THE QUARTERLY JOURNAL OF EXPERIMENTAL PSYCHOLOGY
2010, 63 (8), 1457–1466

Psychology Press
Taylor & Francis Group

Rapid communication

Finding memory in search: The effect of visual working memory load on visual search

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There is now substantial evidence that during visual search, previously searched distractors are stored in memory to prevent them from being reselected. Studies examining which memory resources are involved in this process have indicated that while a concurrent spatial working memory task does affect search slopes, depleting visual working memory (VWM) resources does not. In the present study, we confirm that VWM load indeed has no effect on the search slope; however, there is an increase in overall reaction times that is directly related to the number of items held in VWM. Importantly, this effect on search time increases proportionally with the memory load until the capacity of VWM is reached. Furthermore, the search task interfered with the number of items stored in VWM during the concurrent change-detection task. These findings suggest that VWM plays a role in the inhibition of previously searched distractors.

Keywords: Visual working memory; Visual search; Attention; Inhibition; Dual-task interference.

Does visual search remember the past, or is it doomed to repeat it? While early studies suggested that search has no memory (Horowitz & Wolfe, 1998), there is now substantial evidence that memory plays a significant role in visual search (e.g., Beck, Peterson, & Vomela, 2006b; Boot, McCarley, Kramer, & Peterson, 2004; Oh & Kim, 2004; Peterson, Beck, & Vomela, 2007; Peterson, Kramer, Wang, Irwin, & McCarley, 2001). The precise role played by different memory systems, however, remains somewhat less clear. For example, several studies have demonstrated that in the presence of a concurrent spatial working memory (SWM) load, search efficiency is reduced, as measured by an increase in search slope per item (Oh & Kim, 2004; Woodman & Luck, 2004). In contrast, placing a concurrent load on object working memory (or simply, visual working memory; VWM) has no effect on the search slope, although increases in

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Thanks to Steve Thomas for help with data collection. This research was supported by Natural Sciences and Engineering Research Council of Canada (NSERC) grants to S.F. and J.P. and a Canadian Institutes of Health Research (CIHR) grant to S.F. (Reference No. 79256).

http://www.psypress.com/qjep
DOI:10.1080/17470218.2010.483768

overall reaction time (RT) are observed (Woodman, Vogel, & Luck, 2001). These findings have been interpreted as evidence that SWM plays a role in the inhibition of previously searched items, but VWM does not. That is, although a concurrent VWM load increases overall search times, the absence of a change in the search slope suggests that search *efficiency* remains unaffected. In other words, regardless of the load on VWM, items are searched at the same rate.

Recent electrophysiological evidence, however, provides evidence that visual search efficiency may in fact depend on VWM processes. Tasks that are mediated by VWM (e.g., change-detection tasks) elicit an event-related potential (ERP) known as the contralateral delay activity (CDA). Increases in CDA amplitude have been shown to be directly related to individual VWM capacity (Vogel & Machizawa, 2004). While recording ERPs during a lateralized search task, we recently demonstrated that the CDA is also present during visual search (Emrich, Al-Aidroos, Pratt, & Ferber, 2009). Although our search task differed from a change-detection task in terms of number of items in the display and duration of the stimuli, the amplitude of this contralateral search activity (CSA) was identical to the CDA elicited in the change-detection task, suggesting that a similar number of items were encoded in VWM. Importantly, we also observed that the amplitude of the CSA increased gradually over the course of the search trial, suggesting that VWM was being filled only after items had been sampled. Furthermore, a strong relationship between measures of VWM (both behavioural and electrophysiological) and search reaction times strongly suggests that VWM may support efficient visual search. That is, individual differences in both the increase in CSA amplitude and VWM capacity were correlated with search RT, indicating that the more items that were stored in VWM, the faster the target was found.

Given the electrophysiological and behavioural evidence that visual search efficiency is tied to VWM processes, why did previous studies not find an effect of a concurrent VWM load on search slopes? The answer may lie in the limited capacity of VWM. That is, the number of items that can be stored in memory, preventing them from being revisited, should be limited by the capacity of the memory system that mediates this inhibition. Once this memory system has been filled to capacity, however, the remaining items will then be searched without inhibition.

