Shared filtering processes link attentional and visual short-term memory capacity limits

Katherine C. Bettencourt
Department of Psychology, Boston University,
Boston, MA, USA, &
Department of Psychology, Harvard University,
Cambridge, MA, USA

Samantha W. Michalka
Department of Psychology, Boston University,
Boston, MA, USA

David C. Somers
Department of Psychology and Center for Neuroscience,
Boston University, Boston, MA, USA

Both visual attention and visual short-term memory (VSTM) have been shown to have capacity limits of 4 ± 1 objects, driving the hypothesis that they share a visual processing buffer. However, these capacity limitations also show strong individual differences, making the degree to which these capacities are related unclear. Moreover, other research has suggested a distinction between attention and VSTM buffers. To explore the degree to which capacity limitations reflect the use of a shared visual processing buffer, we compared individual subject's capacities on attentional and VSTM tasks completed in the same testing session. We used a multiple object tracking (MOT) and a VSTM change detection task, with varying levels of distractors, to measure capacity. Significant correlations in capacity were not observed between the MOT and VSTM tasks when distractor filtering demands differed between the tasks. Instead, significant correlations were seen when the tasks shared spatial filtering demands. Moreover, these filtering demands impacted capacity similarly in both attention and VSTM tasks. These observations fail to support the view that visual attention and VSTM capacity limits result from a shared buffer but instead highlight the role of the resource demands of underlying processes in limiting capacity.

Keywords: attention, visual short-term memory, capacity, vision, multiple object tracking, distractor filtering

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Introduction

The magic number four has become a pervasive concept throughout human visual processing research (Cowan, 2001), with an upper bound of four objects being found anywhere from subitizing (Cowan, 2001; Trick & Pylyshyn, 1994) to visual spatial attention (Cavanagh & Alvarez, 2005; Pylyshyn & Storm, 1988; Scholl, Pylyshyn, & Feldman, 2001; Yantis, 1992) to visual short-term memory (Awh, Barton, & Vogel, 2007; Luck & Vogel, 1997). This pervasiveness has led to the suggestion that there may be an underlying capacity-limited buffer system that is shared across a variety of processes (Cowan, 2001; Drew & Vogel, 2008). This would not be the first example of shared processing between attention and short-term memory. Overlaps similar to this have been seen in other facets of attention and short-term memory. Both processes appear to activate the brain in similar ways (Awh & Jonides, 2001) and shifts in one can impact performance in the other (Awh & Jonides, 2001; Downing, 2000). Several researchers have even gone as far as to suggest that VSTM is simply an emergent property of attention, in that VSTM is simply prolonged attention to a stimulus representation (Postle, 2006), while others have suggested just the opposite, that attention arises from the relative importance of a particular feature, object, or location in VSTM (Courtney, 2004). However, to date, there is no clear evidence for a link between attentional and VSTM capacity limitations within individuals.

The research into capacity limitations has shown strong indications that there is some degree of shared processing buffer in both visual attention and VSTM. Besides both processes showing an equivalent four-object limit, both have also shown capacity-related modulations when object complexity (Alvarez & Cavanagh, 2004; Horowitz et al., 2007; Luria, Sessa, Gotler, Jolicoeur, & Dell'Acqua, 2010; Xu & Chun, 2006) or hemifield spatial location (Carlson, Alvarez, & Cavanagh, 2007; Cavanagh & Alvarez, 2005; Delvenne, 2005) is varied. Moreover, IPS and contralateral delay (CDA)-related activity has been implicated in both attention and VSTM capacity limits (though generally not in the same subjects on the same day; Culham et al., 1998; Culham, Cavanagh, & Kanwisher,

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2001; Cusack & Mitchell, 2008; Drew, Horowitz, Wolfe, & Vogel, 2011; Jovicich et al., 2001; Vogel & Machizawa, 2004; Xu & Chun, 2006). Xu and Chun's (2006) work even seems to support the view that the attention and VSTM are simply different components of the same process, as they found evidence for a variable VSTM capacity limit that was bounded on the upper end by a fixed attentional selection mechanism. Relatedly, Oksama and Hyönä (2008) have proposed a model to suggesting that in MOT tasks in which objects differ in identity (dubbed Multiple Identity Tracking), identity and location information are bound together and stored in VSTM and periodically updated by serial attention processes as the objects move about the screen, suggesting that, at least in some cases, MOT may be, in reality, a type of VSTM task. If both VSTM and attentional capacity limits are driven by the same general visual processing bottleneck, it would provide evidence that these limitations may simply be different representations of the same phenomenon.

