodman, 2012) suggest that the protection mechanism operates during VSTM maintenance itself (i.e., consistent with Matsukura et al., 2007). The contralateral delay activity (CDA) component of the event-related potentials (ERPs) is a lateralized marker of VSTM maintenance to measure the retention of task-relevant information (Vogel & Machizawa, 2004). Using this CDA component, Williams and Woodman showed that maintenance activity of the task-relevant information was reduced as soon as attention was oriented to the cued set of items (approximately 100 ms after the cue offset). These CDA modulations suggest that the mechanism that protects the cued memory representation from decay or interference "kicks in" immediately after the cue is presented, rather than waiting until the test probe presentation.³

Moreover, the three recent studies consistently showed the increased retention probability of the cued item relative to uncued

² These example references are limited to spatial cueing effects. For object-based cueing effects during VSTM maintenance, see Awh, Dhaliwal, Christensen, and Matsukura (2001), Matsukura and Vecera (2009, 2011), Hollingworth and Maxcey-Richard (2013, Experiment 3), Pertzov et al. (2013, Experiment Version B), and Woodman and Vecera (2011). For the category-based cueing effect, see Lepsien and Nobre (2007) and Lepsien, Thornton, and Nobre (2011).

³ However, given their retention-interval cue was presented at 250 ms from the memory array offset (well within the range of iconic memory), whether or not the reported effects purely reflect the selection mechanism during VSTM maintenance alone should be carefully interpreted. Because it takes at least 500 ms for information persistence to disappear (e.g., Irwin & Yeomans, 1986; Sperling, 1960), the reported effects may reflect the iconic-memory-level selection to some extent.

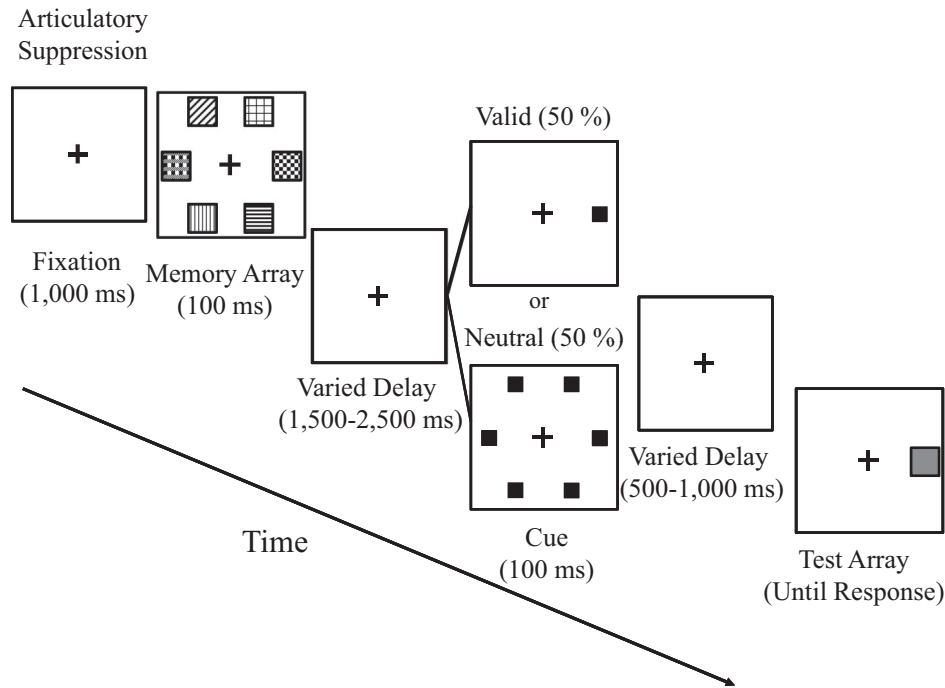


Figure 1. Trial event sequence of Experiment 1 (set size 6, different-color trial). Note that, for illustrative purpose, the stimuli are drawn much larger than they appeared in the actual computer display. Different fill patterns are used to represent different colors. The fixation and square dot cues were presented in white on a gray background.

items (Hollingworth & Hwang, 2013; Williams et al., 2013; the results of Murray et al., 2013) but failed to observe any increase in the cued item's precision (but see Williams et al., 2013).⁴ These findings further support the idea that the retention-interval cueing benefit is produced by preferential retention of the cued item relative to other uncued items within the limited VSTM capacity, without changing the quality of VSTM (Matsukura & Hollingworth, 2011, but see Sligte et al., 2008, for the account that use of the retention-interval cue allows the observers to access a high-capacity stage of VSTM).

The Present Study

As briefly reviewed so far, the overwhelming consensus is that attention can select the item already stored in VSTM. Of deserving a special notice, however, the most of these earlier retention-interval cueing studies were conducted by using some form of the endogenous cue, such as an arrow or word presented at the center of the computer screen. Because of interruption masking concerns, use of the cue that appears at the exact same perceptual location with the cued item represented in VSTM has been discouraged in general.

While the exogenous (peripheral) cue use was seen with some reservations, the results from recent neuroimaging studies suggest that VSTM operates by retaining "reasonable copies" of scenes constructed during sensory processing (Serences et al., 2009, p. 207). If VSTM operations are subserved by the same neural mechanisms that encode the sensory information, then visual attention may operate in similar manners across observers' percep-

tual and memory representations to a certain extent. One such possibility is that, provided that there is no methodological artifacts associated with the retention-interval cueing paradigm (i.e., interruption masking, eye movements), attention can be efficiently guided by the exogenous cue during VSTM maintenance. Interestingly, in pursuit of other theoretical questions, a handful of recent studies (Makovski & Jiang, 2007; Murray et al., 2013; Pertzov et al., 2013; Shimi et al., in press; Sligte et al., 2008) started using the exogenous cue with the change-detection task and demonstrated significant cueing effects (all with the cue validity above 50%). Yet, a particular study conducted by Berryhill et al. (2012) suggests otherwise; failure to observe a significant retention-interval cueing benefit with the exogenous cue led them to argue that attention cannot be directed to a specific item's location stored in VSTM with the exogenous cue.

⁴ See Hollingworth and Hwang (2013) and Williams et al. (2013) for the debate regarding whether or not the cued item's precision is modulated "within the typical VSTM capacity." While Williams et al. found a precision increase of a single cued item in comparison to one of two uncued items (equivalent to no-cue trials), Hollingworth and Hwang reported no precision difference between the validly cued and invalidly cued items. Also note that, while Murray et al.'s (2013) results are consistent with Hollingworth and Hwang and Williams et al., they interpret the increased retention probability of the cued item as evidence that attention transforms the cued item's representation into "a more robust representation to enable comparison with the memory probe" (p. 552) along with Makovski and Jiang (2007), Makovski et al. (2008), and Sligte et al. (2008). Here, leaving such an interpretation aside, we refer to the pattern of the data consistent with Hollingworth and Hwang and Williams et al.

Given all the other studies mentioned above have shown significant cueing effects, it is tempting to conclude that the results of Berryhill et al. (2012) reflect a mere failure to replicate the exogenous cueing benefit and move on. However, the current status of the retention-interval cueing literature suggests that it is premature to conclude so. This is because all these studies mentioned above presented the exogenous cue for validly cued trials alone (except Sligte et al., 2008, whose cues were valid on all trials). That is, change-detection performance accuracy of exogenous valid cue trials was compared with accuracy of neutrally cued trials with a single endogenous (central) cue that appears at the center of the computer screen (Murray et al., 2013; Shimi et al., in press) or equivalent no-cue trials (the fixation cross at the center of the computer screen in Pertzov et al., 2013; no fixation cross after the initial 500 ms of the trial in Makovski & Jiang, 2007). Despite lack of sensory benefit brought by the bona fide exogenous cue (such as the one observed during perceptual processing, with the cue validity lower than 50%), such an experimental design might have allowed the observers to shift between two different degrees of the goal-directed selection of attention. Specifically, unlike the endogenous cue, the exogenous cue appears at the exact same perceptual location with the cued item represented in VSTM; while the exogenous valid cue enables the observers to bypass the steps of interpreting the meaning of the cue before orienting attention to a specific location represented in VSTM, the endogenous neutral cue still requires the observers to interpret the meaning of the cue. Given such a difference, at present, whether the observers can successfully use the exogenous cue in comparison to the analogous (equivalent) exogenous neutral cue condition remains unknown. The observed difference in change-detection performance accuracy between exogenous valid cue trials and endogenous neutral cue trials in the existing studies might have been exaggerated because the observers were required to switch between the exogenous valid cue trials and the endogenous neutral cue trials.

To resolve such an ambiguity, in the present study, neutrally cued trials were designed to diffuse attention across all items represented in VSTM without requiring the observers to interpret the meaning of the cue. The neutral cue was a set of dots that appeared at each of memory-array items' locations (Figure 1). In addition, we used only valid and neutral cues as invalid cues do not readily distinguish the different effects of attention. Particularly, we cannot distinguish whether the cueing cost is generated through the active use of the valid cue (as a researcher usually intends) or the observers intentionally forget the uncued items due to the demand characteristics of the experiment. We also made validly cued and neutrally cued trials equiprobable to increase statistical power (e.g., Matsukura & Hollingworth, 2011; Matsukura et al., 2007).