The effects of a limited-capacity memory system on search performance can be best understood through the concepts of sampling with, and without, replacement in visual search (Horowitz & Wolfe, 2001, 2003). Performing search with inhibitory tagging of previously visited items can be considered equivalent to *sampling without replacement*, as the inhibitory mechanisms prevent items from being resampled. Thus, the average number of items that have to be sampled before the target is found in a search without replacement is smaller (roughly half) than that in a search in which no inhibitory tagging takes place (i.e., *search with replacement*). If inhibition during search is mediated by a capacity-limited memory system, and the sample size exceeds this capacity limit, visual search would rely on both sampling with replacement and sampling without replacement. In other words, only a subset of distractors can be inhibited at a given moment, while the remaining items would be sampled with replacement, resulting in a less efficient search once the capacity limit has been reached.

To illustrate how memory systems with different capacity limits affect search, Figure 1 presents theoretical data from three simplified cases in which varying degrees of memory resources are available to remember and inhibit previously selected search items.[1] These data were calculated

[1] The RTs in both the no memory and the memory conditions converge at a set size of one because nothing is inhibited prior to the selection of the first item, and so memory plays no role on establishing the initial RT. Further, the inflection point in RTs (the point at which the slope changes) occurs at one item above capacity—if three items were inhibited, the fourth item is the first item that will be searched with replacement, making it the origin of the change in slope.

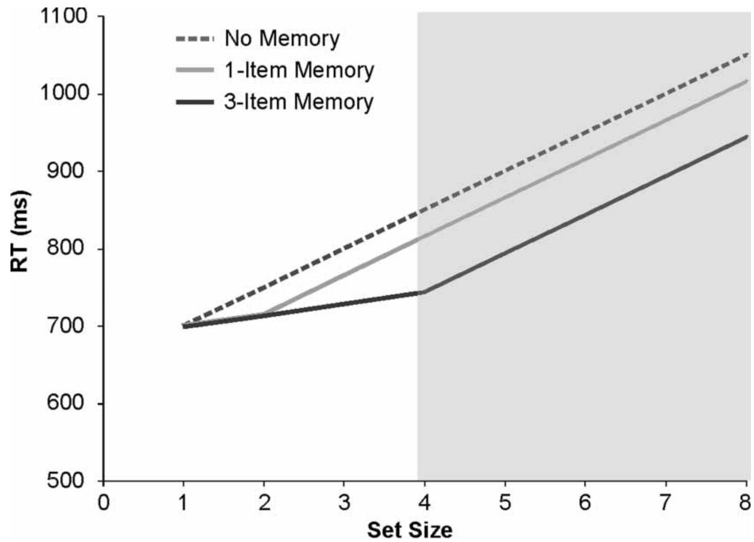

Figure 1. *Theoretical data for visual search reaction times (RTs) with different memory capacities. Above the highest capacity (shaded region), all RTs increase at a rate that is consistent with the no memory condition.*

using a model that assumes a relatively efficient search slope of 25 ms/item when items are sampled without replacement (i.e., when search items can be stored in memory) and a less efficient 50-ms/item slope when items are sampled with replacement (i.e., when search items cannot be stored in memory).

In the no memory case, search with replacement occurs regardless of the set size of the search array (i.e., search slope is constant across set sizes and relatively inefficient). In the 1-item memory case, a single search item can be stored in memory and inhibited. Because one of the items in the search array is never revisited (it is sampled without replacement), the search slope is initially reduced. With the addition of more search distractors, however, memory resources quickly become depleted, and the remaining items are searched with replacement, resulting in a search slope equivalent to the no memory case. Similarly, increasing the number of items that can be stored in memory to three allows the search to remain efficient over a larger range of set sizes (with a relatively flat search slope), but once the number of distractors exceeds the capacity, search ultimately proceeds with replacement for the remaining items.