However, dissociations between attention and VSTM capacity limits have also been seen. While both tasks have been shown to interfere and decrease capacity in each other (Fougnie & Marois, 2006, 2009), a second VSTM task was shown to more severely impact VSTM capacity than a concurrent attentional task (Fougnie & Marois, 2006). This suggests that while visual attention and VSTM capacities are highly interrelated, this relationship may be driven by the underlying processes the two share and not by being part of the same overarching mechanism.

Several lines of research seem to support this process-oriented relationship between capacities. Oksama and Hyönä (2004) found that subjects' capacity limits in attention and VSTM tasks were correlated with each other, albeit minimally (explaining only 3.1% of the variance between tasks), but that the strength of the correlation seemed to increase (explaining 24% of the variance) when the attention task was modified to require the storing of identity as well as location information. Similarly, Allen, Mcgeorge, Pearson, and Milne (2006) found that MOT capacity decreased during a dual-task paradigm only when the second task required the visual or spatial processing as well.

Distractor suppression has been shown to be a strong, if not the most vital, predictor of performance on both attentional (Bettencourt & Somers, 2009; Pylyshyn, 2006) and VSTM tasks (Vogel, McCollough, & Machizawa, 2005; Zanto & Gazzaley, 2009), and the two tasks have also been shown to interact when distractor suppression is needed (de Fockert, Rees, Frith, & Lavie, 2001; Forster & Lavie, 2007; Jiang, Chung, & Olson, 2004; Poole & Kane, 2009; Todd, Fougnie, & Marois, 2005; Yi, Woodman, Widders, Marois, & Chun, 2004). In fact, Poole and Kane (2009) found that working memory skill only predicts performance on a classical attentional task, visual search, when subjects were cued as to which locations were valid target locations, creating an opportunity to suppress distractor locations. Increasing VSTM load, however, has been shown to have opposing effects on distractor suppression depending on the attentional task. Todd et al. (2005) found that increasing VSTM load improved performance by increasing the suppression of distracting stimuli, even to the point of inducing inattentional blindness, while others have shown that an increase in working memory load can increase the effect of distractors, decreasing performance (de Fockert et al., 2001). These two results are not completely contradictory though. In de Fockert et al.'s (2001) study, working memory load was modulated separately from the attentional task. This prevented working memory from maintaining the task-relevant information necessary to identify and suppress distracting stimuli, allowing these distractors to better interfere with task performance. Thus, both de Fockert et al. and Todd et al. demonstrate that working memory appears to play a role in attentional selection and suppression. However, Yi et al. (2004) found that while increasing the attentional demands in a working memory task, by degrading the images, decreased the processing of distractor stimuli, there was no effect on distractor stimuli processing when the working memory load was increased. This suggests that working memory itself does not drive distractor suppression, but the interaction between the two processes does.

By exploring the links between capacity limits in visual attention and VSTM, we can help explain the degree to which the cognitive framework of these two processes is intertwined. If visual attention and VSTM are simply two components of the same phenomenon, then they should share the same general-purpose capacity-limited buffer, and capacity should be correlated within individuals across virtually any VSTM and attentional tasks. However, if capacity limits are due to specific underlying processes, instead of a more general fixed buffer system, such as distractor suppression, then only tasks that share this critical process should show correlations in capacity. To explore these hypotheses, we designed a set of experiments that exploit the individual differences in subject capacity to examine possible correlations in capacity measurements within subjects across multiple tasks (similar to the experiments of Oksama and Hyönä, 2004). The use of individual differences to study shared processes is complementary with dual-task interference studies (e.g., Allen et al., 2006; Fougnie & Marois, 2006, 2009). Both approaches examine the relationship between tasks, but each has their own strengths. Dual-task experiments can demonstrate a direct competition between the processes or resources used by a task by showing decrements in performance. However, often, it is difficult to tease apart the cause of the impairment. For example, decrements in performance in MOT with a concurrent VSTM task could be due to both processes using the same capacity buffer or maybe due to difficulties in reporting two types of information (i.e., forgetting the answer for the task reported second). Individual difference approaches, on the other hand, can allow for a cleaner comparison between performance on two tasks, as the likelihood of unrelated interference is low, but do not reveal direct competition for resources. Experiment 1 used an MOT task and a VSTM change detection task, the most common capacity assessment tasks in the literature, to compare VSTM and attentional capacities. Experiment 2 varied the number of distractors in the attentional and VSTM tasks used in Experiment 1 to examine how the relationship between capacities is affected by the process of distractor filtering. We found that correlations in capacity were only seen when the tasks shared the same spatial filtering demands. These filtering demands affected VSTM and attentional capacity limits in a similar manner, supporting the view that capacity limits are driven by the demands of underlying processes that consume resources in a similar manner across VSTM and attentional tasks.

