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Visual Working Memory Supports the Inhibition of Previously Processed Information: Evidence From Preview Search

Naseem Al-Aidroos
Princeton University

Stephen M. Emrich
University of Toronto

Susanne Ferber
University of Toronto and Rotman Research Institute, Baycrest, Toronto, Ontario

Jay Pratt
University of Toronto

In four experiments we assessed whether visual working memory (VWM) maintains a record of previously processed visual information, allowing old information to be inhibited, and new information to be prioritized. Specifically, we evaluated whether VWM contributes to the inhibition (i.e., visual marking) of previewed distractors in a preview search. We evaluated this proposal by testing three predictions. First, Experiments 1 and 2 demonstrate that preview inhibition is more effective when the number of previewed distractors is below VWM capacity than above; an effect that can only be observed at small preview set sizes (Experiment 2A) and when observers are allowed to move their eyes freely (Experiment 2B). Second, Experiment 3 shows that, when quantified as the number of inhibited distractors, the magnitude of the preview effect is stable across different search difficulties. Third, Experiment 4 demonstrates that individual differences in preview inhibition are correlated with individual differences in VWM capacity. These findings provide converging evidence that VWM supports the inhibition of previewed distractors. More generally, these findings demonstrate how VWM contributes to the efficiency of human visual information processing—VWM prioritizes new information by inhibiting old information from being reselected for attention.

Keywords: attention, visual working memory, preview search, visual marking, inhibition

Most natural visual environments contain more information than we can process in detail at once. As a consequence, to process a visual scene efficiently we must select the behaviorally relevant portions for further processing while ignoring the behaviorally irrelevant parts. How do we determine what should be selected? Our visual systems employ a number of strategies that involve attention and memory to address this problem. For example, attentional capture reflexively biases selection toward salient stimulus events (Jonides, 1981; Posner & Cohen, 1984; Yantis & Jonides, 1984, 1990)—in particular, those that match our internally defined goals (e.g., Folk, Remington, & Johnston, 1992; Folk, Remington, & Wright, 1994). In addition, long-term memory of contextual information can guide selection, such as when we look to the sides of doorways to find light switches (Brockmole & Henderson, 2006a, 2006b; Brockmole, Castelhano, & Henderson, 2006; Chun & Jiang, 1998, 2003; Henderson, Weeks, & Hollingworth, 1999; Hollingworth, 2009; Olson & Chun, 2002). Of primary interest in the present study, human vision also has a selection bias against portions of a visual scene that have already been processed (e.g., Emrich, Al-Aidroos, Pratt, & Ferber, 2009, 2010; Goolsby, Shapiro, & Raymond, 2009; McCarley, Wang, Kramer, Irwin, & Peterson, 2003; Peterson, Beck, & Vomela, 2007; Posner & Cohen, 1984; Watson & Humphreys, 1997). That is, once we have processed a portion of a scene in detail, there is little value in processing it again, and we are able to use inhibition to prevent it from being reselected. Understanding how we achieve this inhibition of old information—to favor new information—is important for understanding how efficiency is attained in human vision.

The preview search paradigm, originated by Watson and Humphreys (1997), has proved particularly useful in studying how we can prevent recently processed information from being reselected. This paradigm employs a modified visual search task where some distractors are presented shortly before the search target appears. By previewing these distractors, their effect on search time is typically reduced, indicating that they have been deprioritized for selection relative to new search items (i.e., the target and any new distractors). Watson and Humphreys suggested that this preview

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Naseem Al-Aidroos, Department of Psychology, Princeton University; Stephen M. Emrich, Department of Psychology, University of Toronto, Toronto, Ontario; Susanne Ferber, Department of Psychology, University of Toronto and Rotman Research Institute, Toronto, Ontario; Jay Pratt, Department of Psychology, University of Toronto.

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Correspondence concerning this article should be addressed to Naseem Al-Aidroos, Green Hall, Princeton University, Princeton, NJ 08540. E-mail: nzal@princeton.edu

effect is due to top-down inhibition of the previewed distractors—a process they termed visual marking—and evidence for such inhibition has been found in a variety of studies (Humphreys, Watson, & Jolicoeur, 2002; Kunar, Humphreys, & Smith, 2003; Kunar, Humphreys, Smith, & Hulleman, 2003; Watson, 2001; Watson & Humphreys, 1997, 2000; Watson, Humphreys, & Olivers, 2003). Following the visual marking account, the present study is designed to examine what resources might support this inhibitory process. In particular, what memory system maintains the record that is required to segregate old, previously processed information from new, unprocessed information? One potential memory resource is visual working memory (VWM). Therefore, in the present study we specifically ask: Can VWM support the inhibition of previewed distractors in a preview search?

Before investigating this question it is important to note that, beyond visual marking, there are three additional mechanisms through which preview effects can be generated. Whereas visual marking describes the inhibition of individual previewed distractors, groups of previewed distractors can be deprioritized through feature inhibition if they all share a similar feature (Braithwaite & Humphreys, 2003; Braithwaite, Humphreys, & Hodsoll, 2003; Braithwaite, Humphreys, Hulleman, & Watson, 2007; Braithwaite, Humphreys, Watson, & Hulleman, 2005; Olivers, Humphreys, & Braithwaite, 2006; Olivers, Watson, & Humphreys, 1999; Watson & Humphreys, 1998). Furthermore, in contrast to inhibitory mechanisms, new items can also be prioritized through facilitation if their appearance causes attentional capture (Donk & Theeuwes, 2001, 2003; Donk & Verburg, 2004; Donk, Agter, & Pratt, 2009; Pratt, Theeuwes, & Donk, 2007). Lastly, new items can also be differentiated from previewed distractors through temporal segregation cues (Jiang & Wang, 2004; Jiang, Chun, & Marks, 2002a, 2002b). Though initially proposed as competing accounts of the preview effect, these multiple accounts (including visual marking) are now thought to describe complementary mechanisms that, together, allow visual search efficiency to be optimized across varying search environments (see Donk, 2006; Olivers et al., 2006). Within the context of the present study, the existence of these alternate mechanisms highlights that measures of the preview effect do not always reflect the ability to inhibit previously processed information. Thus, it will be important in the present study to establish under what circumstances our observed preview effects do indeed reflect the inhibition of previewed distractors, and when they reflect the contribution of other mechanisms.

Visual Working Memory

There are a number of reasons to expect that the VWM system can support the inhibition of previewed distractors by maintaining a record of previously processed information. For example, VWM can maintain the featural and spatial information from a small number of visual objects for short periods of time (Baddeley, 2003; Logie, Zucco, & Baddeley, 1990), making this information available for other behaviors (e.g., for integrating visual information across saccades; Hollingworth, Richard, & Luck, 2008; Irwin, 1991, 1992; Irwin & Andrews, 1996; Richard, Luck, & Hollingworth, 2008). In addition, the time required to encode information in VWM is between 50 and 350 ms (Jolicoeur & Dell'Acqua, 1998; Vogel, Woodman, & Luck, 2006), which is comparable to the amount of time that distractors must be previewed to observe a preview effect (Kunar, Humphreys, & Smith, 2003; Watson & Humphreys, 1997). Furthermore, VWM representations are relatively robust. They are insensitive to sensory changes and changes in retinal position (Phillips, 1974), and so should not be disrupted by the onset of additional search items, or during the search process itself. Finally, there is evidence that VWM can bias visual processing through inhibition (Belopolsky & Theeuwes, 2009; Brockmole & Henderson, 2005; Castel, Pratt, & Craik, 2003; Downing & Dodds, 2004; Emrich et al., 2009, 2010; Theeuwes, Olivers, & Chizk, 2005; Woodman & Luck, 2007; see also, Conway & Engle, 1994; Engle, Conway, Tuholski, & Shisler, 1995). Therefore, VWM should be capable of encoding the locations and identities of previewed distractors, maintaining their representations for the duration of a preview search, and guiding selection by marking the distractors for inhibition.

There are also reasons, however, to expect that VWM would not support top-down inhibition in the preview effect. For example, VWM is a capacity-limited resource that can maintain representations of only about four objects (Cowan, 2001; Luck & Vogel, 1997). As a result, it is difficult to imagine how VWM-based inhibition could usefully contribute to visual processing within scenes that contain many objects, such as those often used in preview searches (e.g., Donk & Theeuwes, 2001; Jiang, Chun, & Marks, 2002a; Theeuwes, Kramer, & Atchley, 1998; Watson & Humphreys, 1997). Other evidence comes from the many recent studies investigating interactions between the contents of VWM and attention. These studies tested whether the featural properties of the objects maintained in memory will bias attention toward, or away from, new stimuli that possess the same properties. Though a small number of these studies have observed inhibition of stimuli that resemble the contents of memory (Carlisle & Woodman, 2011; Downing & Dodds, 2004; Woodman & Luck, 2007), the majority have instead observed enhancement (e.g., Cosman & Vecera, 2011; Downing, 2000; Houtkamp & Roelfsema, 2006; Huang & Pashler, 2007; Olivers, Meijer, & Theeuwes, 2006a; Soto, Heinke, Humphreys, & Blanco, 2005; Soto, Humphreys, & Heinke, 2006; Soto, Wriglesworth, Bahrami–Balani, & Humphreys, 2010). Indeed, based on these studies, some researchers have argued that attention is automatically captured by stimuli that are similar to the contents of VWM (for a review, see Soto, Hodsoll, Rotshtein, & Humphreys, 2008). From this conclusion, one might predict that if previewed distractors were encoded in VWM, these distractors would actually be prioritized over new ones, rather than inhibited. Given the conflicting evidence, it is unclear whether VWM can, or cannot, support the inhibition of previewed distractors in a preview search.

The Present Study

Our primary goal for the present study was to test whether or not VWM can support the inhibition (i.e., visual marking) of previewed distractors in a preview search. There has been one prior study to investigate the memory systems that support the preview effect (Jiang & Wang, 2004). In this study, Jiang and Wang noted two important points before testing for the capacity of the preview effect. First, it is possible to dissociate the contributions of inhibition and facilitation in the preview effect by selectively manipulating either the number of previewed distractors or the number of new distractors, respectively (see also, Donk & Theeuwes, 2001;

Jiang, Chun, & Marks, 2002a). Second, it is difficult to compare the effectiveness of preview inhibition/facilitation against the capacity of VWM, because the preview effect is measured through time (i.e., it is an effect on search time), but memory capacity is measured through accuracy (i.e., accuracy on a change detection task or other memory task; Luck & Vogel, 1997). To overcome this second problem, Jiang and Wang (2004) developed a novel preview-search paradigm that measured search accuracy rather than search time. Using this task, the authors observed evidence that the preview effect is supported by a high-capacity fast-decaying memory system and a limited-capacity slow-decaying memory system; the capacity of the second system was comparable to that of VWM. Of importance, the contribution of the low-capacity memory system to the preview effect varied with the number of new distractors and not the number of previewed distractors. From this, the authors concluded that VWM is used to facilitate the processing of a small number of new items, and that it is not used to inhibit previewed distractors.

There are two reasons, however, why the results of Jiang and Wang (2004) may be insufficient to rule out a role for VWM in the inhibition of previewed distractors. First, it may be that VWM can be used flexibly to either facilitate or inhibit the processing of information (see, Woodman & Luck, 2007), and that the tasks employed by Jiang and Wang biased participants to adopt the facilitatory role. Indeed, the number of previewed distractors in their tasks almost always exceeded the (approximate) four-item capacity of VWM. As participants could not have inhibited all previewed distractors, they may have instead chosen to facilitate a small number of new items, thus guaranteeing that the first few processed objects would always be new. Second, because Jiang and Wang employed an accuracy-based preview search task, it is important to evaluate whether their results extend to more typical preview searches that measure search time. Therefore, in the present study we directly tested whether VWM can support the inhibition of previewed distractors by using more typical preview-search tasks, and by controlling the number of previewed distractors to encourage the use of VWM-based inhibition.