The hypothetical data highlight an important, but previously overlooked, point when testing for memory in search: Significant differences in search slope between different memory load conditions should only be observed if search set sizes are below the capacity of the memory system. Importantly, changes in the search slope at small set sizes will still result in significant changes to the intercept (i.e., overall RT) at larger set sizes. Thus, when all sampled set sizes exceed memory capacity (as in the shaded region), changes in search efficiency related to memory manifest only as changes in overall search RT. Early attempts at finding interference effects between VWM and visual search efficiency have observed large changes in overall RT, while the search slope remained constant (Woodman et al., 2001). Previously, this change in the *y*-intercept was attributed to other dual-task interference factors that operate independently of performing the search but may delay the start of the search process or affect decision-making processes. This example demonstrates, however, that the increase in overall RT may be directly tied to the effect of a limited-capacity memory system that supports inhibition during search.

Accordingly, in the current study we test whether the changes in overall RT observed by Woodman et al. (2001) reflect the contribution of VWM to search efficiency by examining how VWM load manipulations effect changes in overall search RT. That is, according to the model outlined in Figure 1, we predict that if VWM does in fact mediate inhibition during search, search should occur at a rate that is consistent with sampling without replacement for only a small number of items, as VWM is limited to, at most, an average of three or four objects (Cowan, 2001; Luck & Vogel, 1997; see also, Alvarez & Cavanagh, 2004; Zhang & Luck, 2008). It follows, then, that when the number of search items exceeds this limit, the remaining items should be searched at a rate that is consistent with a no memory condition (sampling with replacement). Thus, if the set sizes of a search task exceed this capacity, placing an additional concurrent load on VWM resources should not affect the search slope but should result in changes to overall search RT. To test our predictions, we adapted the paradigm employed by Woodman et al. (2001), in which overall RTs were longer in the dual-task condition when participants held four items in VWM but the slope of the search task was unaffected relative to when there was no concurrent memory task (i.e., search remained efficient even when VWM processes were occupied). We varied the number of items in the concurrent VWM task and predicted that if VWM does in fact support inhibition, then the increase in overall RT under a VWM load should be proportional to the number of items encoded in memory.

Method

Participants

A total of 20 students (8 male; $M = 23.3$) who reported having normal or corrected-to-normal vision from the University of Toronto community participated in the study. All participants in this study provided written consent and received partial credit in an undergraduate psychology course or financial payment ($10 CAD) for participation in the experiment.

Stimuli and design

The experimental procedure and stimuli were similar to those of Experiment 1 in Woodman et al. (2001); however, in the present experiment, we tested a range of memory loads in a change-detection task, both within and above the capacity of VWM. As in the original experiment, participants performed dual-task, memory-only, and search-only conditions (Figure 2).

The search task consisted of 4 or 8 "C"-shaped stimuli. Target stimuli were Cs with the gap facing up or down, with distractor stimuli facing left and right. Stimuli were always arranged in groups of four in a given quadrant; thus, search was contained to either one or two quadrants. Stimuli subtended 0.45° of visual angle and were located on an $8° \times 8°$ invisible grid around fixation, with a minimum of 1° separating the stimuli from each other and the fixation cross. To manipulate load, the memory task consisted of 2, 4, or 6 coloured square stimuli (chosen from a set of 7), subtending 0.45° of visual angle and appearing in 8 locations in a grid 1° around the fixation. Thus, while the memory task was presented centrally around the fixation, the search task was presented more peripherally, preventing any spatial overlap between the two tasks. The factors of memory load and search set sizes were fully crossed within the dual-task condition, resulting in two different designs for the two tasks being assessed: The design was a 2 (set size: 4 or 8 search items) × 4 (memory load: 2, 4, 6, or search only) for the search task and a 3 (set size: 4 or 8 search items, or memory only) × 3 (memory load: 2, 4, or 6 items) for the memory task.