Upon linking the observers' ability to utilize the exogenous cue during VSTM maintenance to the sensory recruitment hypothesis, we should acknowledge an important property of selective attention that operates during VSTM maintenance. In the present study, we do not assume that selective attention that operates within VSTM representations (memory-level attention) shares a common *functional* mechanism with selective attention that operates during sensory processing (perception-level attention). While some studies (Hollingworth & Maxcey-Richard, 2013; Maxcey-Richard & Hollingworth, 2013) characterized that Matsukura et al. (2007) assumed that perception-level attention is sustained through the

VSTM maintenance, Matsukura et al. explicitly stated that different selection mechanisms are assumed to be involved when the observers perform the memory-level attention task (e.g., color change detection with the retention-interval cueing manipulation) and the perception-level attention task (e.g., spatial precueing task, p. 1430). Although memory-level and perception-level selection mechanisms are functionally dissociable, a common set of attentional control mechanisms can still be used across many different types of attention tasks (e.g., Experiment 5 in Matsukura et al., 2007; Wojciulik & Kanwisher, 1999). Therefore, the anticipated results that memory-level attention can be guided by the exogenous cue (thus, shares some similarities with perception-level attention) do not necessarily refute a functional dissociation between memory-level and perception-level selections.

To preview our results, consistent with the sensory recruitment hypothesis, the observers were able to direct attention to a specific item's location represented in VSTM with the exogenous cue. Significant exogenous cueing benefits were observed near and above the typical VSTM capacity of 3–4 items, and these benefits cannot be attributed to interruption masking or corrective eye movements that are more likely to occur in neutrally cued trials. These results strongly suggest that lack of the exogenous cueing benefit reported by Berryhill et al. (2012) should not be interpreted as a quintessential feature of memory-level attention.

Experiment 1

The goal of Experiment 1 was to examine whether the observers are able to direct attention to a specific item's location represented in VSTM with the exogenous cue in a well-controlled setting. We first examined the retention-interval cueing benefits across memory-array set sizes 4 and 6 with the between-subjects design (Experiment 1A), and then replicated the same pattern of results with the within-subjects design (Experiment 1B). The set-size manipulation was included to ensure that our conclusion regarding the exogenous cueing benefit during VSTM maintenance would generalize "near and above" the VSTM capacity, as observed with the endogenous cue (Matsukura et al., 2007). For attention to be maximally utilized to select the cued item from VSTM, the set size of the to-be-remembered items should exceed the typical VSTM capacity (see the view of process-oriented attention in Luck & Vecera, 2002).

One of the major challenges with any retention-interval cueing experiment is to include enough number of trials per condition within a single experimental session without tiring the observers (e.g., see a sudden drop of change-detection accuracy in the experimental session that exceeds 60 min in Matsukura & Hollingworth, 2011). The longer length of each trial relative to a typical change-detection or perception-level attention task (e.g., spatial cueing, visual search) makes it difficult to have a reasonable number of trials that are necessary to make any inference regarding the cueing benefit, especially with the within-subjects factor of set size. To circumvent this problem, we first demonstrated significant cueing benefits across set sizes 4 and 6 in separate groups of the observers in Experiment 1A. To anticipate the results, significant cueing benefits were observed for both set sizes 4 and 6. Next, to rule out the possibility that the observed pattern of the results in Experiment 1A was driven by the between-subjects variability, we replicated the same experiment with the

within-subjects factor of set size in Experiment 1B. To preview the results, significant cueing benefits were replicated across set sizes 4 and 6.

Experiment 1A

Experiment 1A also included the control condition with set size 6, in order to eliminate an alternative account that the observed exogenous cueing benefits were produced by interruption masking. Because neutrally cued trials contained a larger number of locations that exogenous cues and to-be-remembered items overlap compared to validly cued trials (see Figure 1), neutrally cued trials are more susceptible to detrimental effects of masking. Even though randomly varied interstimulus intervals (ISIs) between the memory array offset and the cue onset (the first delay) as well as between the cue offset and the test probe onset (the second delay) go outside of the integrative masking range, interruption masking can still take place. If change-detection accuracy for neutrally cued trials were lowered due to such masking, then the effects that look like cueing benefits could be easily generated across set sizes 4 and 6.

A well-known form of interruption masking, object substitution masking (e.g., Enns, 2004; Enns & DiLollo, 1997), is believed to occur by interrupting rapid visual sampling activities of a percept, when spatial attention is widely distributed (the reentrant theory of perception, e.g., Di Lollo, Enns, & Rensink, 2000; Lamme, Zipser, & Spekreijse, 2002). Because each ISI in the present experiments goes beyond the range of iconic memory (it takes at least 500 ms for information persistence to disappear; Irwin & Yeomans, 1986; Sperling, 1960), rapid visual sampling activities denoted in the object substitution masking literature are not possible in the current retention-interval cueing paradigm. Accordingly, some may argue that it is not necessary to examine whether the exogenous cueing benefit could be generated by object substitute masking *per se*. However, given exclusion of the object substitution masking possibility would not necessarily prevent other types of interruption masking unknown to us from taking place, it was necessary to ensure that the observed cueing benefits across set sizes 4 and 6 were not products of any type of interruption masking.

To achieve this goal, in the control condition of Experiment 1A, while keeping validly cued trials constant with the set-size-6 condition, set-size-6 neutral cues were scaled down with the cortical magnification factor (Wolfe, O'Neill, & Bennett, 1998). Use of the cortical magnification factor scaling allowed us to present 6 neutral cues in the locations that did not overlap with to-be-remembered items in the memory array (i.e., the imaginary circle of six neutral cues in the set-size-6 condition were brought *inward*), while the scaled images activate equivalent portions of the cortex with neutrally cued trials in the set-size-6 condition.

If the cueing benefits observed in the set-size-4 and -6 conditions were produced by interruption masking, then the cueing benefit should not be replicated in the control condition. Specifically, in the control condition, change-detection accuracy of neutrally cued trials should be as high as that of validly cued trials. In contrast, if the cueing benefits in the set-size-4 and -6 conditions reflected sound operations of selective attention during VSTM maintenance, then the cueing benefit comparable to the set-size-6 condition should be observed. To anticipate the results, with a nearly identical range of change-detection accuracy, a significant

cueing benefit comparable to the set-size-6 condition was observed in the control condition.

Method

Participants. Sixteen observers participated in each set-size and control condition. All observers were University of Iowa undergraduates who participated to receive partial course credits for their involvement; all were between the ages of 18 to 30 years, and all reported having normal or corrected-to-normal visual acuity. None of these observers had participated in any of other experiments reported in the present study.

Stimuli. Stimuli were viewed from a distance of 60 cm and were presented on a gray background (22.6 cd/m^2) with a continuously visible white fixation cross (51.5 cd/m^2). For a set size of 6, the stimuli were presented at six locations that were evenly spaced around an imaginary circle with a radius of 3.8° that was centered at fixation (see Figure 1). Each memory array consisted of a $1.1^\circ \times 1.1^\circ$ filled square at each of the six locations. The set-size-4 display was identical to the set-size-6 display except that four locations were evenly spaced around the imaginary circle. The exogenous cue was a white, $0.38^\circ \times 0.38^\circ$ filled square. In the control condition, the imaginary circle with an approximate radius of 1.24° was used to present the six neutral cues, white $0.09^\circ \times 0.09^\circ$ filled squares. Again, validly cued trials in the control condition were kept constant with those in the set-size-6 condition.

The colors were selected at random (without replacement) from a set of seven easily discriminable colors: violet ($x = .245, y = .111, 6.4 \text{ cd/m}^2$), red ($x = .636, y = .315, 12.9 \text{ cd/m}^2$), blue ($x = .152, y = .659, 5.6 \text{ cd/m}^2$), green ($x = .313, y = .554, 20.2 \text{ cd/m}^2$), yellow ($x = .464, y = .451, 38.14 \text{ cd/m}^2$), black ($x = .299, y = .255, .5 \text{ cd/m}^2$), and brown ($x = .582, y = .310, 3.1 \text{ cd/m}^2$).

Procedure. Each trial started with an observer beginning an articulatory suppression task, in which the observer was required to repeat either "A, B, C, D" or "1, 2, 3, 4" aloud through the duration of the trial. This concurrent task effectively discourages verbal recoding of visual information (e.g., Baddeley, 1986; Besner, Davies, & Daniels, 1981; Murray, 1968).