In the four experiments that follow, we test three predictions derived from the hypothesis that VWM can support the inhibition of previewed distractors in a preview search. First, preview inhibition should be more effective when the number of previewed distractors is below the capacity of VWM than above. Second, changes in visual search difficulty (i.e., shorter vs. longer search times) should not affect the contribution of VWM to the preview effect (i.e., the contribution should always reflect the inhibition of up to about four distractors). Third, individual differences in the magnitude of the preview effect should be related to individual differences in VWM capacity. To foreshadow the results, all three predictions are confirmed, providing converging evidence that VWM contributes to the efficiency of visual information processing by allowing previously processed information to be ignored.

Experiment 1

In Experiment 1, we tested the first prediction of the proposal that VWM supports preview inhibition—there should be a clear effect of WVM capacity on preview efficiency. Because VWM can only maintain the representations of about four objects, when the number of previewed distractors exceeds four, some will not be remembered and therefore not be inhibited, causing an overall decrease in the effectiveness of preview inhibition. Accordingly, in Experiment 1 we tested this prediction that the effectiveness of preview inhibition is greater when the number of previewed distractors is below the capacity of VWM than when the number of previewed distractors exceeds the capacity of VWM.

Participants performed a visual search for a green letter *H* among green distractor letters. In one preview condition stimuli were isoluminant with the background and in a second they were presented with luminance onsets. This manipulation allowed us to assess whether VWM contributes to preview inhibition even when prioritization by attentional capture (a highly efficient preview mechanism; Donk & Theeuwes, 2001; Donk & Verburg, 2004) is possible. We varied the number of previewed distractors (between zero and five, or seven items) while holding constant the number of new items (there were always eight). Search RTs should, therefore, be shortest when there are no items previewed and grow increasingly longer with the addition of each previewed distractor. The critical prediction is that if VWM supports the inhibition of previewed items, then the RT cost of adding previewed distractors should vary depending on whether or not the total number of previewed distractors exceeds the capacity of VWM. If the number of previewed distractors is below the capacity of VWM, then adding one more should impose little cost, if any, to search time, as the distractor can be represented in memory and inhibited. If, however, the total number of previewed distractors exceeds the capacity of VWM, then this distractor should impose a larger cost on search time. Put another way, if VWM supports the inhibition of previewed distractors, then the search slope should be shallower for preview set sizes from zero to three (below the capacity of memory) than preview set sizes from four to seven (above the capacity of memory).

Methods

Participants. Forty-nine University of Toronto undergraduate students participated for partial credit toward an introductory psychology course. All participants were naïve to the purpose of the experiment, and reported having normal or corrected-to-normal vision. Informed consent was obtained from all participants. Three participants were excluded from the analyses because they made errors on more than 10% of trials.

Apparatus and stimuli. The experiment was conducted on a PC computer with a VGA monitor and a head/chin rest, and responses were made on a standard keyboard. Displays were presented at a resolution of 1024×768 pixels, using a refresh rate of 85 Hz. The target of the visual searches was an uppercase letter *H*. Search distractors were randomly selected without replacement from a pool of 16 uppercase letters (*A, B, C, E, F, G, J, K, M, N, P, R, S, T, U, V*). Letters were drawn in green on a gray background, subtended approximately 0.8° of visual angle in width and height, and were presented at random locations on a virtual 8×8 square grid (16° in width) around a central fixation cross ($0.4° \times 0.4°$). These stimulus sizes and positions were chosen to ensure that stimuli were always separated by at least 1.2° (edge to edge), which should be sufficient to prevent density effects at large preview set sizes (Cohen & Ivry, 1991, 1989; Pashler, 1987).

Design and procedure. On all trials, participants performed a visual search to determine if the target letter, an *H*, was present (see Figure 1). Search displays were composed of two sets of

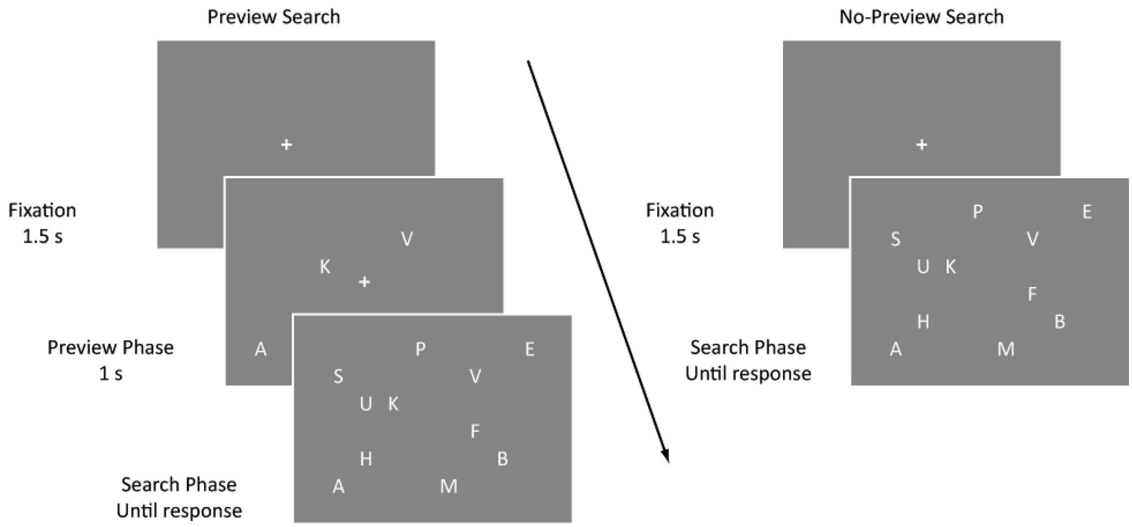

Figure 1. A depiction of the trial sequences for the preview (i.e., onset preview and isoluminant preview) and no-preview conditions in Experiment 1.

items: old items and new items. The set of old items contained anywhere between zero and five or seven distractor letters. The new items were eight distractor letters, or seven distractors plus the target. Participants were randomly assigned to one of three conditions. In the two preview conditions, the fixation cross was presented for 1.5 s, and then the set of old items were previewed for 1 s. Next, the set of new items was presented, and the fixation cross was removed from the display to signal that participants should begin their search. Participants were instructed that the set of old items would never contain the target, and that they should maintain fixation until the fixation cross disappeared. Of the two preview conditions, one was an onset condition where all stimuli had greater luminance than the background (13.14 cd/m^2 vs. 0.74 cd/m^2), and the other an isoluminant condition where perceptual luminance was equated. To equate luminance, each participant began the experiment by adjusting the luminance of a green patch (the stimulus color) until it matched that of a gray patch (the background color). Each participant performed 10 such adjustments, with the initial luminance of the green patch alternating between above and below the luminance of the gray patch. The onset condition was included to assess whether or not evidence for VWM involvement is observed even when prioritization can be achieved through attentional capture by the onset of new items (Donk & Theeuwes, 2001). As a baseline for the two preview conditions, a no-preview condition was included in which old and new items appeared simultaneously (i.e., the 1-s preview was eliminated), and with the same intensities as in the isoluminant condition. Thus, there was one between-participants condition, preview type (isoluminant preview vs. onset preview vs. no preview), and one within-participant condition, set size (zero to five or seven old items, plus eight new items). Participants performed 532 trials, making a speeded keyboard response on each to indicate the presence (50% of trials) or absence of the target. Trials were separated by a 1-s blank intertrial interval.

Results and Discussion

Error trials (3.5%) and trials for which reaction times (RTs) did not fall within 2.5 standard deviations of the participant's mean (2.3%) were not analyzed. Mean RTs for target-present trials are plotted in Figure 2. Reaction times for target absent trials are presented in Table 1, but were not analyzed because, although memory may bias search priorities by inhibiting old items, it is

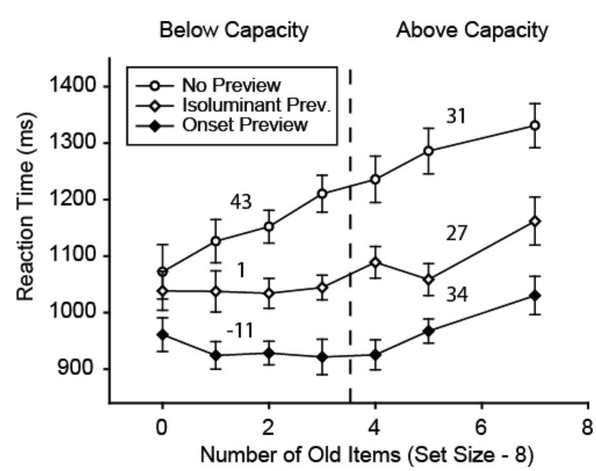

Figure 2. The mean RTs in the three search conditions of Experiment 1. Search slopes (ms/item) across set sizes below/above VWM capacity appear above the plotted lines. Of note, the RT differences at set size 0 likely result from having different groups complete each condition, and the manipulation of luminance. To avoid such differences, in all subsequent experiments preview type was a within-subject manipulation and luminance was not manipulated. Error bars in this figure, and all subsequent figures, are within-subject 95% confidence intervals (Cousineau, 2005). For Experiment 1, but not subsequent experiments, error bars only reflect differences across set size within a search type, as search type was a between-participants factor.

Table 1
Mean (SD) Search Times From Target-Absent Trials in Experiment 1

	Set size						
Preview type	0	1	2	3	4	5	7
No preview	1405 (338)	1556 (389)	1685 (422)	1809 (449)	1880 (482)	2002 (507)	2280 (551)
Isoluminant preview	1634 (451)	1633 (449)	1702 (411)	1753 (409)	1861 (481)	1921 (535)	2059 (548)
Onset preview	1386 (209)	1278 (88)	1344 (97)	1362 (118)	1426 (162)	1473 (190)	1623 (231)

possible that participants will nevertheless choose to search these items before terminating their search and concluding that no target was present (Chun & Wolfe, 1996). Because the number of new items was held constant across all conditions, figures are plotted by the number of items previewed. In the preview conditions, the search slope is roughly flat until about three or four items and increases thereafter. This finding is in line with the hypothesis that the preview effect is supported by the representation of old items in VWM: the benefit afforded by previewing distractors is greatest when the number of previewed items is within the capacity of VSTM.

A 3 (preview type) × 7 (set size) mixed analysis of variance (ANOVA) was performed on mean RTs to assess the general differences among the three preview conditions. This analysis revealed a main effect of set size, $F(6, 258) = 26.65$, mean standard error [MSE] $= 1.29 \times 10^5$, $p < .001$, indicating that RTs were slower when more distractors were present, as is typically seen in visual searches. Of importance, this analysis also revealed a main effect of preview type, $F(2, 43) = 4.81$, $MSE = 1.63 \times 10^6$, $p = .012$, that was qualified by a significant interaction with set size, $F(12, 258) = 5.18$, $MSE = 2.51 \times 10^4$, $p < .001$. These two results suggest that RTs were faster in the preview conditions than the no-preview condition, but that this benefit in RT varied depending on how many distractors were previewed.