Procedure

In the dual-task condition, participants first saw the memory array for 500 ms, followed by a 100-ms fixation period. Next, the search array was presented for 4,000 ms. Participants were told to make a right-handed key response as quickly as possible and to indicate whether the target was an upward or downward facing C. The search display was followed by another 100-ms fixation period, and afterwards a memory test array was

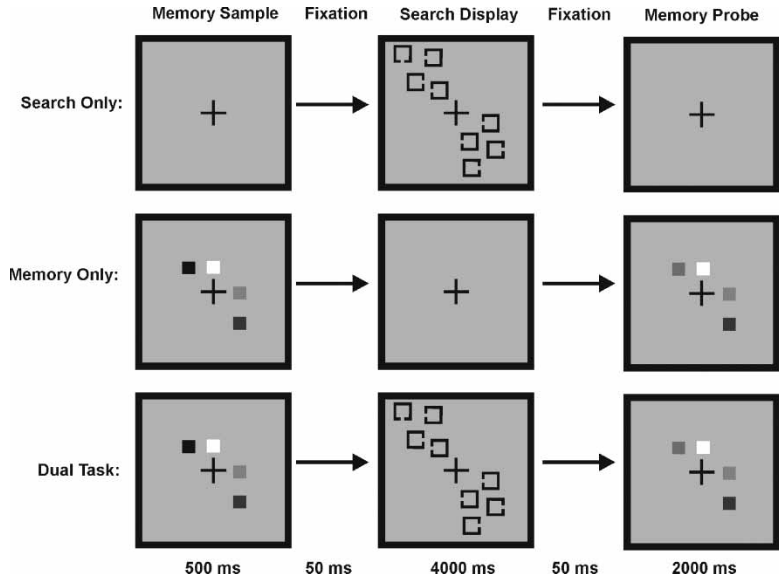

Figure 2. *Schematic of experimental trials. In the search task (top), participants were told to indicate whether an upward or downward facing "C" shape was present. In the memory task (middle), participants were told to remember the coloured items over the delay and to indicate whether any of the items changed colour, which happened on half of the trials. In dual-task trials (bottom) participants performed the search task during the memory delay of the memory task.*

presented for 2,000 ms. The memory test array was identical to the memory array except, on 50% of the trials, one of the items in the memory test contained a colour that was not present in the original memory array. Participants were told to indicate with a left-hand key-press whether the test array matched the memory-array or not. In the search-only condition, both memory arrays were replaced with a blank fixation display, and in the memory-only condition, the search task was replaced with a blank fixation display. All tasks were performed in separate blocks, with 32 trials per set size, and blocks were pseudorandomly counterbalanced across participants. Throughout all three tasks, participants performed a concurrent articulatory-suppression task, repeatedly saying aloud a sequence of four digits, to prevent verbal encoding of colours or locations.

Results

Response times in the search task were analysed for statistical outliers, and RTs that exceeded 2.5 standard deviations were excluded from analysis, with an average of $<1\%$ of the data removed.

RTs

Analysis in the search task was restricted to correct responses. As illustrated in Figure 3, the RTs in the dual-task conditions were consistently greater than those during search alone. A 2 (set size) $\times$ 4 (memory load) repeated measures analysis of variance (ANOVA) confirmed this effect, with a significant main effect of memory load, $F(3, 57) = 11.68$, $p < .001$. The main effect of set size was also significant, $F(1, 19) = 169.46$, $p < .001$, as RTs increased with search set size. The interaction did not reach significance, $F(3, 57) < 1$, indicating that the RTs increased with set size at a similar rate regardless of the memory load. Planned t tests revealed that all RTs in all of the memory conditions were significantly slower than those in the search-only condition, all ps $< .005$. RTs increased between memory loads 2 and 4, $t(19) = -2.75$, $p = .013$, but there was no significant difference in RTs between the load 4 condition and load 6 condition, $t(19) = -1.7$, $p = .11$.

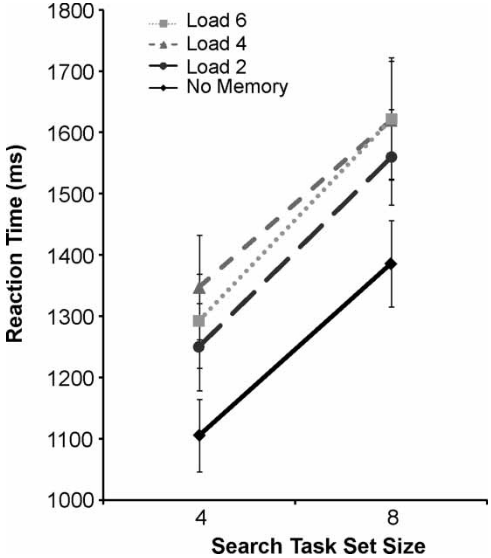

Figure 3. *Mean reaction times (RTs) observed in the search task by memory load condition. Although the search slopes did not change, RTs increased as a function of memory load. Error bars denote standard errors of the mean.*