Experiment 1

Equivalent four-item limits in capacity have been seen in both MOT (Pylyshyn & Storm, 1988; Scholl et al., 2001; Yantis, 1992) and VSTM change detection paradigms (Cowan, 2001; Luck & Vogel, 1997). The consistency of this four-item limit across a variety of task manipulations has led many to suggest that attention and VSTM share a capacity limit (Cowan, 2001; Drew & Vogel, 2008). Further support for such a shared visual processing buffer has come from research that has shown a similar effect on this four-item limit by stimulus complexity and between and within hemisphere location differences in both attentional and VSTM tasks (Alvarez & Cavanagh, 2004; Carlson et al., 2007; Cavanagh & Alvarez, 2005; Delvenne, 2005; Horowitz et al., 2007; Luria et al., 2010; Xu & Chun, 2006). However, to our knowledge, this putative shared capacity limitation has only been observed through meta-analyses and group-averaged data across studies. As these capacity limits show strong individual differences, it remains unclear whether or not there exists an overarching visual processing capacity limitation that governs both of these tasks. A previous individual difference study showed modest correlations between attention and VSTM tasks (Oksama & Hyönä, 2004) but used a task that, while a theoretically similar measure, was very different from the standard VSTM change detection task used to measure capacity. Thus, this experiment was designed to test for such a shared buffer system by using an MOT and a change detection paradigm, standard tasks used to measure capacity in attention and VSTM, respectively, to compare attentional and VSTM capacities in individual subjects. If a general capacity limitation exists, as argued by Cowan (2001), then even when two very dissimilar tasks, which share few common processes, are used to measure capacity, we should see correlations in VSTM and attentional capacities in individual subjects. However, if these limits are a result of separate buffer systems, as hinted at by dual-task paradigms (Allen et al., 2006; Fougnie & Marois, 2006), then even though a similar limit is seen across groups of subjects, little or no correlations should be seen within subjects.

Methods

Fifty-four Boston University undergraduate students participated in this experiment. The two tasks used were based on commonly used capacity assessment tasks in both attentional (Pylyshyn & Storm, 1988; Scholl et al., 2001; Yantis, 1992) and VSTM (Luck & Vogel, 1997; Xu & Chun, 2006) literature. In both tasks, capacity was measured using K score.

K score was calculated as

$$K = (H + \mathrm{CR} - 1.0)^{*}n, \tag{1}$$

where H is hit rate, CR is correct rejection rate, and n is number of targets. Peak performance is achieved at different set sizes for different subjects; for subjects with lower capacity, additional targets function like distractors and can lower K measures. Since *a priori* we cannot know a subject's capacity, subjects were tested at different set sizes and K was computed at each set size. The maximum K across set sizes was used as that subject's capacity measurement.

Attention task

The display (see Figure 1a) consisted of a number of white disks (diameter = 1.2°) on a black screen (32.5° × 24.0°), with a small fixation cross in the center of the screen. At the beginning of each trial the target disks were highlighted in red for 1 s. In the standard MOT condition, 3, 4, 5, or 6 targets were selected out of 12 total disks. Subjects were instructed to attend to the highlighted disks and to track them as they moved about the screen. Subjects were asked to maintain fixation on a central fixation cross in order to mirror other MOT experiments in the literature, but eye movements were not recorded. After the cue period, the disks moved in random directions across the screen at a constant speed of 4.8°/s for 10 s. The disks were controlled by a repulsion algorithm that aggregated the distance (as measured from the center of each disk) between each disk, the fixation cross, and the walls to determine the direction movement, such that as a disk came closer to any of these objects, it was more likely to be directed away. This caused each disk to repulse off the other disks, the walls, and the fixation cross to prevent any overlap. When the disks stopped, one disk was highlighted in blue for 2 s and subjects were asked to report, through a single forced-choice probe, whether or not the probed disk was one of the original red targets. Subjects completed 30 trials per condition in the attention task, for a total of 120 trials.