The critical test for Experiment 1 is that preview inhibition is more effective (as measured by search slope) when the number of old items is below the capacity of VWM (set sizes zero to three) than when it exceeds the capacity of memory (set sizes four to seven). Starting with the onset preview condition, the search slope (in ms/item) was shallower for old-item set sizes below the capacity of memory, mean [M] $= -11.39$, standard deviation [SD] $=$ 33.34, than above, $M = 34.43$, $SD = 34.40$, as confirmed by a planned paired-samples t test, $t(16) = 4.33$, $p < .001$. The same was true in the isoluminant preview condition: The search slope was significantly shallower below the capacity of memory, $M =$ 1.49, $SD = 30.65$, than above, $M = 26.60$, $SD = 27.19$, $t(15) =$ 3.55, $p = .003$. In both preview conditions, preview inhibition was most effective when the number of previewed distractors was less than the capacity of VWM. Furthermore, as there was no significant difference between set sizes below, $M = 43.01$, $SD = 11.93$, and above, $M = 30.86$, $SD = 35.37$, the capacity of memory in the baseline no-preview condition, $t(12)$, $p = .447$, this change in the effectiveness of preview inhibition is likely related specifically to the number of previewed distractors, and not the total number search items. By confirming the prediction that preview inhibition is more effective when the number of previewed distractors is below the capacity of VWM than above, these results provide the first piece of evidence that VWM can support preview inhibition.

To further explore how the effectiveness of preview inhibition changes with set size, we compared the observed search slopes (both above and below capacity) in the two preview conditions directly against the search slopes in the no-preview baseline. Although the isoluminant no-preview condition does not provide a perfect baseline for the onset preview condition, the similarities between search slopes in the two preview conditions suggest that the differences in luminance did not impact the primary findings (luminance was held constant in all subsequent experiments). As would be expected, when the number of old items was below the capacity of memory, the slopes in both the isoluminant and onset conditions were more shallow than the slope in the no-preview condition, $t(27) = 3.90$, $p < .001$, and $t(28) = 4.94$, $p < .001$, respectively. These results reflect a typical preview effect: The cost of distractors on search time is smaller when they are previewed than not previewed. Of note, above the capacity of VWM, neither the isoluminant nor onset search slopes differed from that of the no-preview condition, $t(27) = -1.09$, $p = .286$, and $t(28) =$ 0.30, $p = .765$, respectively. Therefore, search was not significantly more efficient in the preview conditions than the no-preview condition. Although there is an overall difference in RT between preview and no-preview searches at set sizes 4, 5, and 7, the important finding is that the search slope across these set sizes does not vary among preview conditions. To elaborate, across set sizes 1 through 4 of the isoluminant preview and no-preview conditions, overall differences in RT grow because items are successfully inhibited in the preview condition. Once the number of old items exceeds the capacity of VWM, however, the differences in overall RT cease to increase (i.e., the slope is the same between condition) because no new distractors are inhibited (for a similar argument, see Emrich et al., 2010). Put another way, the preview effect in the present study exhibited a capacity limit, and the capacity limit was comparable to that of VWM. This potential capacity limit is a surprising finding given that almost all past preview-search studies show effectively capacity-unlimited preview effects (although see Emrich, Ruppel, Al-Aidroos, Pratt, & Ferber, 2008; e.g., Jiang, Chun, & Marks, 2002a; Theeuwes et al., 1998; Watson & Humphreys, 1997; Watson & Kunar, in press), a point we address in Experiments 2A and 2B.

To summarize, Experiment 1 demonstrated two important findings. First, and most importantly, the initial prediction—that the preview effect would be more effective when the number of previewed distractors is below the capacity of VWM than above—was confirmed. Second, beyond a mere change in effectiveness, the preview effect appeared to be entirely limited by the capacity of VWM in the present task. What can explain the difference between the apparently capacity-limited preview effect in Experiment 1 and capacity-unlimited preview searches in past studies?

Experiment 1 differed from most preview studies in two major ways: Whereas we focused on small preview set sizes (i.e., those close to the capacity of VWM) and allowed participants to moves their eyes freely, most prior studies only tested preview set sizes above the capacity of VWM while subjects maintained fixation. To help integrate the present study with past preview research, we first test whether we can observe the more commonly reported capacity-unlimited preview effect when we add a very large preview set size (Experiment 2A) and when fixation is controlled during search (Experiment 2B), before Experiments 3 and 4 test two more predictions drawn from the proposal that VWM supports preview inhibition.

Experiment 2A

As noted earlier, there are numerous mechanisms that can support the preview effect (e.g., visual marking, attentional capture, feature-based inhibition, and temporal segregation) depending on the number and types of search items used. In the current study, however, we eliminated the contribution of many of these alternate preview mechanisms. Feature inhibition was prevented by having participants perform a search for a green *H* through a chromatically homogenous display of green letters, and attentional capture was prevented by including an isoluminant preview condition. Of importance, we also attempted to encourage the use of VWM-based inhibition by limiting the number of previewed distractors so that, more often than not, VWM would be able to optimally inhibit the entire set of previewed distractors. Given that the magnitude of the preview effect varied as a function of the number of previewed items, this task appears to have been successful in encouraging participants to focus on the inhibition of previewed items rather than the facilitation of new items (Jiang & Wang, 2004; Jiang, Chun, & Marks, 2002a). Indeed, participants appear to have employed inhibition even in the onset-preview condition, where prioritization through facilitation of new items can allow well over 15 previewed distractors to be ignored (e.g., Donk & Theeuwes, 2001). These results suggest that, as hoped, limiting the number of previewed distractors to set sizes that can be maintained in VWM may have provided strong encouragement to participants to employ VWM-based inhibition during preview searches.

The purpose of Experiment 2A was to help reconcile the results of Experiment 1—in particular what appeared to be a capacity limit on the preview effect—with past preview-search studies showing capacity-unlimited preview effects. One reason that we might have observed a capacity limit where past studies have not is that, unlike past studies, we used very small preview set sizes. Accordingly, we designed Experiment 2A to replicate the basic results of Experiment 1 and present participants with one additional "very-large set size" condition in which VWM-based inhibition should be of little value. In this additional condition, the number of preview distractors far exceeds the capacity of memory. If our interpretation is correct, then we should observe a capacity-limited preview effect at set sizes just above the capacity of VWM (i.e., set sizes 5 to 7), but a capacity-unlimited preview effect should emerge for the very large set size, as VWM-based inhibition alone is no longer effective.

Drawing from Experiment 1, we modified Experiment 2A in a number of ways. The number of preview set sizes was reduced, and only included the critical set sizes for assessing search efficiency below the capacity of memory (1 and 3 items), slightly above the capacity of memory (5 and 7 items), and considerably above the capacity of memory (17 items). The need for no-target trials was eliminated by having participants report the side of the display on which the target appeared (catch trials were included to ensure that participants searched both sides). There was no manipulation of luminance in Experiment 2A (or 2B, 3 or 4) because attentional capture did not appear to contribute to the preview effect in Experiment 1. All participants completed both the preview and no-preview conditions making preview type a within-participant factor (preview type was a between-participants factor in Experiment 1). Finally, a stimulus (a box around the fixation point) was included in the display that was used to indicate the beginning of the preview phase (including on no-preview trials). Using this task we should replicate two findings from Experiment 1. First, we should replicate the basic finding that preview inhibition is more effective for set sizes below the capacity of VWM than above. Second, we should also replicate the capacity limit at preview set sizes just above the capacity of VWM. The open question is whether or not we will observe a capacity limit at the very large set size. Do we observe the more common capacity-unlimited preview effect when sets sizes are more comparable to those used in previous studies?

Methods

Participants. Twenty-seven University of Toronto undergraduate students participated for partial credit toward an introductory psychology course. All participants were naïve to the purpose of the experiment, and reported having normal or corrected-to-normal vision. All participants correctly omitted responses on at least 80% of catch trials, and made fewer than 10% errors on noncatch trials. Informed consent was obtained from all participants.

Apparatus and stimuli. With three exceptions, the apparatus and stimuli were the same as in Experiment 1. First, stimuli were always presented with the same luminance as the onset preview condition in Experiment 1. Second, the fixation stimulus from Experiment 1 was modified by adding a surrounding box (1° in width and height), whose disappearance was used to signal to participants the beginning of the preview phase. Because preview and no-preview trials were mixed within blocks in the present experiment, this signal allowed participants to identify the start of the preview phase on no-preview trials, despite the fact that no search stimuli were presented. Third, to accommodate the addition of the large set size, the pool of search items included all letters from the English alphabet—the target was once again the letter *H*.

Design and procedure. Search displays were composed of two sets of items: old items (1, 3, 5, 7, or 17 distractor letters) and new items (seven new distractors plus the target, or eight new distractors on catch trials). The identity of each distractor was randomly determined. All participants performed preview and no-preview searches, which were randomly mixed across trials. On preview trials, the fixation stimulus was presented for 1 s, after which the old items were previewed. To mark the beginning of the preview phase, the box surrounding the fixation cross was offset at the same time that the old items were onset. After old items were previewed for 1 s, the new items were added to the display. To mark the beginning of the search phase, the fixation cross was offset at the same time that the new items were onset. Participants were instructed that the set of old items would never contain the target, and that they should maintain fixation until the fixation cross disappeared. No-preview trials were identical to preview trials, with the exception that the presentation of old items was delayed, so that old items and new items onset at the beginning of the search phase of the trial. Trials were separated by a 1-s blank intertrial interval. There were two within-participant conditions, which were fully crossed: preview type (preview vs. no preview), and set size (1, 3, 5, 7, or 17 old items, plus eight new items).

Participants completed a total of 360 experimental trials and 20 catch trials during the experimental session. Because only RTs for target present trials are relevant for the analyses that follow, the target was included in the set of new items on all experimental trials. Unlike in Experiment 1 where participants reported target presence, participants instead reported with a key press whether the target was to the left or right of the fixation cross. Target location was randomly determined. On catch trials, no target was presented and participants were required to inhibit responding for 4 s.

Results and Discussion

All participants successfully withheld responding on at least 80% of catch trials. Catch trials were not analyzed further. Trials on which participants made an incorrect response (1.7%) or for which RT did not fall within 2.5 *SD*s of mean RT (0.7%) were excluded from the analyses.

Mean search times are plotted in Figure 3 (as with previous figures, set size is plotted as the number of old items; there were always an additional 8 new items). A 2 (preview type) × 5 (set size) repeated-measures ANOVA on RT revealed the typical effects observed in preview tasks: significant main effects of preview type, $F(1, 26) = 104.97$, $MSE = 1.10 \times 10^6$, $p < .001$, and set size, $F(4, 104) = 155.58$, $MSE = 1.45 \times 10^6$, $p < .001$, and a significant two-way interaction, $F(4, 104) = 19.54$, $MSE = 9.41 \times 10^4$, $p < .001$. These effects indicate that adding items to search displays slowed participants' responses, but that the cost of these items was smaller if they were previewed than if they were presented at the same time as the search target.

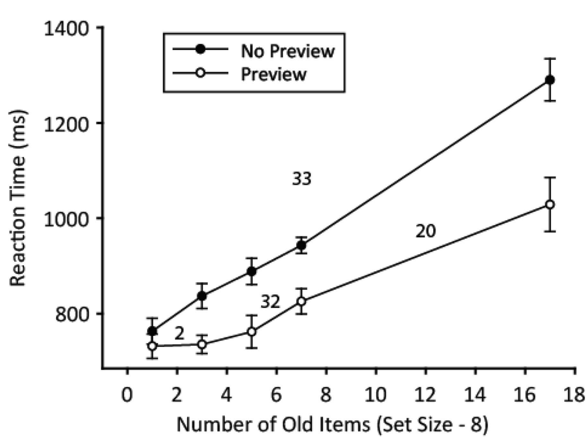

Figure 3. The mean RTs in the two search conditions of Experiment 2A. The search slope (ms/item) of the no-preview condition, as well as the slopes for the critical set sizes in the preview condition, are given above each plot line.