As illustrated in Figure 1, the memory array appeared for a duration of 100 ms after a 1,000-ms fixation screen. The offset of the memory array was followed by a blank delay period that was randomly varied within the range from 1,500 to 2,500 ms. Then, either a single dot cue (validly cued trials) or multiple dot cues (neutrally cued trials) appeared for 100 ms. The offset of the cue was followed by another blank period that varied randomly within the range from 500 to 1,000 ms, and then a single test probe was presented and remained on the computer display until the observers made a response. These delay durations between the memory array offset and the cue onset as well as between the cue offset and the test probe onset were randomly varied to prevent the observers from predicting the presentation timing of the cue and a single test probe, respectively (e.g., Griffin & Nobre, 2003; Matsukura et al., 2007).

As mentioned earlier, validly cued and neutrally cued trials were equiprobable to increase statistical power and randomized throughout the experiment (e.g., Matsukura & Hollingworth, 2011; Matsukura et al., 2007). In validly cued trials, a single dot cue appeared at one of the four or six locations that had been occupied by color squares in the memory array, and the test probe always appeared at this

location. In neutrally cued trials, the cue was a set of four or six dots that appeared at each of these four or six locations, and the test probe could appear at any of these locations with equal probability.

On half of the trials, the test probe had the same color as the item appeared at the corresponding location in the memory array (*same-color* trials). On the remaining trials, the test probe was selected at random from the colors that had not been present in the memory array (*different-color* trials, i.e., without replacement). The observers pressed “1” if the test probe and the corresponding item in the memory array shared the same color and “2” if the test probe and the corresponding item in the memory array had different colors.

Because we are interested in how well the observers remembered validly cued items relative to neutrally cued items, the observers made an unspeeded manual response. This method also prevented the observers from prioritizing accuracy over reaction time (RT) for some trials and RT over accuracy for other trials (but see different approaches and methods in Astle et al., 2012; Griffin & Nobre, 2003).⁵

Each observer participated in a single 60-min experimental session. At the beginning of the session, the observers were given both written and verbal instructions. After a few minutes of practice with the task, each observer completed 432 trials in six blocks of 72 trials.

Results and Discussion

Figure 2A shows mean change-detection accuracy (percent correct, collapsed across same-color and different-color trials) of Experiment 1A as a function of cue type (valid vs. neutral) and set size (4, 6, control).⁶

For all conditions, the observers recognized validly cued items more accurately than neutrally cued items (i.e., the retention-interval cueing benefit). Given the goal of the control experiment was to rule out the possibility that the cueing benefits observed across set sizes 4 and 6 were driven by interruption masking, we will compare the cueing benefits in the set-size-4 and -6 conditions first, then move onto examining whether there was any statistical difference between the set-size-6 and control conditions.

An analysis of variance (ANOVA) with a within-subjects factor of cue type (valid vs. neutral) and a between-subjects factor of set size (4 vs. 6) was conducted. Higher accuracy in validly cued trials than in neutrally cued trials led to a significant main effect of cue type, $F(1, 30) = 63.19, p < .0001$. While overall accuracy in the set-size-4 condition was higher than in the set-size-6 condition, this difference did not reach significance for a main effect of set size, $F(1, 30) = 2.73, p = .11$. Finally, the two-way interaction of cue type and set size was not significant, $F(1, 30) = .006, p = .94$, indicating that the size of the retention-interval cueing benefit did not significantly differ between the two set-size conditions. Planned pairwise comparisons confirmed that the observed cueing benefit was significant for both the set-size-4 condition, $t(15) = 5.88, p < .0001$, and the set-size-6 condition, $t(15) = 5.50, p < .0001$.

Having observed significant cueing benefits both near and above the VSTM capacity, we now move onto ruling out the possibility that these cueing benefits were generated by interruption masking occurred in neutrally cued trials. An ANOVA with a within-subjects factor of cue type and a between-subjects factor of condition type (set size 6 vs. control) enabled us to compare the magnitude of the cueing benefit between the set-size-6 and control

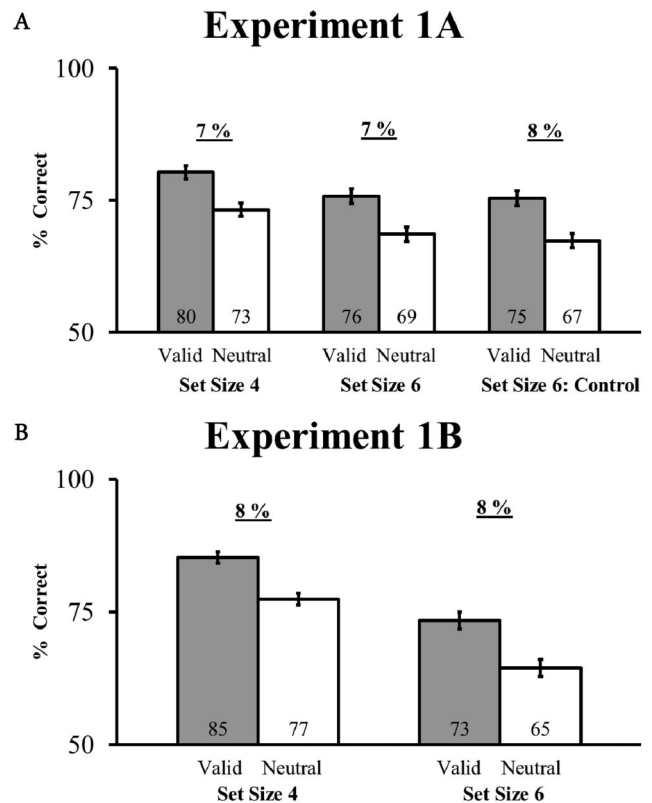


Figure 2. (A) Mean change-detection accuracy from Experiment 1A as a function of cue type (valid, neutral) and set size (4, 6, control). (B) Mean change-detection accuracy from Experiment 1B as a function of cue type (valid, neutral) and set size (4, 6). Underlined percentages represent the size of the retention-interval cueing benefit (accuracy of validly cued trials minus accuracy of neutrally cued trials). For this and all subsequent figures, error bars represent 95% within-subjects confidence intervals (Loftus & Masson, 1994).

conditions. Higher accuracy in validly cued trials than in neutrally cued trials led to a significant main effect of cue type, $F(1, 30) = 75.94, p < .0001$. There was no main effect of condition type, $F(1, 30) = .11, p = .75$, indicating that mean change-detection accuracies in the set-size-6 and control conditions were approximately the same. Confirming the hypothesis that the previously observed exogenous cueing benefits were not driven by interruption masking, the two-way interaction of cue type and condition type was not

⁵ All RT analyses of correct trials in the present study yielded the same pattern as did the analyses of percent correct. When RTs shorter than 150 ms or longer than 2,000 ms were excluded from the analyses, less than 4.8% of correct trials were removed. Median RT analyses without trimming produced the same pattern of the results.

⁶ To rule out possible distortions from response bias, all the data in the present study were also analyzed with d' , a measure of sensitivity based on the signal detection theory (Macmillan, & Creelman, 1991). The analyses of d' yielded the same pattern of results as did the analyses of percent correct. Because the retention-interval cueing paradigm essentially violates the critical assumption that the observers try to maintain as many items as possible in VSTM by requiring the observers to remember a single cued item, it is not appropriate to estimate the capacity of validly cued trials (Matsukura & Hollingworth, 2011).

significant, $F(1, 30) = .21, p = .65$. Lack of this two-way interaction indicates that the size of the cueing benefit did not significantly differ between the set-size-6 and control conditions. Planned pairwise comparisons confirmed that the observed cueing benefit was significant for both the set-size-6 condition (as reported earlier), and the control condition, $t(15) = 7.11, p < .0001$.

Experiment 1B

Having ruled out the account that the cueing benefits observed in Experiment 1A were produced by interruption masking per se, we now need to rule out the possibility that significant cueing benefits observed across set sizes 4 and 6 were caused by the between-subjects variability.

Method

The method of Experiment 1B was identical to that in Experiment 1A except (1) an independent group of 16 observers from Experiment 1A participated in the experiment, (2) there was no control condition, and (3) each observer experienced both set-size-4 and set-size-6 trials as a within-subjects factor (216 trials for each set size, 432 trials in total). Both cue type and set size were randomized throughout the experiment (i.e., mixed-trial design).

Results and Discussion

Figure 2B shows mean change-detection accuracy of Experiment 1B as a function of cue type (valid vs. neutral) and set size (4 vs. 6). As observed in Experiment 1A, accuracy was higher in validly cued trials than in neutrally cued trials across both set sizes, and these observations were supported by an ANOVA with within-subjects factors of cue type and set size. Higher accuracy in validly cued trials than in neutrally cued trials led to a significant main effect of cue type, $F(1, 15) = 74.35, p < .0001$. Higher accuracy in set-size-4 trials than in set-size-6 trials also led to a significant main effect of set size, $F(1, 15) = 86.07, p < .0001$. The two-way interaction of cue type and set size was not significant, $F(1, 15) = .39, p = .54$, as the size of the cueing benefit was approximately the same between set-size-4 and -6 trials. Planned pairwise comparisons confirmed that the cueing benefit was significant for both set-size-4 trials, $t(15) = 7.76, p < .0001$, and set-size-6 trials, $t(15) = 5.86, p < .0001$.