Errors

Mean error rates for the search task are presented in Table 1. A repeated measures ANOVA revealed a significant main effect of set size, $F(1, 19) = 9.03$, $p < .01$, and a marginally significant effect of memory load, $F(3, 57) = 2.75$, $p = .051$. Examining the simple effects revealed that the error rates increased only with a memory load of four items relative to when search was performed in isolation. The interaction between set size and memory load was not significant, $F(3, 57) = 4.1$, $p = .56$.

Table 1. *Mean percentages of error and standard errors in the search task*

	Search 4		*Search 8*	
Memory condition	*M*	*SE*	*M*	*SE*
Search only	0	0	1.9	0.7
Memory load 2	2.2	0.9	3.4	1.2
Memory load 4	2.8	1.1	3.4	1.1
Memory load 6	2.5	1.1	3.0	1.1

Memory performance

If visual search utilizes the same resources as the change-detection task, then performance on the change-detection task should be impaired while performing a concurrent visual search. Mean accuracy scores (hits and correct rejections) on the change-detection task are presented in Figure 4. A 3 (memory load) × 3 (set size) repeated measures ANOVA revealed a main effect of set size, $F(2, 38) = 9.77$, $p < .001$, in addition to the main effect of memory load, $F(2, 38) = 93.45$, $p < .001$. Thus, accuracy in the memory task was impaired while performing a concurrent visual search task. The interaction between search task and memory task was not significant, $F(4, 76) = 1.95$, $p = .11$.

In addition to examining pure accuracy on the change-detection task, *K*-estimates of the number of remembered memory items were calculated using Cowan's *K* formula (Cowan, 2001): K = set size × (hits − false alarms). These *K*-estimates adjust for the relationship between set size and accuracy and are presented in Table 2. To examine the effect of performance relative to capacity, search conditions were collapsed across set sizes (as both set sizes met or exceeded VWM capacity), as well as memory loads 4 and 6 (i.e., those greater than VWM capacity), which

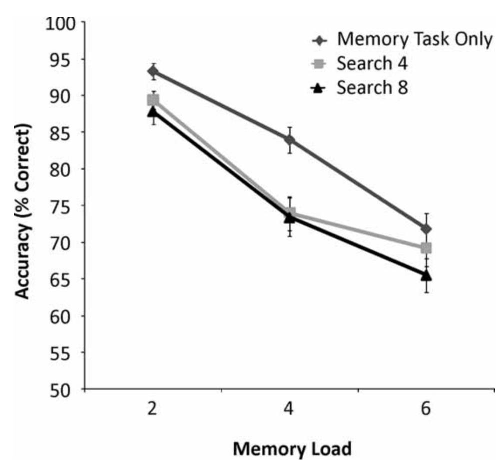

Figure 4. *Accuracy in the change-detection task as a function of search condition. Memory accuracy decreased under dual-task conditions. Error bars denote standard errors of the mean.*

Table 2. *K-estimates and standard errors obtained from the change detection task*

Search condition	*Memory load 2* *M*	*SE*	*Memory load 4* *M*	*SE*	*Memory load 6* *M*	*SE*
Memory only	1.7	0	2.7	0.1	2.6	0.3
Search 4	1.6	0	1.9	0.2	2.3	0.3
Search 8	1.5	0.1	1.9	0.2	1.9	0.3

did not differ when performing the change detection task in isolation, $t(19) < 1$. The resulting 2 (task: single vs. dual) × 2 (memory load) repeated measures ANOVA on *K*-estimates revealed main effects of task, $F(1,\ 19) = 14.91$, $p = .001$, and memory load, $F(1,\ 19) = 37.14$, $p < .001$. In addition, a significant interaction was observed, $F(1,\ 19) = 7.28$, $p = .014$, indicating that performing search during a change-detection task affected the number of items held in memory, but only when the initial memory load met or exceeded VWM capacity (Figure 5).