We performed three a priori *t* tests to assess whether or not we were able to replicate the capacity-limited preview effect at small set sizes observed in Experiment 1, while also replicating the typical capacity-unlimited preview effect at large set sizes. These tests compared search slopes in the preview condition at specific set sizes to the search slope in the no-preview condition. As in Experiment 1, search slopes were calculated as a linear regression over the relevant set sizes. Beginning with the replication of Experiment 1, the search slope between set sizes one and three in the preview condition, $M = 1.85$, $SD = 29.03$, was significantly smaller than the search slope in the no-preview condition, $M = 32.78$, $SD = 11.73$, $t(26) = 4.82$, $p < .001$, and the search slope between set sizes five and seven in the preview condition was not, $M = 31.83$, $SD = 41.16$, $t(26) = 0.13$, $p = .901$. In other words, there is a benefit to previewing a small number of search items, but once the number of previewed items exceeds the approximate capacity of VWM, the cost of additional search items is the same regardless of whether they are previewed or not. Thus, when the number of previewed items is small (in this case seven items or less), the preview effect shows a capacity limit that is approximately equivalent to the capacity of VWM (i.e., three or four objects), replicating the limit observed in Experiment 1. Of importance, the search slope between 7 and 17 items in the preview condition, $M = 20.32$, $SD = 11.78$, was significantly smaller than the search slope in the no-preview condition, $t(26) = 4.89$, $p < .001$. In other words, at set sizes larger than seven items, the preview search again became more efficient as compared with a search in which no distractors are previewed. Thus, when the number of previewed items is very large (in this case more than seven items), the preview effect is not limited by the three to four object capacity of memory. Therefore, Experiment 2A reconciles the capacity-limited preview effect observed in Experiment 1, with the more common capacity-unlimited preview effect reported in previous studies. When the majority of previewed distractors can be stored in VWM, the preview effect appears to be driven by VWM-based inhibition, and exhibits a capacity limit. When the potential contribution of VWM is constrained (e.g., by previewing a number of distractors that greatly exceeds the capacity of VWM), however, additional capacity-unlimited preview mechanisms are employed.

Of importance, because preview trials with small and large set sizes were mixed within blocks, it would seem that participants can rapidly switch between mechanisms (i.e., on a within-trial basis). Indeed, this type of rapid tuning of attention based on within-trial task demands has been proposed in a prominent model of attention (Logan & Gordon, 2001). Moreover, it is also possible that both preview mechanisms can operate in parallel on all trials—making rapid switching unnecessary—with search RT being determined by the most effective mechanism (as has been observed for other cognitive abilities; e.g., Godijn & Theeuwes, 2002). Although the present experiment does not answer how these multiple preview mechanisms interact, this experiment does help to integrate the present study with past research by showing that multiple mechanisms (with different capacity limits) can both contribute to preview inhibition.

If individuals have access to capacity-unlimited preview mechanisms, why would they ever rely on a capacity-limited mecha-

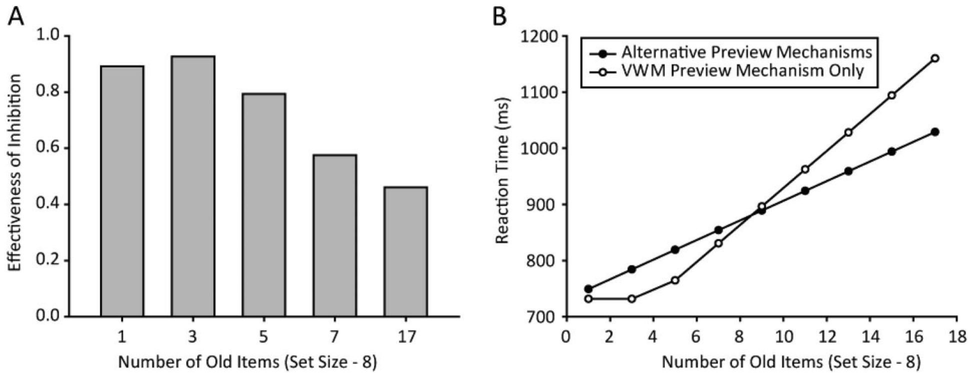

Figure 4. A) Change in the effectiveness of preview inhibition with set size. Effectiveness is calculated at the group level, and is the proportion of successfully inhibited preview items. B) Predicted search times were participants to rely on either only VWM (open circles) or only alternative (closed circles) preview mechanisms (see text for details). Search times are optimized (i.e., minimized) by adopting a VWM-based inhibition from set sizes one to seven, and then alternative mechanisms thereafter.

nism such as VWM? Though this question goes beyond the scope of the present study, Experiment 2 does provide a preliminary answer. Specifically, people employ VWM because, under the right conditions, VWM-based inhibition is more effective than inhibition by alternative mechanisms. It is possible to infer the proportion of distractors that were successfully inhibited at each set size (see the Appendix), and these estimates of the effectiveness of inhibition are plotted in the left panel of Figure 4. Nearly all previewed distractors were successfully inhibited at small set sizes, whereas only about half of the distractors were inhibited at large set sizes. This pattern can also be seen in the search RTs in Figure 3; looking at the largest set-size conditions (i.e., set sizes 7 and 17), although the cost of previewed distractors is less than nonpreviewed distractors, these distractors nevertheless produce a search cost. That is, the search slope in the preview condition at these set sizes is not zero, $t(26) = 8.96$, $p < .001$; a common finding in visual marking studies (e.g., Theeuwes et al., 1998; Watson & Humphreys, 1997, 1998). Furthermore, a *t* test comparing the search slope in the preview condition between very small set sizes (i.e., one to three) and very large set sizes (i.e., 7 to 17) confirms that preview inhibition was more effective when VWM could be used to inhibit all distractors than when alternative mechanisms were required, $t(26) = 2.99$, $p = .006$. Therefore, although VWM is capacity limited, people employ VWM-based inhibition because, at least in the present study, it was more effective (at small set sizes) than inhibition by other available preview mechanisms.

To clarify this point, if we assume that participants only used VWM-based inhibition at small set sizes, and only used alternative mechanisms at large sizes, we can predict search times at all set sizes for both types of mechanisms in isolation.[1] Presented in Figure 4B, these search times provide a visual depiction of which mechanism results in the fastest search times at a given set size. Of interest, this figure reveals that the advantage of VWM-based inhibition should occur for a few set sizes that exceed the capacity of VWM (i.e., set sizes five to eight). Although VWM cannot be used to inhibit all of the previewed distractors, VWM-based inhibition can result in faster search times than alternative mechanisms. This explains why we observe a capacity limit to the preview effect at these set sizes—the number of inhibited distractors ceases to increase because the capacity of VWM has been exceeded, but there are not enough distractors to warrant employing alternative preview mechanisms.

In summary, Experiment 2A provides two important findings. First, it replicates the key finding from Experiment 1 that preview inhibition is more effective when the number of previewed distractors is below the capacity of VWM (one to three distractors) than above (both 5 to 7, and 7 to 17 distractors). Second, it provides an initial explanation for why we observe a capacity limited preview effect. Specifically, inhibition at set sizes below the capacity of VWM was sufficiently more effective than inhibition at the very large set size, that behavioral performance was determined by VWM-based inhibition across set sizes 1–7 (thus revealing a capacity limit at set sizes 5–7).

Put another way, we observed a capacity limit in the present study because, other than VWM-based inhibition, preview inhibition had a relatively poor efficiency. Although this finding provides some reconciliation with prior studies, it raises the question: Why was preview inhibition so inefficient at the very large set size? Using search slope, which is the more typical measure of preview efficiency, preview efficiency from set sizes 7–17 was 20 ms/item in Experiment 2A. Though such a large search slope is not uncommon in preview studies, there are also many demonstrations of very efficient preview inhibition even at large set sizes. In particular, when it is possible to prioritize new search items through attentional capture, as was the case in Experiment 2A, the search slope for preview set sizes typically ranges from 0–10

[1] We calculated search times for the alternative-preview-mechanisms-only condition as the straight line between the recorded RTs in the preview condition at set size 17 and the *y*-intercept of the no-preview condition (i.e., predicted search times at set size zero). We calculated search times for the VWM-preview-mechanism-only condition by extrapolating from the same *y*-intercept, and assuming that the first four distractors produce no cost on search time (i.e., VWM capacity of four items), and the remaining distractors produce the same cost as the nonpreviewed distractors (i.e., the observed slope from the no-preview condition).

ms/item (Donk & Theeuwes, 2001; Donk & Verburg, 2004; Jiang, Chun, & Marks, 2002a).

One major difference between the procedure of Experiment 2A and these prior studies of attentional-capture-based preview effects is that we encouraged participants to move their eyes freely during search, whereas the prior studies encouraged fixation. Because attentional signals are not always updated across saccades, attentional capture may have been prevented from contributing to the preview effect in Experiments 1 and 2A (Golomb, Chun, & Mazer, 2008; Posner, 1980). Two prior studies have investigated the contribution of eye movements to the preview effect. Under a task that encouraged feature-based inhibition (i.e., search for a blue *H* among green *H*s, after previewing blue *H*s), the production of eye movements did not influence the preview effect (Watson & Inglis, 2007). In a different task that was very similar to the present experiments, however, the preview effect did have a clear relation to eye movements: Preview inhibition did not extend beyond the first four eye movements (Emrich et al., 2008). To test whether the production of eye movements can explain our observed large search slope, Experiment 2B replicates Experiment 2A while controlling for eye movements. In line with past preview studies, we should observe two findings. First, the preview search slope in Experiment 2B should be shallower than in 2A, and fall around the 0–10 ms/item range identified in previous studies. Second, because of the increase in preview efficiency, VWM-based inhibition will no longer solely determine the preview effect, and there should be little or no evidence of the contribution of VWM to the preview effect.

Experiment 2B

Methods

Participants. Twenty-seven University of Toronto undergraduate students participated for partial credit toward an introductory psychology course. All participants were naïve to the purpose of the experiment, and reported having normal or corrected-to-normal vision. Three participants were removed from the analyses reported below: one for incorrectly generating responses on 32% of catch-trials, one for making errors on 26% of noncatch trials, and one for failing to follow the task instructions. All participants correctly omitted responses on at least 80% of catch trials, and made fewer than 15% errors on noncatch trials. Informed consent was obtained from all participants.

Apparatus, stimuli and procedure. The apparatus, stimuli and procedure from Experiment 2A were modified to encourage participants to maintain fixation during visual search. An additional box (width 1.1°, height 2.0°) was added to the box-and-crosshair fixation stimulus from Experiment 2A. The disappearance of the outer box indicated to participants that the preview phase had begun, while the disappearance of the inner box indicated that the search phase had begun, and the crosshair was visible throughout the trial to encourage central fixation during the search process. Because the more peripheral stimuli in Experiment 2A could not be accurately discriminated while maintaining fixation, we scaled stimulus size and separation with eccentricity. Stimuli were presented on an imaginary 6 × 6 square grid, with positions 2, 5, and 10° to the left/right and above/below the fixation point. Stimulus size increased from 1 to 1.5 to 2° with eccentricity. Finally, participants were repeatedly given verbal instructions to maintain fixation, and the experimenter monitored compliance using a closed-circuit TV camera directed at participants' eyes. In all other respects, Experiment 2A and 2B were identical.