Together, Experiment 1 results suggest that attention can be directed to a specific location represented in VSTM with the exogenous cue, when the number of to-be-remembered items is near and above the VSTM capacity. Both Experiments 1A and 1B showed robust exogenous retention-interval cueing benefits across set sizes 4 and 6.

Experiment 2

Although the results of Experiment 1 ruled out the interruption masking account of exogenous cueing benefits in VSTM, another alternative remains. That is, corrective eye movements were more likely to occur during the delay between the offset of the cue and the onset of the test probe in neutrally cued trials. Such eye movements could have disrupted the comparison between the test probe and the corresponding item in the memory array (Hyun, Woodman, Vogel, Hollingworth, & Luck, 2009) and brought

down accuracy in neutrally cued trials. In order to exclude this eye movement account, in Experiment 2, we replicated Experiment 1B while monitoring the observers' eye movements. If large cueing benefits across two set sizes are replicated in the absence of eye movements, then such results indicate that covert attention can be directed to a specific location represented in VSTM with the exogenous cue.

Method

Participants. Sixteen University of Iowa students either volunteered to participate or participated to receive partial course credits for their involvement; all were between the ages of 18 to 30 years, and all reported having normal or corrected-to-normal visual acuity.

Stimuli and procedure. The stimuli and procedure were identical to those of Experiment 1B except that the observers received 120 trials in five blocks of 24 trials. Eye position was measured with an Applied Science Laboratories Eye Trac Model 210. All observers were instructed to maintain fixation because trials with eye movements would be removed from the data analysis. Eye movements were monitored by the experimenter, who kept a trial-by-trial record of whether an eye movement occurred. Eye movements were monitored from the start of a trial to the key press that the observers made in responding to the test probe. Eye movements were defined as a movement of more than 1° to the left or right of fixation (Matsukura et al., 2007).

Results and Discussion

Figure 3 shows mean change-detection accuracy of Experiment 2 as a function of cue type and set size. Less than 1.7% of the trials were removed because of eye movements. Replicating Experiment 1B results, the observers recognized validly cued items more precisely compared to neutrally cued items in both set-size-4 and -6 trials, and these observations were supported by an ANOVA with within-subjects factors of cue type and set size. Higher accuracy in validly cued trials than in neutrally cued trials led to a significant main effect of cue type, $F(1, 15) = 18.05, p < .001$. Higher accuracy in set-size-4 trials than in set-size-6 trials led to a significant main effect of set size, $F(1, 15) = 55.74, p < .0001$.

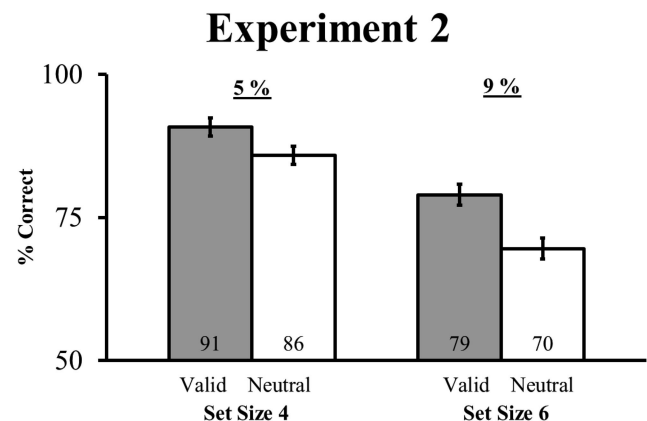


Figure 3. Mean change-detection accuracy from Experiment 2 as a function of cue type (valid, neutral) and set size (4, 6).

The two-way interaction of cue type and set size did not reach significance, $F(1, 15) = 1.81, p = .2$, as the magnitude of the cueing benefit was approximately equivalent across two set sizes. Planned pairwise comparisons also confirmed that the cueing benefit was significant for both set-size-4 trials, $t(15) = 2.27, p < .004$, and set-size-6 trials, $t(15) = 3.76, p < .002$.

The results of Experiment 2 did not only rule out the account that the cueing benefits observed in Experiment 1 were by-products of the observers' corrective eye movements, but also replicated the results of Experiment 1B.

Experiment 3

Having ruled out the accounts that the exogenous cueing benefits are produced by interruption masking and corrective eye movements, at first glance, the results of Experiments 1 and 2 appear to suggest that the exogenous cue can guide memory-level attention as efficiently as the endogenous (e.g., central arrow) cue when the number of to-be-remembered items is near and above the typical VSTM capacity. However, the current status of the retention-interval cueing literature lacks evidence for us to make such a claim. That is, to date, significant endogenous cueing benefits have never been demonstrated with the within-subjects set-size manipulation and unspeeded responses.⁷ Matsukura et al. (2007, Experiment 1), who used the identical experimental procedure with the current series of experiments, demonstrated significant endogenous cueing benefits across set sizes 4 and 6 with the between-subjects design. Thus, unless the endogenous cueing benefits across set sizes 4 and 6 are replicated with the within-subjects set-size manipulation, we cannot rule out the possibility that the endogenous cueing benefits observed in Matsukura et al. (2007) were driven by the between-subjects variability. In the strictest sense, unless these endogenous cueing benefits are replicated with the within-subjects set-size manipulation, we do not have any empirical ground to be able to claim that the exogenous cue can guide memory-level attention as efficiently as the endogenous cue when the number of to-be-remembered items is near and above the VSTM capacity.

Even with a number of differences in the experimental procedure (e.g., inclusion of invalidly cued trials, speeded responses), a recent work conducted by Astle et al. (2012) suggests the possibility that the observers adopt different strategies to perform the change-detection task with the retention-interval cueing manipulation when the number of to-be-remembered items is near and above the VSTM capacity. Given this record in the literature, whether use of the endogenous cue can produce comparable results with the exogenous cue experiments with the within-subjects set-size manipulation is not a trivial question. To resolve these ambiguities once and for all, in Experiment 3, we replicated Experiment 1B (the within-subjects set-size manipulation) with the endogenous cue. If the results replicate significant cueing benefits across set sizes 4 and 6 with a nearly identical range of change-detection accuracy with Experiment 1B, then we can safely conclude that the pattern of the data observed in Experiments 1 and 2 is not specific to the exogenous cue use.

Method

The method of Experiment 3 was identical to that in Experiment 1B except (1) a new group of 16 observers participated in the

experiment, and (2) the dot cue was replaced with the central arrow cue, which was a white arrow (51.5 cd/m^2), 1.9° in length (Matsukura et al., 2007). In validly cued trials, a single central arrow pointed to one of the four or six locations that had been occupied by color squares in the memory array, and the test probe always appeared at this location. In neutrally cued trials, the cue was a set of four or six arrows pointing to each of these four or six locations, and the test probe could appear at any of these locations with equal probability.

Results and Discussion

Figure 4 shows mean change-detection accuracy of Experiment 3 as a function of cue type (valid vs. neutral) and set size (4 vs. 6). Replicating Experiment 1B results, the observers recognized validly cued items more accurately compared to neutrally cued items in both set-size-4 and -6 trials, and these observations were supported by an ANOVA with within-subjects factors of cue type and set size. Higher accuracy in validly cued trials than in neutrally cued trials led to a significant main effect of cue type, $F(1, 15) = 46.53, p < .0001$. Higher accuracy in set-size-4 trials than in set-size-6 trials led to a significant main effect of set size, $F(1, 15) = 67.82, p < .0001$. The two-way interaction of cue type and set size was not significant, $F(1, 15) = .20, p = .66$, as the size of the cueing benefit was approximately the same between set-size-4 and -6 trials. Planned pairwise comparisons confirmed that the cueing benefit was significant for both set-size-4 trials, $t(15) = 4.60, p < .0001$, and set-size-6 trials, $t(15) = 5.97, p < .0001$.

These results with a nearly identical range of change-detection accuracy with Experiment 1B let us confirm that the pattern of the data observed in Experiments 1 and 2 is not specific to the exogenous cue use. Indeed, a between-experiments analysis with Experiment 1B failed to produce a significant three-way interaction of cue type, set size, and experiment type, $F(1, 30) = .00, p = .99$.

Experiment 4

While Experiments 1 and 2 showed robust exogenous cueing benefits during VSTM maintenance, one question remains: Why did the observers in Berryhill et al. (2012) fail to show the exogenous cueing benefit? To be clear, the goal of the present study is to examine whether or not selective attention can be guided by the exogenous cue during VSTM maintenance in a well-controlled setting, but not to identify the exact source of failure to observe the exogenous cueing benefit in a particular setting that Berryhill et al. employed. However, given there are some conflicting reports regarding the relationship between the exogenous cue use and the delay duration between the cue offset and the test probe onset in the literature, this ambiguity should be at least resolved before we conclude that attention can be directed to a specific item's location represented in VSTM with the exogenous cue.

There are three major differences between the current series of experiments and Berryhill et al.'s (2012) experiment. First, while

⁷ But see Makovski et al. (2008). In their Experiment 3, change-detection accuracy of endogenous valid cue trials was compared with that of the trials that a single endogenous valid cue appeared simultaneously with a single test probe, across different memory-array set sizes.