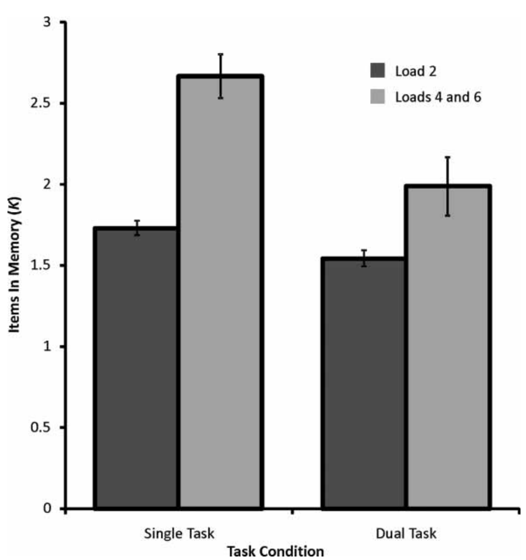

Figure 5. K-*estimates obtained in the change-detection task.* K-*estimates were collapsed across change-detection loads of 4 and 6 and across search set sizes. The number of items remembered in the high-load conditions decreased while performing the search task concurrently with the change-detection task.*

Discussion

In the present experiment, we examined the effect of a concurrent VWM load on search RTs. Consistent with the earlier work by Woodman et al. (2001), manipulating the availability of memory resources through a concurrent change-detection task had no effect on the search slope, but did result in a general slowing of RT. The absence of an effect on the search slope has been interpreted as evidence that a concurrent VWM load does not affect search efficiency, and, therefore, VWM is not involved in the inhibition of previously searched items. Our study demonstrates, however, that the magnitude of the overall slowing varied as a function of the memory load. Specifically, a memory load of only two items exhausted some, but not all, memory resources available to the search process, leading to a 159-ms increase in RT relative to the search-only condition; in contrast, when the memory load was equal to or greater than the capacity of VWM, thereby depleting all available memory resources, further RT increases were observed (238 and 211 ms for loads of four and six items, respectively). Importantly, RTs did not continue to increase when the capacity of VWM was exceeded (i.e., between loads 4 and 6), suggesting that the increase in RT is directly related to the effect on memory capacity, rather than simply reflecting task difficulty.

As noted in the introduction, the absence of an effect of memory load on search slopes does not refute the hypothesis that VWM supports inhibition during visual search, as was suggested by Woodman et al. (2001). In fact, it is predicted by the hypothesis that search items are stored in VWM. That is, if search items are stored in VWM, then a search through three to four items should fill VWM to capacity, regardless of other memory manipulations; after the capacity of VWM is reached, no additional items can be stored in memory, and thus the search slope from four to eight items should proceed at a rate that is consistent with VWM resources being fully occupied. In other words, any time search items cannot be stored in memory, search proceeds at a rate that is consistent with sampling with replacement, resulting in a search slope that is equivalent (or similar) to a no-memory condition.

According to this account, memory will always be filled to capacity by a search through four distractor items; therefore, a concurrent change-detection task should have no effect on the search slope of any search task with more than four items, but rather should impact only the overall RTs. Specifically, the increase in overall RTs as a result of the memory load reflects the reduction in the number of available VWM "slots" that can be used to store search items. That is, every change-detection item that is stored in VWM prevents a search item from being stored in memory, leading to a concomitant increase in RT. Consistent with this account, the additional memory resources that were available in the search-only and load 2 conditions, relative to the high-load conditions, did have a significant effect on overall RT, likely reflecting the subset of items that were sampled without replacement. Therefore, our results support the conclusion that VWM does in fact play a role in the inhibition of previously searched items, but that the number of items that can be inhibited is limited to the three-to-four-item capacity of VWM. This interpretation is consistent with finding that distractor devaluation requires VWM (Goolsby, Shapiro, & Raymond, 2009). Furthermore, previous studies have demonstrated that inhibition during search may be limited to roughly four distractors (Beck, Peterson, Boot, Vomela, & Kramer, 2006a; Emrich, Ruppel, Al-Aidroos, Pratt, & Ferber, 2008; McCarley, Wang, Kramer, Irwin, & Peterson, 2003). The results presented here, along with the finding that the electrophysiological signature of VWM is present during visual search (Emrich et al., 2009), suggests that this limit is tied to the capacity of VWM.