Results and Discussion

All participants successfully withheld responding on at least 80% of catch trials. Catch trials were not analyzed further. Trials on which participants made an incorrect response (4.9%) or for which RT did not fall within 2.5 *SD*s of mean RT ($<$0.1%) were excluded from the analyses.

Mean search times are plotted in Figure 5 (as with previous figures, set size is plotted as the number of old items; there were always an additional 8 new items). A 2 (preview type) × 5 (set size) repeated-measures ANOVA on RT revealed the typical effects observed in preview tasks: significant main effects of preview type, $F(1, 23) = 96.10$, $MSE = 1.90 \times 10^6$, $p < .001$, and set size, $F(4, 92) = 103.33$, $MSE = 1.09 \times 10^6$, $p < .001$, and a significant two-way interaction, $F(4, 92) = 20.85$, $MSE = 1.39 \times 10^4$, $p < .001$. These effects indicate that adding items to search displays slowed participants' responses, but that the cost of these items was smaller if they were previewed than if they were presented at the same time as the search target.

This first critical finding to assess was the overall efficiency of inhibition in the preview condition. As would be expected if the difference in eye movements can reconcile the present and past research, the preview search slope across all set sizes was 11.79 ms/item, thus falling around the commonly reported 0–10 ms/item range, and was significantly reduced relative to the 20.32 ms/item slope in Experiment 2A (measured across non-VWM set sizes, 7–17), $t(49) = 2.35$, $p = .023$.

The second finding to assess is that, given this increase in preview efficiency, we should find little, or no, evidence of the contribution of VWM to the preview effect. Because the efficiency of non-VWM preview mechanisms rivals that of VWM, VWM-based inhibition will no longer determine behavioral performance, and the preview effect will no longer be capacity limited. To test this prediction we performed the same three a priori *t* tests from

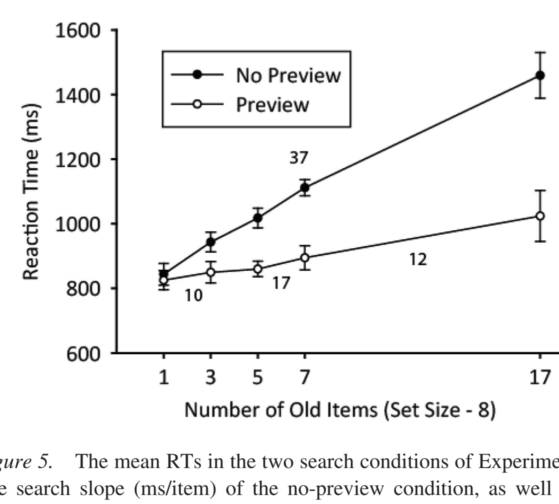

Figure 5. The mean RTs in the two search conditions of Experiment 2B. The search slope (ms/item) of the no-preview condition, as well as the slopes for the critical set sizes in the preview condition, are given next to each plotted line.

Experiment 2A that compared search slopes at specific set sizes between the preview and no-preview conditions. As in Experiment 2A, the no-preview search slope, $M = 36.52$, $SD = 14.49$, was steeper than preview search slopes across set sizes 1–3, $M = 10.04$, $SD = 39.61$, $t(23) = 3.50$, $p = .002$, and set sizes 7–17, $M = 12.34$, $SD = 17.67$, $t(23) = 4.32$, $p < .001$. Unlike Experiment 2A, however, the no-preview search slope was also steeper than the preview search slope from set sizes 5–7, $M = 16.85$, $SD = 51.71$, $t(23) = 2.11$, $p = .046$. Whereas a capacity limit emerged in Experiment 2A at set sizes just above the capacity of VWM, we saw no evidence for this limit in Experiment 2B.

The results of Experiment 2B reveal that when participants perform a search without eye movements, VWM does not measurably contribute to the preview effect; instead, search times across all preview set sizes appear to be determined by a different, highly efficient mechanism—likely new information is prioritized through attentional capture (Donk & Theeuwes, 2001). This conclusion is consistent with a previous demonstration that only the first four eye movements during a preview search are biased away from old items (Emrich et al., 2008). The results of the present experiment, together with those of Experiment 2A, provide a compelling explanation for the discrepancy between the results of Experiment 1 and those of previous studies: VWM is used to support the inhibition of a small number of old items, and under natural viewing conditions (i.e., when participants are able to make eye movements). To better understand this process, the remaining two experiments focus on preview searches that involve eye movements, and using small preview set sizes.

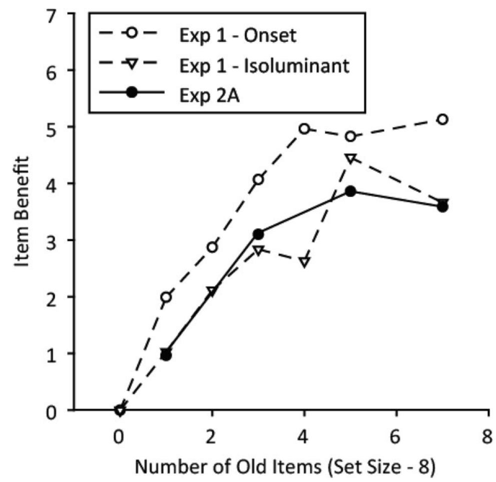

Figure 6. Estimates of the number of successfully inhibited distractors in the preview conditions of Experiments 1 and 2A. These estimates were calculated based on group mean reaction times. For clarity, the very large set size from Experiment 2A is not included.

Experiment 3

In Experiment 3 we test a second prediction of the proposal that VWM supports the inhibition of previewed distractors. According to this proposal, the magnitude of the preview effect is determined by how many distractors can be remembered and inhibited, and this number is determined by the capacity of VWM (when up to seven items are previewed). Consequently, as long as the memory demands of encoding previewed distractors is held constant, there should be some stability in the magnitude of the preview effect across different types of visual searches. More specifically, whereas the RT difference between preview and no-preview searches may vary across search types (e.g., easy vs. hard visual searches), this RT difference should always reflect the inhibition of about four distractors.

It is possible to estimate the number of inhibited distractors in our preview searches using a relatively simple calculation (see Appendix). This calculation converts the decrease in RT from no-preview to preview searches into an estimate of the number of successfully inhibited items: the item benefit. Figure 6 plots the item benefits for each preview condition of Experiments 1 and 2A (focusing on those set sizes around the capacity of VWM). These estimates recharacterize the RT data from Figures 2 and 3 so that it is easier to infer how many previewed distractors were successfully inhibited. Thus, not surprisingly, these estimates suggest the same conclusions that were drawn from the RT data. At set sizes below the capacity of VWM, preview inhibition is efficient and increases in a roughly one-to-one relationship with the number of previewed distractors. At set sizes above the capacity of memory, there is little indication of any benefit to previewing distractors. Thus, these estimates support the RT data by suggesting that a maximum of about four previewed distractors were inhibited across all three tasks. Experiment 3 uses the item benefit calculation to test the prediction that the number of inhibited previewed distractors does not vary with search difficulty.

Participants in this experiment performed two types of preview searches: a hard search and an easy search. In the hard search participants had to locate a lowercase *q* among *p* and *d* distractors. In the easy search, participants searched instead for *d* targets among *p* and *q* distractors. These three letters are all composed of a line and a circle, and differ only in the location of the line on the circle. In the hard search, participants must locate the item with a line that is both on the right and extends downward. This difficult discrimination should result in a steeper search slope than in the easy search, where participants need only locate the item with a line that extends upward. Of importance, the memory capacity for these three letters should be equivalent; due to their visual similarity, these letters should induce comparable visual information loads (Alvarez & Cavanagh, 2004). If VWM supports the inhibition of previewed distractors, then item benefits should not differ between easy and hard searches, but RT benefits should.

Methods

Participants. Twelve University of Toronto undergraduate students participated for partial credit toward an introductory psychology course. All participants were naïve to the purpose of the experiment, and reported having normal or corrected-to-normal vision. Informed consent was obtained from all participants. Two participants were removed from the analyses that follow (one who responded on 85% of catch trials, and a second who made errors on more than 10% of noncatch trials), resulting in a final sample of 10 participants.

Apparatus and stimuli. The apparatus was the same as in Experiment 2A. The identities of the search stimuli were the lowercase letters *d*, *p*, and *q*, but were presented at the same locations and with the same sizes, colors, and intensities as in Experiment 2A.

Design and procedure. Each participant performed a preview task twice, once with hard searches where the target was a *q*, and once with easy searches where the target was a *d*; task order was counterbalanced among participants. Search displays were composed of two sets of items: old items and new items. Old items were either two or six distractor letters. New items were seven distractors plus the target, or eight distractors. The identity of each distractor was randomly determined to be one of the two nontarget letters. All participants performed preview and no-preview searches (see Figure 7), which were randomly mixed across trials. On preview trials, the fixation stimulus was presented for 1 s, after which the old items were previewed. As in Experiment 2A, to mark the beginning of the preview phase, the box surrounding the fixation cross was offset at the same time that the old items were onset. After old items were previewed for 1 s, the new items were added to the display. To mark the beginning of the search phase, the fixation cross was offset at the same time that the new items were onset. Participants were instructed that the set of old items would never contain the target, and that they should maintain fixation until the fixation cross disappeared. No-preview trials were identical to preview trials, with the exception that both old items and new items onset at the beginning of the search phase of the trial. Trials were separated by a 1-s blank intertrial interval. There were three within-participant conditions, which were fully crossed: search difficulty (easy vs. hard), preview type (preview vs. no preview), and set size (two vs. six old items, plus eight new items).

Participants completed a total of 816 experimental trials and 72 catch trials during the experimental session. Because only RTs for target present trials are relevant for the analyses that follow, the target was included in the set of new items on all experimental trials. As in Experiment 2A, participants reported with a key press whether the target was to the left or right of the fixation cross. Target location was randomly determined. On catch trials, no target was presented and participants were required to inhibit responding for 4 s.

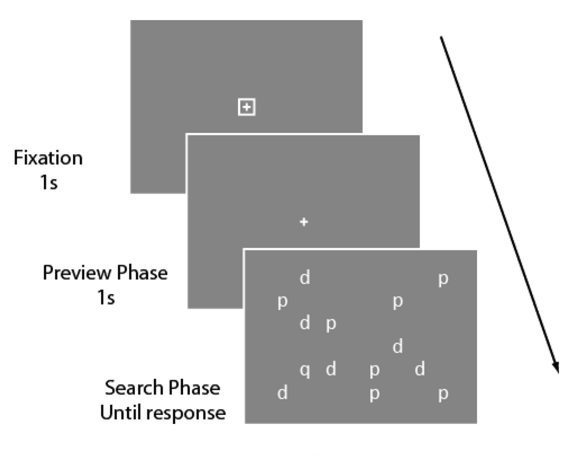

Figure 7. An example trial sequence from a no-preview trial in Experiment 3.

Results and Discussion

All participants successfully withheld responding on at least 80% of catch trials. Catch trials were not analyzed further. Trials on which participants made an incorrect response (5.1%) or for which RT did not fall within 2.5 *SD*s of mean RT (2.8%) were excluded from the analyses.