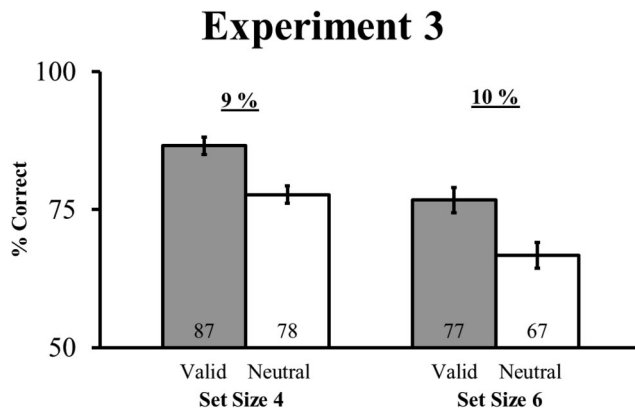


Figure 4. Mean change-detection accuracy from Experiment 3 as a function of cue type (valid, neutral) and set size (4, 6).

the delay duration between the retention-interval cue offset and the test probe onset (the second delay) in the current experiments goes beyond the iconic memory range (randomly varied in the range between 500 and 1,000 ms), the corresponding delay duration in Berryhill et al. was 400 ms, well within the range of iconic memory (Irwin & Yeomans, 1986; Sperling, 1960). Second, as in all the other studies that used the exogenous cue manipulation, Berryhill et al. also compared accuracy of exogenous valid cue trials with accuracy of endogenous neutral cue trials. Third, Berryhill et al. used the four place holders for the set-size-4 test array; that is, a single test probe color filled one of these four place holders at the time of the test.

While it is tempting to conclude that the short iconic-memory-range interval between the cue offset and the test item presentation induced some form of masking between the cue and a single test probe and wiped off the exogenous cueing benefit (in this case, by driving accuracy of exogenous valid cue trials down to match accuracy of endogenous neutral cue trials), the results of Makovski and Jiang (2007, Experiment 2A) suggest another possibility. Investigating whether the observers could use multiple retention-interval cues, Makovski and Jiang presented zero, one, two, three, or six exogenous cues equiprobably during the retention interval and compared accuracy of each cue-set-size condition with accuracy of the no-cue (cue set size 0) condition. As expected, no significant accuracy difference was observed between the no-cue and cue-set-size-6 conditions. When accuracy of the cue-set-size-1 condition (equivalent to validly cued trials in the present study) was compared to that of the cue-set-size-6 condition (equivalent to neutrally cued trials in the present study), a significant cueing benefit was observed.

Given the sole difference between Berryhill et al. (2012) and Makovski and Jiang (2007) is whether the test array contained the place holders or not, the most likely explanation for lack of the exogenous cueing benefit in Berryhill et al. is that some form of masking occurred between the images of the exogenous valid cue and the place holders within this 400-ms delay. However, given a statistical comparison between the cue-set-size-1 and -6 conditions in Makovski and Jiang was made based on a very small number of trials (48 trials for each condition), it is difficult for us to endorse such a result as a healthy exogenous cueing benefit. To resolve this

ambiguity, in Experiment 4, we replicated our set-size-6 experiment (Experiment 1A) with the delay durations that both Berryhill et al. and Makovski and Jiang used. Both studies had 1,000 ms for the first delay between the memory array offset and the cue onset and 400 ms for the second delay between the cue offset and the test probe presentation (Landman et al., 2003). As illustrated in Figure 5A, in Experiment 4, the retention-interval cue appeared 1,000 ms after the memory array offset and a single test probe was presented 400 ms after the cue offset. As in Makovski and Jiang's experiment, a single test probe appeared without any placeholder in the test array. Given solid evidence for the exogenous cueing benefits across memory-array set sizes 4 and 6 was established in earlier experiments, the only set-size-6 condition that heavily taxes the observers' VSTM capacity was tested in Experiment 4. This design also increased statistical power for each validly cued and neutrally cued trials.

If lack of the cueing benefit in Berryhill et al. (2012) was driven by masking between the exogenous valid cue and a single test probe *because of the short 400-ms ISI* (without the place holders), then no cueing benefit should be observed in Experiment 4. In contrast, if lack of the exogenous cueing benefit in Berryhill et al. was caused by masking between the exogenous valid cue and *the place holders in the test array*, then a significant cueing benefit should be observed in Experiment 4. Note that, while an exact replication of Berryhill et al.'s experiment would not allow us to make any conclusion regarding why no exogenous cueing benefit was observed in their study, the design of Experiment 4 enables us to determine whether lack of the exogenous cueing benefit in Berryhill et al. derives from (A) the 400-ms duration between the cue offset and a single test probe presentation or (B) the place holder use in the test array.

Method

As illustrated in Figure 5A, the method of Experiment 4 was identical to that in the set-size-6 condition of Experiment 1A except (1) a new group of 16 observers participated in the experiment, and (2) the retention-interval cue was presented 1,000 ms after the memory array offset and a single test probe appeared 400 ms after the cue offset.

Results and Discussion

Figure 5B shows mean change-detection accuracy of Experiment 4 as a function of cue type (valid vs. neutral). Replicating the results of the set-size-6 condition in Experiment 1A with a nearly identical change-detection accuracy range, the observers recognized validly cued items more accurately compared to neutrally cued items. This observation was supported by a one-way ANOVA with the within-subjects factor of cue type. Even with the 400-ms ISI between the cue offset and a single test probe presentation, accuracy in the validly cued trials was significantly higher than that in neutrally cued trials, $F(1, 15) = 36.13, p < .0001$. A between-experiments analysis with the set-size-6 condition of Experiment 1A also confirmed lack of a significant interaction between cue type and experiment type, $F(1, 30) = .02, p = .9$.

Together, these results suggest that lack of the exogenous cueing benefit in Berryhill et al. (2012) was driven by some form of masking occurred between the images of the exogenous valid cue and the

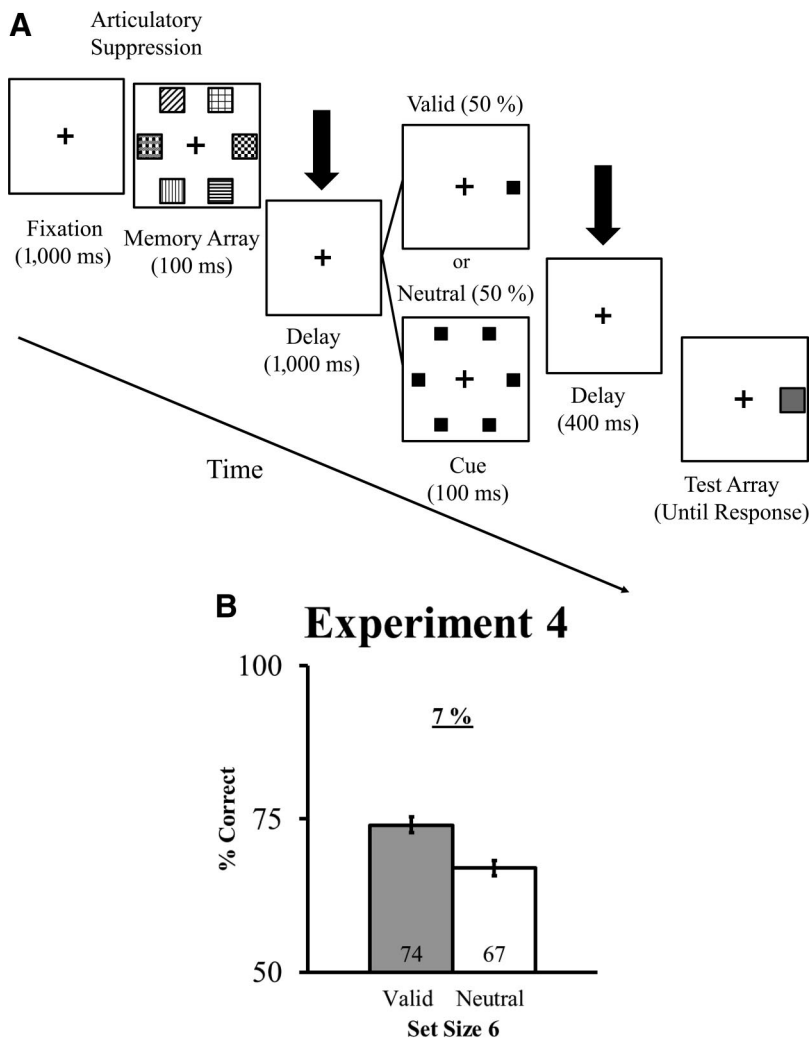


Figure 5. (A) Trial event sequence of Experiment 4 (different-color trial). Black arrows indicate the fixed durations that Berryhill et al. (2012) and Makovski and Jiang (2007) used. (B) Mean change-detection accuracy from Experiment 4 as a function of cue type (valid, neutral).

place holders in the test array, and attention can be directed to a specific location represented in VSTM with the exogenous cue even with the ISI as short as 400 ms. While identifying the exact form of masking took place between the images of the exogenous valid cue and the place holders in the test array is beyond the scope of the present study, the results of Experiment 4 at least enable us to conclude that the short 400-ms ISI between the cue offset and the test probe presentation itself was not a culprit for the complete disappearance of the exogenous retention-interval cueing benefit observed in Berryhill et al.