In addition to the effects of the memory task on search, our results demonstrate that performing a search through as few as four items led to a decrease in the number of items that were held in VWM, suggesting that the effect of VWM on search is reciprocal. This effect was only observed at the loads that met or exceeded capacity, suggesting that the search task interfered with the maintenance of change-detection items only if there were no available resources left to maintain some distractor information during search. Importantly, even though the search task may have pushed some items out of memory in these high-load conditions, there still remained a greater number of items maintained in VWM than in the low-load condition. Maintaining more change-detection items results in fewer VWM "slots" available for inhibition of search items and leads to an increase in overall search time.

While our demonstration that a concurrent VWM load during search results in a proportionate increase in overall RT provides evidence that VWM contributes to the inhibition of search distractors, it is possible that there are alternative explanations for why such an increase was observed. For example, numerous studies have examined the role of VWM in maintaining a template of the search target in order to automatically guide attention towards the target (Han & Kim, 2009; Kumar, Soto, & Humphreys, 2009; Soto, Heinke, Humphreys, & Blanco, 2005; Woodman, Luck, & Schall, 2007). It is possible, therefore, that the concurrent change-detection task interferes with the process of maintaining the target template, thereby increasing overall search time. There are two arguments why this alternative interpretation does not apply to our study. First, Woodman, Luck, and Schall (2007) demonstrated that the effects of a concurrent VWM load on this biased competition was only present when different target templates had to be maintained across trials. Because the target never changed in our task, participants needed to retain only one template, and thus the concurrent memory load should have had no effect on maintaining a single target template. Second, even if it were possible for the VWM-load to bias attention towards the target, it is unlikely that these effects would affect RTs proportionally with the memory load. That is, if only a single target needed to be maintained in memory, then a memory load of two items should have had a negligible effect on RTs, since there would still be resources left to maintain the target template. Overall, while it is impossible for our single experiment to rule out all alternative explanations, the finding that RTs increase proportionally with the memory load is most parsimonious with a mechanism in which the effect of memory on RTs is load specific. As outlined in the introduction, a load-dependent increase in RTs is consistent with capacity-limited inhibition during search (i.e., search without replacement).

How can our finding that VWM plays a significant role in the inhibition of previously searched items be reconciled with the argument that inhibition is mediated by purely spatial mechanisms (Beck et al., 2006b; Oh & Kim, 2004; Woodman & Luck, 2004)? Given that SWM has also been implicated in the search process, it is possible that these multiple mnemonic resources perform independent but complementary functions in search. For example, VWM may play a role in remembering which items have already been selected, whereas SWM may play a role in the planning of upcoming saccades (Peterson et al., 2007). It is also possible that both VWM and SWM contribute to the inhibition of previously searched items, thereby combining information about locations and identity. Although future studies should address how these memory systems interact during search, the current findings clearly indicate that the availability of VWM resources is necessary for visual search to be performed efficiently.

Overall, these findings, together with the finding that VWM and visual search share the same electrophysiological signature (Emrich et al., 2009), provide evidence that the same resources used to perform a change-detection task are involved in the inhibition of previously searched items. Critically, these findings demonstrate that because VWM is a limited resource (Cowan, 2001; Luck & Vogel, 1997), inhibition during search (i.e., search without replacement) can only have a limited effect on search efficiency, as the number of items inhibited will be limited to the roughly four-item capacity of VWM. The present results also demonstrate the importance of examining multiple measures of search efficiency—our conclusions would not have been possible without examining changes in overall RT, in addition to examining the search slope.

Original manuscript received 8 December 2009
Accepted revision received 8 February 2010
First published online 5 July 2010

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