Mean search times are plotted in Figure 8A (as with previous figures, set size is plotted as the number of old items; there were always an additional 8 new items). As would be expected, participants performed easy searches more quickly than hard searches and were able to find the target item more quickly when fewer items were present. Of importance, previewing distractors resulted in a RT benefit (i.e., no-preview RT minus preview RT), and this benefit was greater at set size 6 than 2. That is, consistent with the results of Experiments 1 and 2A (see Figure 6), the maximum preview effect is observed when the number of previewed items is greater than or equal to the capacity of VWM. To verify this pattern of results, a 2 (search difficulty) $\times$ 2 (preview type) $\times$ 2 (set size) within-participants ANOVA was performed on the mean RTs. This analysis revealed significant main effects of search difficulty, preview type, and set size (all F values >33, all p values $< .001$). All two-way interactions were also significant. Search difficulty interacted with set size, $F(1, 9) = 8.46$, $MSE = 3.68 \times 10^4$, $p = .017$, confirming that easy searches were in fact more efficient than hard searches. Preview type also interacted with set size, $F(1, 9) = 7.63$, $MSE = 1.09 \times 10^4$, $p = .022$, confirming that the preview effect increases with set size. Of importance for the purposes of this experiment, search difficulty also interacted with preview type, $F(1, 9) = 12.56$, $MSE = 2.43 \times 10^4$, $p = .004$, suggesting that the preview effect was greater for hard searches than easy searches, as predicted. The three-way interaction was not significant ($F < 1$).

The primary question of Experiment 3 is whether the item benefit from the preview effect remains relatively constant across search difficulty (despite large changes in the RT benefit), indicating that a similar number of items were in fact inhibited during easy and hard searches. As can be seen in Figure 8, which depicts the mean RT benefit (panel B) and the mean item benefit (panel C), search difficulty had a large effect on the magnitude of the RT benefit, but little if any effect on the item benefit. Instead, regardless of search difficulty, participants inhibited previewed distractors up to the capacity of VWM. To assess this interpretation statistically, the RT benefit was compared across search difficulty and set size using a 2 $\times$ 2 within-participants ANOVA, and an equivalent analysis was also performed on individual estimates of the item benefit. The analysis of the RT benefit revealed a significant main effect of set size, $F(1, 9) = 7.60$, $MSE = 2.17 \times 10^4$, $p = .022$, and a significant main effect of search difficulty, $F(1, 9) = 14.53$, $MSE = 4.85 \times 10^4$, $p = .004$, confirming that search difficulty altered the RT benefit. The two-way interaction was not significant ($F < 1$). In contrast, the same analysis applied to the item benefit revealed only a main effect of set size, $F(1, 9) = 6.39$, $MSE = 19.32$, $p = .032$. The main effect of search difficulty and the two-way interaction were both nonsignificant (F values < 1). Thus, increasing the difficulty of the search process resulted in a larger preview effect when measured through RTs; however, this increase did not reflect an increase

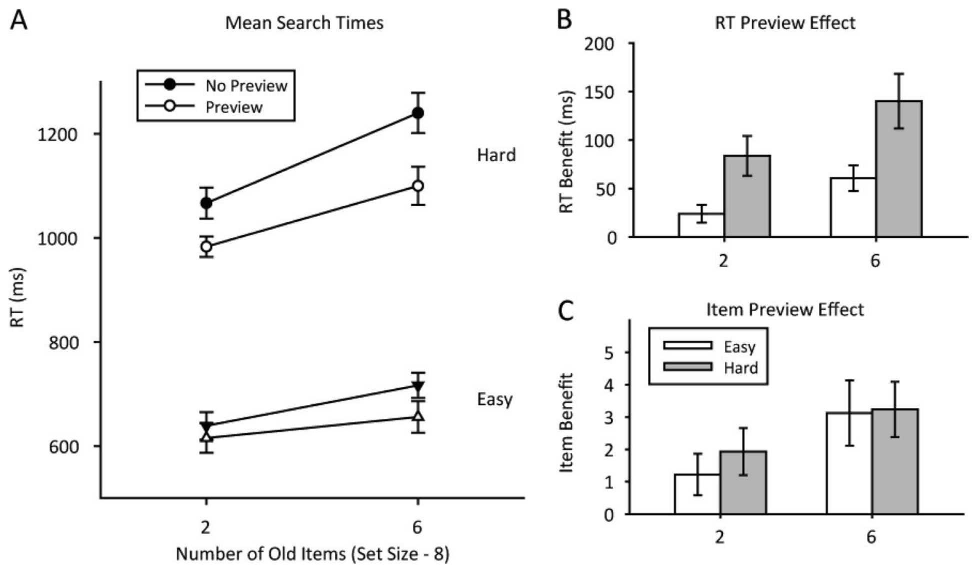

Figure 8. A) Mean RTs for easy and hard searches in Experiment 3. B) The preview effect in RT, calculated as the difference between no-preview RT and preview RT. C) The preview effect characterized as an item benefit.

in the number of inhibited distractors. Instead, these results confirm the second prediction from the proposal that VWM supports preview inhibition: If the magnitude of the preview effect is characterized as an item benefit, it remains stable across changes in search difficulty.

Experiment 4

Through Experiments 1 to 3, we have tested and confirmed two predictions of the proposal that VWM supports preview inhibition. In Experiment 4 we test a third prediction. If VWM supports preview inhibition, then individual differences in the magnitude of the preview effect should correlate with individual differences in VWM capacity. More specifically, in the experimental tasks used for the present studies, in particular at set sizes just above the capacity of VWM, the preview effect appears to reflect solely the operation of a capacity-limited inhibitory system. If this system is VWM, then it can be predicted that measures of the number of inhibited items at these set sizes should correlate with measures of VWM capacity. For this reason, in Experiment 4 we recorded individual estimates of the item benefit at preview set size 6, and VWM capacity. To measure VWM capacity, participants performed two change-detection tasks; they were required to remember spatial locations in one, and colors in the other. There are reasons to believe that spatial information and object identity information are maintained in separate storage subsystems of VWM (Logie & van der Meulen, 2009; Logie, 1995, 2003; Luck, 2009), and that the capacities of these subsystems are determined by different constraints (Xu & Chun, 2006). As such, we measured the capacities of both subsystems. If VWM supports the inhibition of previewed distractors, then there should be some correspondence between the number of objects that an individual can remember in a VWM task and the number of distractors that they can inhibit in a preview search.

Methods

Participants. Thirty-six University of Toronto undergraduate students participated for partial credit toward an introductory psychology course. All participants were naïve to the purpose of the experiment, and reported having normal or corrected-to-normal vision. Informed consent was obtained from all participants. Three participants were removed from the analyses (one who erroneously responded on 45% of catch trials in the preview search, one who reported being unable to differentiate between some of the colors used in the memory task, and one who failed to follow the task instructions), resulting in a final sample of 33 participants.

Apparatus and stimuli. The apparatus was the same as in Experiments 1–3. The preview search task used the same target and distractor stimuli as Experiment 2, 2A and 3 (an *H* target among other uppercase letter distractors) as well as the same fixation cross and warning box. In the spatial and nonspatial (color) memory tasks, participants were required to remember either the locations or colors of circles (radius 0.4°), respectively. In the spatial memory task, all circles were presented in blue but at different locations selected randomly from a 4 × 4 grid (3° in width and height) that was centered around a fixation point (a black circle 0.4° in radius). In the color memory task, circle colors were chosen randomly without replacement from a set of 10 easily discriminable colors, and all were presented at the same location: on top of the fixation point.

Design and procedure. Figure 9 depicts typical trial sequences for the two change-detection tasks in Experiment 4. All participants completed the preview search task first. In this task, there was no manipulation of search difficulty, but otherwise the procedure was identical to that of Experiment 3. Thus, there were 816 experimental trials and 72 catch trials in the preview search task, and two conditions: preview type (preview vs. no preview) and set size (two vs. six old items, plus eight new items).

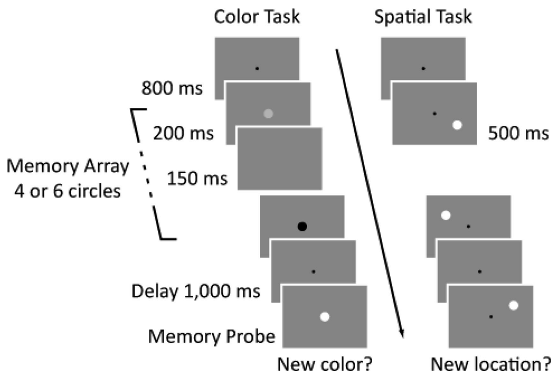

Figure 9. An example trial sequence for the color and spatial visual working memory tasks in Experiment 4.

Participants then completed the color and spatial memory tasks; task order was counterbalanced across participants. Each trial of the color memory task began with a fixation point, which was presented for 800 ms. The memory array of colored circles was then presented at fixation, one circle at a time, thus preventing spatial information from contributing to task performance. Each circle was shown for 200 ms followed by a 150-ms blank inter-stimulus interval; this speed was chosen to minimize verbalization of the colors. After the last circle was removed, the fixation point reappeared. One second later, one more circle was presented to probe memory. On half of the trials, the memory probe was identical to one of the circles in the memory array; on the other half the probe was presented in a new color that was not present in the memory array. Participants were required to report, using a key press, whether the color of the probe matched, or did not match, the color of any of the circles in the memory array, and the accuracy of their response was recorded. In the spatial memory task, the blue circles in the memory array were presented at different locations, one at a time. Each circle was shown for 500 ms, with no delay between circles. Stimuli were presented sequentially (rather than simultaneously) and with a longer delay between items than in the color task, to prevent subjects from perceiving the individual locations as a single pattern. The memory probe was a blue circle presented at one location and participants were required to report whether the probe matched one of the locations of the memory array or not. Otherwise, the procedure of the spatial memory task was the same as the procedure of the color memory task. On each trial of both memory tasks, the memory array contained either 4 or 6 circles, determined randomly. Each task contained a total of 140 trials. For the memory tasks, there were two within-participant conditions: memory type (color vs. spatial) and array size (four vs. six).

Results and Discussion

All participants successfully withheld responding on at least 80% of catch trials in the preview search task. Catch trials were not analyzed further. Search trials on which participants made an incorrect response (4.8%) or for which RT did not fall within 2.5 *SD*s of mean RT (2.6%) were excluded from the analyses.