It should be noted that, regardless of whether the retention-interval cue is presented peripherally or centrally, we fully expect a gradual size shrinkage of the cueing benefit as the duration between the cue offset and a single probe onset becomes shorter (e.g., the simultaneous cue condition in Makovski et al., 2008; Pertzov et al., 2013; Tanoue & Berryhill, 2012). The shorter delay between the cue offset and a single probe onset (the second delay) does not leave much time for attention to be directed to the cued

item's location represented in VSTM. Accordingly, as the duration of the second delay is reduced, accuracy of validly cued trials is expected to be nearing accuracy of neutrally cued trials. Experiment 4 results simply indicate that the 400-ms ISI was not the primary cause for the absence of the exogenous cueing benefit reported by Berryhill et al. (2012).

General Discussion

In four experiments, we investigated whether attention can be directed to a specific location represented in VSTM with the exogenous (peripheral) cue. Across all experiments, the observers recognized validly cued items more accurately than neutrally cued items by utilizing the cue that appears at the exact same perceptual location with the cued item represented in VSTM. These retention-interval cueing benefits cannot be attributed to either interruption masking (Experiment 1) or corrective eye movements (Experiment 2) that could have lowered accuracy of neutrally cued trials.

Moreover, the exogenous cue seems to be able to guide memory-level attention as efficiently as the endogenous cue when the number of to-be-remembered items is near and above the typical VSTM capacity (Experiment 3). Finally, lack of the exogenous cueing benefit observed in Berryhill et al. (2012) was likely to be driven by some form of masking occurred between the images of the exogenous valid cue and the place holders in the test array, not by the 400-ms ISI between the cue offset and a single test probe onset (Experiment 4). Together, these results suggest that, despite functional dissociations between perception-level and memory-level selections (Hollingworth & Maxcey-Richard, 2013), selective attention mechanisms that operate across perceptual and memory representations share some similarities, which is in line with the sensory recruitment hypothesis (e.g., Awh & Jonides, 2001; Serences et al., 2009).

Importantly, however, such similarities across perception-level and memory-level selections of attention should not be interpreted as evidence that the exogenous cueing benefits observed in the present study are engendered through the selection mechanism that produces the exogenous cueing benefit during sensory processing. As many previous studies demonstrated, the exogenous cueing benefit observed during sensory processing is generated through the mechanism that the observer's attention is unpredictably drawn to the peripherally cued location by virtue of luminance transients (e.g., Jonides, 1981; Posner & Cohen, 1984). Indeed, the automatic nature of the exogenous cue is usually examined by lowering the cue validity below 50%. It has been shown that, despite the cue does not correctly predict the to-be-tested location for the majority of trials (i.e., nonpredictive), sudden onsets of the peripheral cue lead to changes in perceptual processing of the cued location (Luck & Thomas, 1999). Schmidt, Vogel, Woodman and Luck (2002) further demonstrated that sudden onsets of the peripheral cue influence the transfer of the perceptual representations into VSTM.

As we acknowledged in Introduction, in the present study, the term "exogenous" was used only to denote a specific location that the cue appeared during VSTM maintenance. As it is apparent by now, this was because the peripheral cue used in the present study did not share any property of the bona fide exogenous cueing benefit observed during sensory processing. First, every attention-directing cue in the present study appeared long after an icon of the cued item (as well as the memory array) had faded away (Irwin & Yeomans, 1986; Sperling, 1960). Likewise, a single test probe was presented long after an iconic image of the cue itself had disappeared. Thus, unlike the peripheral cue presented during perceptual processing, memory-level attention cannot enjoy sensory benefit brought by sudden onsets of the cue (e.g., luminance transients). Second, across the four experiments, the cue validity in the present study remained at 50% (as in some of the other studies that used the exogenous cue), and the observers were instructed to take advantage of the cueing information. As mentioned earlier, the automatic nature of the exogenous cueing benefit observed during sensory processing has been studied under the circumstances that the cue does not provide any useful information about the location of the target item for the majority of trials. Given these two stipulations, the exogenous cueing benefits observed in the present study are highly likely to be generated through the goal-directed selection of attention.

Some may argue that, unless the cue validity is actually lowered below 50%, we cannot be sure whether the exogenous cue pre-

sented during VSTM maintenance really guides attention in a goal-directed fashion or not. While the issue of whether memory-level attention guided by the exogenous cue is stimulus-driven or goal-directed is not the question we pursued in the present study, a recent study conducted by Shimi et al. (in press) strongly suggests that the exogenous retention-interval cueing benefit is produced through the goal-directed selection. In their remarkably consistent demonstrations across different age groups of the observers, Shimi et al. (in press) reduced the validity of both exogenous (peripheral outline box) and endogenous (central arrow) retention-interval cues to 25% of entire trials and observed the complete disappearance of both exogenous and endogenous retention-interval cueing benefits and costs. Of relevance to the present study, accuracy (d') of exogenous valid cue trials was brought down to match that of endogenous neutral cue trials. Based on these results, Shimi et al. (in press) concluded that, unlike the exogenous cueing benefit observed during sensory processing, attention guided by the exogenous cue during VSTM maintenance operates through the goal-directed selection. That is, unlike the perception-level exogenous cue unpredictably attracts the observers' attention, once the observers figured that the information provided by the retention-interval cue is not useful to perform a given change-detection task, they stop using such cueing information regardless of whether the cue appears at the same perceptual location with the cued item represented in VSTM (peripheral) or at the center of the computer screen (central). Given we did not observe any discernible difference between when accuracy of exogenous valid cue trials was compared to that of exogenous neutral cue trials (the present study) and when accuracy of exogenous valid cue trials was compared to that of endogenous neutral trials (Makovski & Jiang, 2007; Murray et al., 2013; Pertzov et al., 2013; Shimi et al., in press), it is safe to conclude that the exogenous cueing benefits observed in the present study are likely to be produced through the goal-directed selection as well.

Of relevance, Berryhill et al.'s (2012, Experiment 1) experiment consisted of the exogenous (16.7%), endogenous (16.7%), symbolic (16.7%) valid cue trials (50% in total) and endogenous neutral cue trials (50%). Within this setting, the observers were given a specific instruction: that is, while the endogenous neutral cue is not informative in predicting the to-be-tested item's location, "the other cues" are (p. 429). At first glance, 16.7% of the low exogenous cue validity makes us wonder if the reported lack of the exogenous cueing benefit was caused by the aforementioned goal-directed selection. As Shimi et al. (in press) demonstrated, the observers in Berryhill et al. might have stopped using the cueing information provided by the exogenous cue because these observers figured that such information is not useful to perform the color change-detection task. However, Berryhill et al.'s results strongly suggest the opposite; that is, 16.7% of the exogenous valid cues were actually utilized as part of the informative valid cues (50% of entire trials). Specifically, while no exogenous cueing benefit was observed, a significant endogenous cueing benefit was obtained despite its low cue validity (16.7%). The presence of such an endogenous cueing benefit strongly indicates that the observers were indeed using the 16.7% exogenous cues as part of the 50% collective valid cues (along with endogenous and symbolic cues). If the observers stopped using the cueing information due to the low cue validity of each exogenous, endogenous, and symbolic

cues (16.7% each), then the endogenous cueing benefit should not have been observed in the first place (Shimi et al., in press). Indeed, Berryhill et al. (Experiment 3) themselves later showed that accuracy of endogenous valid cue trials fell to the level of endogenous neutral cue trials when the cue validity was reduced to 12.5% (a nonsignificant trend was reported for this cueing benefit, $p = .07$, p. 433).

Again, while identifying the exact source of lack of the exogenous cueing benefit observed in a particular setting that Berryhill et al. (2012) employed is not the goal of the present study, their experimental design and results described above strongly suggest that the peripherally cued item's representation was actually retained as accurately as the centrally cued item in VSTM; however, this cued representation was likely to be wiped off by some form of masking that took place between the images of the exogenous valid cue and the place holders in the test array during the short 400-ms ISI.

Finally, we should acknowledge potential effects of masking that could have occurred between the exogenous valid cue presentation and the item that appeared at the cued location in either memory or test array (e.g., Pertzov et al., 2013; Shimi et al., in press). Even though we did not observe any effect of masking either between the memory-array offset and the cue onset (the first delay) or between the cue offset and a single test probe onset (the second delay) in the present study, several studies noticed the tendency that accuracy of exogenous valid cue trials is lower than accuracy of endogenous valid cue trials. Again, despite we did not observe such a tendency in the present study (Experiments 1–2 vs. Experiment 3), we expect that physical characteristics of the exogenous (peripheral) cue play a certain role in lowering change-detection performance accuracy of validly cued trials, even after an icon of the memory array or the cue faded away. However, such effects should not be as detrimental as driving accuracy of exogenous valid cue trials down to match that of exogenous (or endogenous) neutral cue trials.

For examples, Shimi et al. (in press) noted that accuracy of exogenous valid cue trials was lower than that of endogenous valid cue trials (p. 8). In their case, given a single test probe was presented at the center of the test-array display instead of the spatially cued location (thus, the observers reported whether the test probe was present or absent in the memory array, see Griffin & Nobre, 2003, for a similar method), a possibility of masking between the cue offset and the test probe onset is ruled out; however, masking between the memory-array offset and the cue onset (the first delay) is still possible. The results of Pertzov et al. (2013) also showed a larger degree of error in recalling the spatially cued item's orientation for exogenous valid cue trials compared to color valid cue trials (Table 1, p. 1227). In their orientation recall experiments, instead of reporting whether the test item shared the identical orientation with the cued item (same orientation vs. different orientation), the observers adjusted the orientation of the test item to match the spatially cued item maintained in VSTM using a manual response dial. In their color-based cueing experiment, the observers performed the identical orientation recall task by utilizing a particular cue color presented at the center of the computer display during the retention interval.

One common property shared between Shimi et al. (in press) and Pertzov et al. (2013) is that the peripheral cue was designed to closely fit around the cued item. Specifically, the cue in Shimi et

al. (in press) was a white rectangular outline ($1.64^\circ \times 2.05^\circ$) presented at the cued item's location, while the dimensions of the cued item were also reported as $1.64^\circ \times 2.05^\circ$. Similarly, the cue used in Pertzov et al. in the spatial cueing task was a gray ring that enclosed the cued orientation bar ($2^\circ \times 0.3^\circ$, the exact ring measurement is not reported). In contrast, Makovski and Jiang (2007) and the present study, who used the dot cue substantially smaller than the cued item, did not observe any difference between accuracy of exogenous valid cue trials and accuracy of endogenous valid cue trials. While the exact cue size was not reported, Makovski and Jiang used the round dot cue smaller than the cued disk with 1.31° in diameter. The present study also used the square dot cue ($0.38^\circ \times 0.38^\circ$) considerably smaller than the cued square ($1.1^\circ \times 1.1^\circ$).

The clear pattern emerged across these studies suggests that, despite the delay durations between the memory-array offset and the cue onset (the first delay) as well as between the cue offset and a single test probe onset (the second delay) go beyond the range of iconic memory, reminiscent of object substitute masking, the cue that snugly fits around the cued item may play a certain role in lowering accuracy of exogenous valid cue trials. Note that, however, this possible effect of masking is not as detrimental as driving accuracy of exogenous valid cues completely down to match that of either exogenous or endogenous neutral cues. Given the durations of both first and second delays exceed a typical duration that interruption masking can take place and no iconic representation of the cued item is available at the time of the cue presentation, it makes sense that physical characteristics of the cue alone are not sufficient to entirely wipe off the exogenous cueing benefit.

A related issue is whether lack of the exogenous cueing benefit in Berryhill et al. (2012) was caused by physical characteristics of their peripheral cue. Their cue was a white bar ($2^\circ \times 0.7^\circ$) while the cued disk presented in the memory array was 3.8° in diameter (p. 428). Even though we entertain the possibility that the bar-shaped cue smaller than the cued color disk caused some masking between the memory array offset and the cue onset (the first delay), based on the pattern observed across Shimi et al. (in press) and Pertzov et al. (2013), such a masking effect should not be as damaging as entirely eliminating the cueing benefit as Berryhill et al. reported. This leaves us again with the possibility that the peripherally cued item's representation was retained as accurately as the centrally cued item in VSTM up until the test array presentation; however, this cued representation in VSTM could not survive some form of masking that took place between the images of the white bar-shaped cue and the white ring (or the whole set of four white rings) that enclosed the validly cued probe color disk during the short 400-ms ISI. As the exact dimensions of the place holders were not reported in Berryhill et al., given a single cued color disk "filled in" one of these white-outlined place holders in the test array, the outline of each place holder should have been closely fit around the cued color disk.

The results from the present study raise an interesting question as to how the exogenous retention-interval cueing effects are generated. Although the current status of the literature suggests that attention guided by the exogenous retention-interval cue operates through the goal-directed selection, unlike the endogenous cue, the exogenous cue allows the observers to skip interpreting the meaning of the cue before orienting attention to a particular location represented in VSTM. Despite the exogenous cue pre-

sented during the retention interval cannot enjoy sensory benefit brought by the bona fide exogenous cue, whether or not utilization of the exogenous cue produces differential effects on the efficiency that the cued item is saved from memory-related degradation processes (i.e., decay, interference, or some other kind of degradation), relative to the endogenous cue use, remains to be tested in the future. Before moving onto such a question, the present study first demonstrated that the exogenous (peripheral) cue can guide attention within VSTM representations as efficiently as the endogenous (central) cue in a well-controlled setting. Despite being functionally dissociable from perception-level attention and generated through the goal-directed selection, the present finding is consistent with the sensory recruitment hypothesis, which assumes that VSTM operates by retaining “reasonable copies” of scenes constructed during sensory processing (Serences et al., 2009, p. 207). Finally, the present finding validates the legitimacy of the exogenous cue use in past and future studies that examine the nature of memory-level attention.

References

- Albers, A. M., Kok, P., Toni, I., Dijkerman, H. C., & de Lange, F. P. (2013). Shared representations for working memory and mental imagery in early visual cortex. *Current Biology*, *23*, 1427–1431. doi:10.1016/j.cub.2013.05.065
- Astle, D. E., Summerfield, J., Griffin, I., & Nobre, A. C. (2012). Orienting attention to locations in mental representations. *Attention, Perception, & Psychophysics*, *74*, 146–162. doi:10.3758/s13414-011-0218-3
- Averbach, E., & Coriell, A. S. (1961). Short-term memory in vision. *Bell System Technical Journal*, *40*, 309–328. doi:10.1002/j.1538-7305.1961.tb03987.x
- Awh, E., Dhaliwal, H., Christensen, S., & Matsukura, M. (2001). Evidence for two components of object-based selection. *Psychological Science*, *12*, 329–334. doi:10.1111/1467-9280.00360
- Awh, E., & Jonides, J. (2001). Overlapping mechanisms of attention and spatial working memory. *Trends in Cognitive Sciences*, *5*, 119–126. doi:10.1016/S1364-6613(00)01593-X
- Baddeley, A. D. (1986). *Working memory*. Oxford, United Kingdom: Clarendon.
- Berryhill, M. E., Richmond, L. L., Shay, C. S., & Olson, I. R. (2012). Shifting attention among working memory representations: Testing cue type, awareness, and strategic control. *Quarterly Journal of Experimental Psychology*, *65*, 426–438. doi:10.1080/17470218.2011.604786
- Besner, D., Davies, J., & Daniels, S. (1981). Reading for meaning: The effects of concurrent articulation. *Quarterly Journal of Experimental Psychology*, *33A*, 415–437.
- Christophel, T. B., Hebart, M. N., & Haynes, J.-D. (2012). Decoding the contents of visual short-term memory from human visual and parietal cortex. *The Journal of Neuroscience*, *32*, 12983–12989. doi:10.1523/JNEUROSCI.0184-12.2012
- Di Lollo, V., Enns, J. T., & Rensink, R. A. (2000). Competition for consciousness among visual events: The psychophysics of reentrant visual processes. *Journal of Experimental Psychology: General*, *129*, 481–507. doi:10.1037/0096-3445.129.4.481
- Enns, J. T. (2004). Object substitution and its relation to other forms of visual masking. *Vision Research*, *44*, 1321–1331. doi:10.1016/j.visres.2003.10.024
- Enns, J. T., & DiLollo, V. (1997). Object substitution: A new form of masking in unattended visual locations. *Psychological Science*, *8*, 135–139. doi:10.1111/j.1467-9280.1997.tb00696.x
- Ester, E. F., Anderson, D. E., Serences, J. T., & Awh, E. (2013). A neural measure of precision in visual working memory. *Journal of Cognitive Neuroscience*, *25*, 754–761. doi:10.1162/jocn_a_00357
- Griffin, I. C., & Nobre, A. C. (2003). Orienting attention to locations in internal representations. *Journal of Cognitive Neuroscience*, *15*, 1176–1194. doi:10.1162/089892903322598139
- Harrison, S. A., & Tong, F. (2009). Decoding reveals the contents of visual working memory in early visual areas. *Nature*, *458*, 632–635. doi:10.1038/nature07832
- Hollingworth, A., & Hwang, S. (2013). The relation between visual working memory and attention: Retention of precise color information in the absence of effects on perceptual selection. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *368*, 1–9. doi:10.1098/rstb.2013.0061
- Hollingworth, A., & Maxcey-Richard, A. M. (2013). Selective maintenance in visual working memory does not require sustained visual attention. *Journal of Experimental Psychology: Human Perception and Performance*, *39*, 1047–1058. doi:10.1037/a0030238
- Hyun, J.-S., Woodman, G. F., Vogel, E. K., Hollingworth, A., & Luck, S. J. (2009). The comparison of visual working memory representations with perceptual inputs. *Journal of Experimental Psychology: Human Perception and Performance*, *35*, 1140–1160. doi:10.1037/a0015019
- Irwin, D. E., & Yeomans, J. M. (1986). Sensory registration and informational persistence. *Journal of Experimental Psychology: Human Perception and Performance*, *12*, 343–360. doi:10.1037/0096-1523.12.3.343
- Jonides, J. (1981). Voluntary versus automatic control over the mind’s eye. In J. Long & A. Baddeley (Eds.), *Attention and performance IX* (pp. 187–203). Hillsdale, NJ: Erlbaum.
- Lamme, V. A. F., Zipser, K., & Spekreijse, H. (2002). Masking interrupts figure–ground signals in V1. *Journal of Cognitive Neuroscience*, *14*, 1044–1053. doi:10.1162/089892902320474490
- Landman, R., Sperkreijse, H., & Lamme, V. A. F. (2003). Large capacity storage of integrated objects before change blindness. *Vision Research*, *43*, 149–164. doi:10.1016/S0042-6989(02)00402-9
- Lepsien, J., & Nobre, A. C. (2007). Attentional modulation of object representations in working memory. *Cerebral Cortex*, *17*, 2072–2083. doi:10.1093/cercor/bhl116
- Lepsien, J., Thornton, I., & Nobre, A. C. (2011). Modulation of working-memory maintenance by directed attention. *Neuropsychologia*, *49*, 1569–1577. doi:10.1016/j.neuropsychologia.2011.03.011
- Loftus, G. R., & Masson, M. E. J. (1994). Using confidence intervals in within-subject designs. *Psychonomic Bulletin & Review*, *1*, 476–490. doi:10.3758/BF03210951
- Luck, S. J., & Thomas, S. J. (1999). What variety of attention is automatically captured by peripheral cues? *Perception & Psychophysics*, *61*, 1424–1435. doi:10.3758/BF03206191
- Luck, S. J., & Vecera, S. P. (2002). Attention. In S. Yantis (Ed.), *Stevens’ handbook of experimental psychology: Vol. 1: Sensation and perception* (3rd ed., pp. 235–286). New York, NY: Wiley.
- Luck, S. J., & Vogel, E. K. (1997). The capacity of visual working memory for features and conjunctions. *Nature*, *390*, 279–281. doi:10.1038/36846
- Macmillan, N. A., & Creelman, C. D. (1991). *Detection theory: A user’s guide*. Cambridge, United Kingdom: Cambridge University Press.
- Makovski, T. (2012). Are multiple visual short-term memory storages necessary to explain the retro-cue effect? *Psychonomic Bulletin & Review*, *19*, 470–476. doi:10.3758/s13423-012-0235-9
- Makovski, T., & Jiang, Y. V. (2007). Distributing versus focusing attention in visual short-term memory. *Psychonomic Bulletin & Review*, *14*, 1072–1078. doi:10.3758/BF03193093
- Makovski, T., Sussman, R., & Jiang, Y. V. (2008). Orienting attention in visual working memory reduces interference from memory probes. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *34*, 369–380. doi:10.1037/0278-7393.34.2.369
- Matsukura, M., & Hollingworth, A. (2011). Does visual short-term memory have a high-capacity stage? *Psychonomic Bulletin & Review*, *18*, 1098–1104. doi:10.3758/s13423-011-0153-2