Mean performance on the search task and two memory tasks are presented in Figure 10. Overall, search times were faster in the preview condition of the search task than the no-preview condition (Figure 10A). When converted to an item benefit (see Appendix) the magnitude of the benefit corresponded to the number of preview distractors that could be stored in memory—two distractors for set size two, and about four distractors for set size six (Figure

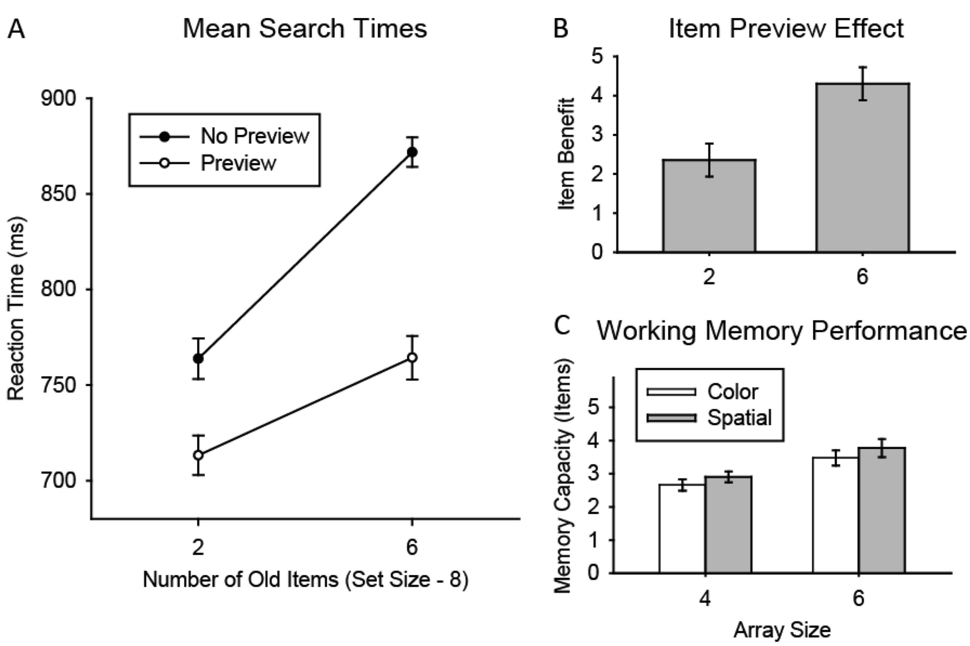

Figure 10. A) Mean RTs for the preview and no-preview conditions in Experiment 4. B) Estimates of the number of successfully inhibited distractors. C) Estimates of the participants mean visual working memory capacity.

10B). A 2 (preview type) × 2 (set size) within participants ANOVA on RTs in the preview search task revealed significant main effects of set size, $F(1, 32) = 142.91$, $MSE = 2.06 \times 10^5$, $p < .001$, and preview effect, $F(1, 32) = 193.43$, $MSE = 2.09 \times 10^5$, $p < .001$, and a significant two-way interaction, $F(1, 32) = 27.18$, $MSE = 2.68 \times 10^4$, $p < .001$. Thus, as expected, there was a significant preview effect on RT, and the magnitude of the effect increased with set size.

Individual estimates of memory capacity were calculated by applying Cowan's *K* estimate (Cowan, 2001; Pashler, 1988) to the recorded accuracies in the color and spatial memory tasks. Memory capacities for both tasks were approximately four items (Figure 10C). A 2 (memory type) × 2 (array size) within-participants ANOVA on memory capacity revealed a significant main effect of array size, $F(1, 32) = 63.26$, $MSE = 23.53$, $p < .001$, but no effect of memory type, $F(1, 32) = 2.48$, $MSE = 2.36$, $p = .125$, and no two-way interaction ($F < 1$). As is typically observed, the number of correctly remembered items was greatest at array sizes slightly above the capacity of memory (e.g., Todd & Marois, 2004; Xu & Chun, 2006).

The primary question of interest in Experiment 4 was to evaluate whether individual differences in memory capacity would predict the item benefit in a preview search task. Any such relationships should be strongest when memory capacity is fully exhausted in both tasks; therefore, we compared individual estimates of the item preview benefit at set size 6 against memory capacities in the two memory tasks at array size 6. As can be seen in Figure 11, there was a significant correlation between spatial-memory capacity and the item preview benefit, $r = .364$, $p = .037$. The relationship between color-memory capacity and the item preview benefit was not significant, $r = .034$, $p = .851$. Although it is interesting that spatial memory, but not color memory, correlates with preview inhibition (the limitations on this conclusion are discussed in the General Discussion), the important result is that individual differences in the item preview benefit were correlated with individual differences in a measure of VWM capacity. Therefore, Experiment 4 confirms a third prediction of the proposal the VWM supports preview inhibition.

General Discussion

In the present study, we investigated whether VWM can support the inhibition of previewed distractors in a preview search by testing, and confirming, three predictions. Experiments 1 and 2 confirmed the prediction that under natural viewing conditions (i.e., when participants are able to move their eyes) and across small preview set sizes (i.e., 0 to 7), preview inhibition is more effective when the number of previewed distractors is below the capacity of VWM than above. Experiment 3 confirmed the prediction that the magnitude of the preview effect is stable across different search difficulties when magnitude is quantified by the number of inhibited distractors (i.e., the item benefit), but not when quantified by RT. Experiment 4 confirmed the prediction that individual differences in the ability to inhibit preview distractors correlates with individual difference in VWM capacity. Together, these four experiments provide converging evidence that VWM supports the inhibition of previewed distractors in a preview search.

Preview Effect Mechanisms

Though our study was not designed to compare the contribution of VWM to the preview effect against other preview mechanisms, it is nevertheless worth considering how our results fit within the context of these other accounts. Of the four major hypothesized preview mechanisms (visual marking, feature inhibition, attentional capture, and temporal segregation), our observation of VWM-based inhibition is most compatible with the visual marking mechanism. Indeed, it may be that visual marking is entirely mediated by VWM. In support of this possibility, both marking and working memory are tied to top-down control. For example, both are disrupted by a secondary attentional task (Olivers, Humphreys, & Braithwaite, 2006), although the disruptions to working memory are limited (Gajewskt & Brockmole, 2006; Johnson, Hollingworth, & Luck, 2008; Woodman & Luck, 2010). It remains to be seen, however, whether other resources can also support marking, or

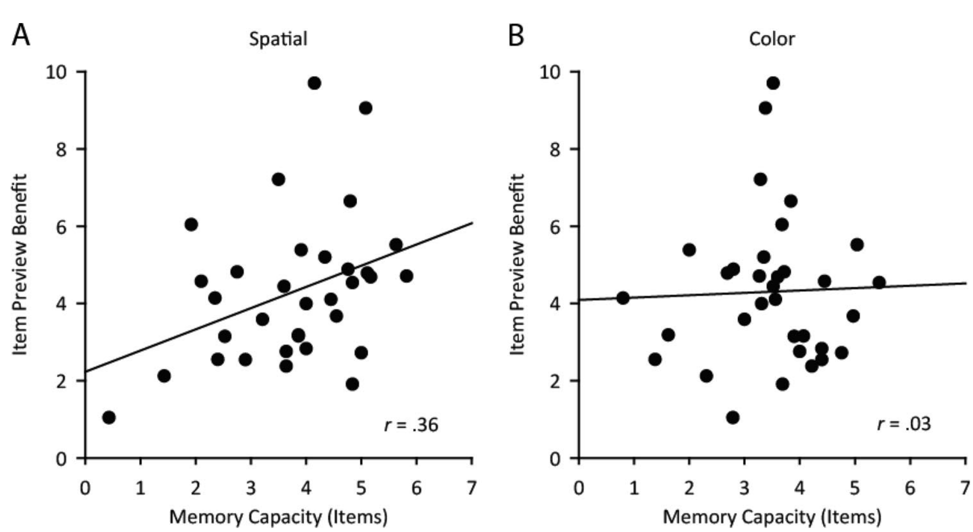

Figure 11. Correlations between individual estimates of visual working memory capacity and individual estimates of the number of successfully inhibited previewed distractors.

whether marking is always limited to the capacity of VWM. Our results may also be compatible with the feature inhibition account of the preview effect. Given that VWM representations encode both featural information and spatial locations, it is possible that VWM can support the inhibition of features throughout the visual field (e.g., Downing & Dodds, 2004; Woodman & Luck, 2007), much as it can support the location-specific inhibition (i.e., visual marking) we demonstrated in the present study.

In addition to the inhibition of old items associated with visual marking and feature inhibition, the facilitation of new items also contributes to the preview effect, as described by both the attentional capture (Donk & Theeuwes, 2001, 2003; Donk & Verburg, 2004; Donk et al., 2009; Pratt et al., 2007) and temporal segregation (Jiang & Wang, 2004; Jiang, Chun, & Marks, 2002a, 2002b) accounts of the effect. On the one hand, it is quite likely that VWM contributes to this facilitation. Jiang and Wang (2004) have demonstrated that the capacity of preview facilitation corresponds closely to the capacity of VWM, and Yantis and Johnson (1990) have demonstrated that prioritization through attentional capture (by abrupt onsets) has the same capacity. Thus, we may use VWM to specify a small set of new objects for prioritized processing. Of interest, this conclusion suggests that memory can be used for both preview inhibition and facilitation; it remains to be determined, what factors determine the appropriate memory strategy.

On the other hand, it is unlikely that VWM is the only memory resource supporting preview facilitation (and preview inhibition). As demonstrated by Experiments 2A and 2B, the size of the preview effect can exceed the capacity of memory; when 17 distractors were previewed in Experiment 2A, the preview effect could only be accounted for through the inhibition of about eight distractors. Is it possible that participants employed mnemonic strategies, such as chunking (Miller, 1956), to increase the number of distractors that could be stored in VWM. Such a chunking strategy could explain the observed decrease in preview efficiency at this set size (e.g., search would be slowed if the target fell in the space between two chunked distractors). It is also possible, however, that participants employed a different memory resource for this very large set size (or a different form of visual short-term memory; Sligte, Scholte, & Lamme, 2008). Additional evidence comes from past attentional capture preview studies. Despite very large set sizes of both old and new items (e.g., 10 to 14 old items and 14 new items), the number of old items had little measurable effect on search time in these studies (e.g., Donk & Theeuwes, 2003; Jiang, Chun, & Marks, 2002a). Thus, preview facilitation appears to be supported by a high-capacity and high-efficiency memory system, the capacity of which does not match the capacity of VWM. Finally, Jiang and Wang (2004) have also previously argued for the contribution of a high capacity, but fast decaying, memory for temporal asynchrony. Therefore, it appears that a number of memory systems contribute to the preview effect, especially those preview effects described by attentional capture and temporal segregation, although the identities of these memory systems have yet to be fully determined. The results of the present study, however, clearly demonstrate that VWM is one system that contributes to the preview effect and, specifically, that it supports the highly effective (Figure 4A) inhibition of previewed distractors. Thus, VWM supports the type of inhibition required for ignoring previously processed information (e.g., Goolsby et al., 2009).

Spatial Memory Versus Object Identity Memory

One interesting result that emerged from this study was that the capacity of preview inhibition correlated with performance on a spatial working memory task but not a color working memory task. This difference is compatible with a growing literature that points to a separation between working memory for spatial information and object identity information (for reviews, see Logie & van der Meulen, 2009; Logie, 1995, 2003; Luck, 2009). Behavioral support for such a separation has come primarily from dual-task paradigms where a spatial memory load, but not an object-identity memory load, will interfere with performance on a second nonmemory task, and vice versa (e.g., Logie & Marchetti, 1991; Woodman & Luck, 2004; Woodman, Vogel, & Luck, 2001). In addition, maintenance of spatial versus identity information in VWM appears to rely on dissociable neural substrates; spatial memory is more often associated with activity in parietal regions (in particular the inferior intraparietal sulcus), and object memory is more often associated with activity in ventral and lateral extrastriate regions (e.g., Courtney, Ungerleider, Keil, & Haxby, 1996; Funahashi, Takeda, & Watanabe, 2004; Todd & Marois, 2004, 2005; Wager & Smith, 2003; Xu & Chun, 2006). Of note, although parietal cortex is known to also subserve the preview effect (thus potentially explaining the relation of preview inhibition to spatial but not object memory), the preview effect is specifically subserved by the superior parietal lobe (Allen, Humphreys, & Matthews, 2008; Humphreys, Kyllingsbaek, Watson, Olivers, & Paulson, 2004; Olivers, Smith, Matthews, & Humphreys, 2005; Pollmann et al., 2003), an area that contributes to both spatial and object memory (Xu & Chun, 2006). Nevertheless, our observation that spatial working memory capacity, but not color working memory capacity, correlates with preview inhibition is compatible with this dissociation between the spatial- and object-memory subsystems.