- Matsukura, M., Luck, S. J., & Vecera, S. P. (2007). Attention effects during visual short-term memory maintenance: Protection or prioritization? *Perception & Psychophysics*, *69*, 1422–1434. doi:10.3758/BF03192957
- Matsukura, M., & Vecera, S. P. (2009). Interference between object-based attention and object-based memory. *Psychonomic Bulletin & Review*, *16*, 529–536. doi:10.3758/PBR.16.3.529
- Matsukura, M., & Vecera, S. P. (2011). Object-based selection from spatially-invariant representations: Evidence from a feature-report task. *Attention, Perception & Psychophysics*, *73*, 447–457. doi:10.3758/s13414-010-0039-9
- Maxcey-Richard, A. M., & Hollingworth, A. (2013). The strategic retention of task-relevant objects in visual working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *39*, 760–772. doi:10.1037/a0029496
- Munneke, J., Belopolsky, A. V., & Theeuwes, J. (2012). Shifting attention within memory representations involves early visual areas. *PLoS One*, *7*, e35528. doi:10.1371/journal.pone.0035528
- Murray, A. M., Nobre, A. C., Clark, I. A., Carvo, A. M., & Stokes, M. G. (2013). Attention restores discrete items to visual short-term memory. *Psychological Science*, *24*, 550–556. doi:10.1177/0956797612457782
- Murray, D. J. (1968). Articulation and acoustic confusability in short-term memory. *Journal of Experimental Psychology*, *78*, 679–684. doi:10.1037/h0026641
- Pertsov, Y., Bays, P. M., Joseph, S., & Husain, M. (2013). Rapid forgetting prevented by retroactive attention cues. *Journal of Experimental Psychology: Human Perception and Performance*, *39*, 1224–1231. doi:10.1037/a0030947
- Pinto, Y., Sligte, I. G., Shapiro, K. L., & Lamme, V. A. F. (2013). Fragile visual short-term memory is an object-based and location-specific store. *Psychonomic Bulletin & Review*, *20*, 732–739. doi:10.3758/s13423-013-0393-4
- Posner, M. I., & Cohen, Y. (1984). Components of visual orienting. In H. Bouma & D. G. Bouwhuis (Eds.), *Attention and performance X: Control of language processes* (pp. 531–556). Hillsdale, NJ: Erlbaum.
- Rerko, L., & Oberauer, K. (2013). Focused, unfocused, and defocused information in working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *39*, 1075–1096. doi:10.1037/a0031172
- Schmidt, B. K., Vogel, E. K., Woodman, G. F., & Luck, S. J. (2002). Voluntary and involuntary attentional control of visual working memory. *Perception & Psychophysics*, *64*, 754–763. doi:10.3758/BF03194742
- Serences, J. T., Ester, E. F., Vogel, E. K., & Awh, E. (2009). Stimulus-specific delay activity in human primary visual cortex. *Psychological Science*, *20*, 207–214. doi:10.1111/j.1467-9280.2009.02276.x
- Shimi, A., Nobre, A. C., Astle, D., & Scerif, G. (in press). Orienting attention within visual short-term memory: Development and mechanisms. *Child Development*.
- Sligte, I. G., Scholte, H. S., & Lamme, V. A. F. (2008). Are there multiple visual short-term memory stores? *PLoS One*, *3*, e1699.
- Sperling, G. (1960). The information available in brief visual presentations. *Psychological Monographs*, *74*, Whole No. 498.
- Tanoue, R. T., & Berryhill, M. E. (2012). The mental wormhole: Internal attention shifts without regard for distance. *Attention, Perception & Psychophysics*, *74*, 1199–1215. doi:10.3758/s13414-012-0305-0
- Vogel, E. K., & Machizawa, M. G. (2004). Neural activity predicts individual differences in visual working memory capacity. *Nature*, *428*, 748–751. doi:10.1038/nature02447
- Vogel, E. K., Woodman, G. F., & Luck, S. J. (2001). Storage of features, conjunctions, and objects in visual working memory. *Journal of Experimental Psychology: Human Perception and Performance*, *27*, 92–114. doi:10.1037/0096-1523.27.1.92
- Williams, M., Hong, S. W., Kang, M.-S., Carlisle, N. B., & Woodman, G. F. (2013). The benefit of forgetting. *Psychonomic Bulletin & Review*, *20*, 348–355. doi:10.3758/s13423-012-0354-3
- Williams, M., & Woodman, G. F. (2012). Directed forgetting and directed remembering in visual working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *38*, 1206–1220. doi:10.1037/a0027389
- Wojciulik, E., & Kanwisher, N. (1999). The generality of parietal involvement in visual attention. *Neuron*, *23*, 747–764. doi:10.1016/S0896-6273(01)80033-7
- Wolfe, J. M., O'Neill, P., & Bennett, S. C. (1998). Why are there eccentricity effects in visual search? Visual and attentional hypotheses. *Perception, & Psychophysics*, *60*, 140–156. doi:10.3758/BF03211924
- Woodman, G. F., & Vecera, S. P. (2011). The cost of accessing an object's feature stored in visual working memory. *Visual Cognition*, *19*, 1–12. doi:10.1080/13506285.2010.521140
- Yantis, S. (2000). Goal-directed and stimulus-driven determinants of attentional control. In S. Monsell & J. Driver (Eds.), *Attention and performance XVIII* (pp. 73–103). Cambridge, MA: MIT Press.

Received October 15, 2013
 Accepted December 2, 2013 ■