There are, however, a number of alternative explanations for the difference in the strength of the correlations with spatial and color memory. For example, it is possible that because all of our preview tasks had uniformly colored displays, color memory may have had little effect on inhibition, and thus the magnitude of inhibition depended most strongly on the spatial subsystem of VWM. Thus, in cases where object identity plays a stronger role in segregating old from new items, nonspatial VWM may play a larger role. For example, past preview studies have demonstrated that changing the identities of previewed distractors disrupts the preview benefit (Jiang, Chun, & Marks, 2002b; Kunar, Humphreys, Smith, et al., 2003), suggesting that participants may have had memory for the distractors' identities in addition to their locations. Therefore, though our results provide some evidence to suggest that the VWM-based inhibition of previewed distractors relies more on the spatial subsystem of VWM than the object-identity subsystem, more research is clearly required before such a conclusion can be made. Nevertheless, given that the magnitude of the preview effect was predicted by individual WM capacity, the results still support the conclusion that VWM supports the inhibition of previewed distractors.

Strategic Inhibition by VWM

One additional implication of our results is that the contents of VWM appear to be able to guide attentional resources through inhibition during perceptual selection. In the observed preview searches, VWM representations were able to mitigate the effect of some previewed distractors on search times. This observation indicates that the contents of VWM allowed the attentional priorities of these search stimuli to be decreased. Indeed, there have been numerous prior demonstrations of attentional guidance through working memory (Cosman & Vecera, 2011; Downing, 2000; Downing & Dodds, 2004; Houtkamp & Roelfsema, 2006; Huang & Pashler, 2007; Olivers, Meijer, & Theeuwes, 2006b; Soto et al., 2005, for a review, see 2008, 2006, 2010; Woodman & Luck, 2007). In contrast to our memory-based inhibition, however, most of these studies have demonstrated a perceptual or selection advantage for stimuli that are visually similar to the contents of working memory. For example, Downing demonstrated that, when maintaining the image of a face in memory, a target probe is detected more quickly if it appears on that image than if it appears on the image of another face. Similarly, Soto et al. (2005) showed that visual search is more efficient when the search target appears inside a placeholder that resembles the contents of VWM than when a distractor appears within that placeholder. Of importance, this perceptual facilitation persists even when allocating attention to memory-matching stimuli is detrimental to task performance, suggesting that the facilitation is automatic (Soto & Humphreys, 2008, 2009; Soto et al., 2005). Through these studies, it has been well established that working memory representations can bias perceptual processing toward the selection of stimuli that are similar to the contents of memory.

The memory-based facilitation of perceptual processing is consistent with a number of models of attentional guidance (e.g., Anderson, Matessa, & Lebiere, 1997; Bundesen, 1990; Logan & Gordon, 2001). This is particularly true for Desimone and Duncan's (1995) biased competition model, which is based on the theory that the objects in our visual environments will compete for representation, analysis, and control, at various points during visual processing. Given the evidence that the early cortical areas involved in sensory processing are recruited to maintain working memory representations (Awh & Jonides, 2001; D'Esposito, 2007; Harrison & Tong, 2009; Jonides, Lacey, & Nee, 2005; Miller, Li, & Desimone, 1993; Postle, 2006; Serences, Ester, Vogel, & Awh, 2009), visual stimuli that are similar to the contents of memory may receive top-down memory-based facilitation, biasing them to win the competition over other dissimilar stimuli. Thus, memory-based facilitation of perceptual processing can be understood as an emergent property of how the visual system maintains working memory representations.

The memory facilitation explanation, however, cannot account for the memory based-inhibition observed in the present study (see also, Downing & Dodds, 2004; Woodman & Luck, 2007). Instead, the evidence of memory based-inhibition would seem to suggest that the interactions between working memory and attention do not only autonomously emerge from properties of visual processing, but that memory can also be used strategically to bias attention. Soto et al. (2008) have noted that inhibition has only previously been observed when working memory loads are quite high, and they used this observation to reconcile memory-based inhibition with the prior evidence that memory-based facilitation is automatic. In particular, they argued that memory representations may become degraded when the working memory resource is exhausted, which could in turn degrade the typical autonomous facilitation (Soto & Humphreys, 2008). This argument, however, does not hold for the inhibition observed in the present study. Specifically, in the present study, the identity of the search target was constant across trials, many of the preview set sizes were below the capacity of working memory, and participants were not required to perform a simultaneous verbal-working memory suppression task. As such, working memory load was not high, and yet memory-based inhibition was observed. Therefore, our results add to the studies supporting the conclusion that working memory can flexibly guide attention by either facilitating or inhibiting perceptual processing, depending on both task constraints and an observer's goals.

Conclusion

In the present study we investigated the memory systems that support inhibition in a preview search by testing specifically for a role of VWM. Based on the findings of this study we conclude that VWM supports preview inhibition by encoding and maintaining a small set of previewed distractors, allowing them to be inhibited. More generally, this finding adds to the growing evidence that we can use VWM to bias selection away from previously processed information, thus improving the efficiency of visual processing. It has long been proposed that some sort of short-term memory system must contribute to the visual search process. In particular Bundesen's (1990) theory of visual attention and Duncan and Humphrey's (1989) stimulus-similarity model both propose that visual search is a multipass (or iterative) process, in which perceptual information from one pass is stored in a short-term memory system, and used to tune the processing of the next pass. Initial support for such models, and more generally for the contribution of VWM to search inhibition, has come from past studies of inhibition of return (IOR)—a bias in cueing tasks for slower responses to targets at recently cued locations. A concurrent spatial working memory load produces oculomotor IOR at remembered spatial locations (Belopolsky & Theeuwes, 2009), and disrupts IOR at locations not stored in memory (Castel et al., 2003), indicating that spatial working memory may specify the to-be-inhibited locations. Evidence has also come from visual search tasks (Emrich et al., 2009, 2010; McCarley et al., 2003; Peterson et al., 2007). For example, performing a visual search elicits the electrophysiological marker of VWM (Emrich et al., 2009). As well, a concurrent VWM-load disrupts search times, and not search slope, at set sizes above the capacity of memory (Emrich et al., 2010); precisely the pattern that would be predicted if visual search employs a capacity-limited memory system to inhibit recently searched distractors. The present study adds to these demonstrations by extending the evidence to the preview search task—a task that was designed specifically to assess how we are able to ignore recently processed information (Watson & Humphreys, 1997). Together, these studies provide converging evidence that VWM provides a significant contribution to the efficiency of human visual information processing, by preventing recently processed information from being reselected.

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Appendix

Quantifying the Preview Effect as an Item Benefit

It is possible to convert preview effects, measured in milliseconds, into an estimate of the number of inhibited previewed distractors (for similar types of conversions, see Olivers, 2004; Yantis & D. N. Johnson, 1990). This conversion is most easily understood in the context of Experiment 2A.

In Experiment 2A, participants completed both a preview condition and a no-preview condition. The only difference between these two types of searches was that, in the preview condition, some distractors were presented before the onset of the rest of the search items. As a result, any differences in RT between these two conditions must be attributable to the previewing of distractors. In the present study, and as is typically found in preview search studies, RTs were faster in the preview condition than the no-preview condition (Figure 3); therefore, we refer to such differences as the RT benefit of previewing distractors. This RT benefit can be calculated for any particular set size (i.e., as the total number of distractors in held constant) as the RT difference between the no-preview and preview conditions. For example, at set size 5 in Experiment 2A, no-preview RT was about 890 ms and preview RT was about 760 ms, leading to a RT benefit of about 130 ms.

In the present studies, we can be confident that the preview effect resulted from the inhibition of previewed distractors (e.g., since the effect varied with the number of old items). Thus, the observed RT benefits reflect the extent to which previewed distractors were successfully inhibited: the greater the number of successfully inhibited distractors, the greater the RT benefit. For a given RT benefit one can, therefore, ask: How many distractors would have to be inhibited in order to observe this size of RT benefit? To answer this question, it helps to know how long it takes to search a single distractor. Conveniently, this value is provided by the search slope of the no-preview condition. In Experiment 2, the search slope in the no-preview condition was about 33 ms/item, indicating that for each distractor that was added to the search display, search time was slowed by 33 ms. With this value, it is trivial to convert RT benefits into an estimate of the number of inhibited distractors. If it takes about 33 ms to search each item, you would have to inhibit about four distractors in order to produce a RT benefit of 130 ms. More formally:

$$Item\ Benefit(i) = \frac{RT\ Benefit(i)}{slope_{np}}, \tag{1}$$

where $slope_{np}$ is the search slope in the no-preview condition, *RT Benefit* is the difference in RT between the preview and no-preview conditions at set size i, and *Item Benefit* is the calculated estimate of the number of previewed distractors that were inhibited at set size i.

(*Appendix continues*)

There is one important caveat to Equation 1: If there are any RT differences between the preview and no-preview conditions that are unrelated to the preview effect, these differences will bias the RT benefit and, therefore, the computed item benefits. In Experiments 2, 3, and 4, no such differences existed, and RT benefits were computed as described above (i.e., the raw difference in RT between preview and no-preview searches for a given set size, *i*):

$$RT\ Benefit(i) = no\ preview_i - preview_i. \quad (2)$$

This caveat does not hold, however, for Experiment 1. There are three reasons why RTs may differ across the three preview conditions of Experiment 1 that are not attributable to the preview effect. First, the luminance of the stimuli varied between conditions. Second, different groups of participants completed each condition. Third, the appearance of the previewed items in the two preview conditions may have acted as a warning signal for the upcoming new items, speeding RT in the two preview conditions relative to the no-preview condition. Of note, no such warning was available when 0 distractors were previewed in the two preview conditions, which may explain why search times in the onset preview condition were slower for 0 previewed items then for 1, 2, 3, or 4 previewed items (see Figure 2)—this problem was avoided in subsequent experiments by signaling the onset of the preview phase by changing the fixation stimulus. Estimating the RT benefit in the two preview conditions of Experiment 1 is nevertheless possible by projecting the search times that would be expected if no items were inhibited, and then calculating the difference between the expected and observed RTs. Equation 3 gives this calculation for any set size of old items (*i*):

$$RT\ Benefit(i) = (observed_0 + slope_{np} \times i) - observed_i, \quad (3)$$

Because a search with 0 previewed items is common to both the preview and no-preview conditions, any main effect of condition on overall RT can be removed by equating the RT at 0 old items for both conditions. Thus, the formula takes the observed RT in the preview condition when no distractors are previewed ($observed_O$), and uses the average search slope from the no-preview condition ($slope_{np}$) to estimate the expected cost of each additional old item on RT. The RT benefit is then calculated as the difference between the expected RT and the observed RT ($observed_p$). It is important to note that, although this adjustment accounts for any differences in overall RT (i.e., the intercept of the search function) between the preview conditions and the no-preview baseline, it does not account for potential differences in search efficiency (i.e., search slope). To avoid this limitation, all experiments in the present study other than Experiment 1 included preview and no-preview conditions that only differed in whether distractors were previewed or not.

As a summary, item benefits in all experiments were calculated using Equation 1, and these item benefits reflect an estimate of the number of successfully inhibited previewed distractors. RT benefits, which are needed for the item benefit conversion, were calculated using Equation 3 in Experiment 1, and Equation 2 in Experiments 2, 3, and 4.

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