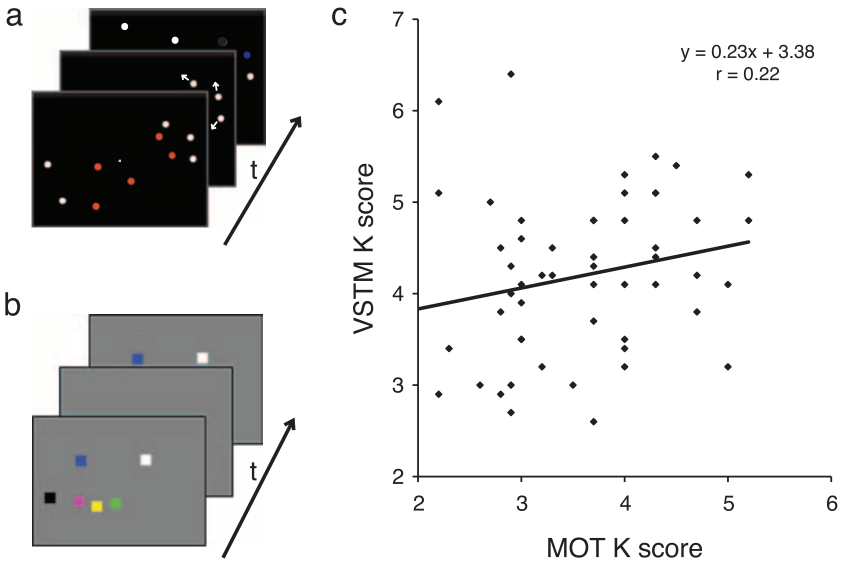

Figure 1. (a) Attentional and (b) VSTM tasks. (c) Results for the comparison between the VSTM and MOT tasks, showing capacity was weakly correlated with the VSTM task.

VSTM task

In the VSTM task (see Figure 1b), subjects viewed (100 ms) 4, 6, or 8 colored squares (side = 1.2°) on a gray screen (32.5° × 24.0°). Square color was randomly chosen from a set of seven colors (blue, red, green, yellow, white, black, and purple). Color could repeat within display, similar to previous VSTM color change detection tasks (i.e., Vogel, Woodman, & Luck, 2001). After a brief delay (900 ms), subjects detected a color change that occurred 50% of the time in the test display (2 s). In change trials, one square changed color to a different color in the color set, regardless of whether another square of that color was present in the initial display. Location was never varied. Subjects did not perform an articulatory suppression task, as similar capacity limitations have been seen both with and without such tasks (see Vogel et al., 2001). Subjects completed 50 trials per condition, for a total of 150 trials.

Prior to this experiment and all following experiments, subjects also completed a practice block of 18 trials in both tasks, in which they were asked to track or remember one, two, or three items in each trial. Subjects repeated practice blocks until reaching at least 80% correct performance.

Results and discussion

The results are shown in Figure 1c. We found a small correlation between *K* score in the MOT and VSTM tasks, which failed to reach significance ($r(52) = 0.22$, $p = 0.11$). This suggests that while attentional and VSTM capacities have previously appeared to be related, at best, only a weak correlation exists within subjects. If there was a general visual processing capacity-limited buffer that governed capacity limits in all visual tasks, then we would expect to see strong within-subject correlations between the attentional and VSTM tasks regardless of the similarity of the tasks. However, as only a weak correlation was found, this fails to support a shared, fixed capacity buffer. A resource-limited account of visual capacity, on the other hand, would suggest a variability in how different processes draw on resources and would suggest that the degree of correlation in capacity across tasks is dependent on the types of processes used. Support for such a resource-limited model comes from both MOT and VSTM literature, where variations in object complexity, distractor number, speed, and interobject distance have been shown to affect capacity (Alvarez & Franconeri, 2007; Bettencourt & Somers, 2009; Franconeri, Alvarez, & Enns, 2007; Horowitz et al., 2007; Tombu & Seiffert, 2011; Vogel et al., 2005; Xu & Chun, 2006; Zanto & Gazzaley, 2009). In this sort of model, we would only expect to find a weak correlation between VSTM and MOT, as they share very few of the processes previously shown to impact capacity. However, if these tasks were modified to have more underlying processes in common, then we would expect to see a stronger correlation in capacity between VSTM and MOT tasks. The next experiment explored this possibility.

Experiment 2

Previous research has hinted at support for process-driven correlations between attention and VSTM tasks (Allen et al., 2006; Oksama & Hyönä, 2004). However, these studies have not explored how the correlation between these capacities is affected as the amount of resources used by a particular process is varied, and thus, it remains unclear the degree to which these correlations are driven by the resource use of particular processes. Distractor suppression has previously been shown to strongly affect performance and capacity in both attentional (Bettencourt & Somers, 2009; Pylyshyn, 2006) and VSTM tasks (Vogel et al., 2005; Zanto & Gazzaley, 2009), making it an ideal process to examine the role of resource use across both types of tasks. However, it is unclear whether the distractor filtering process draws on the same resources in both tasks and whether this process affects attentional and VSTM capacity limitations in a related manner. If the same resources are used in both tasks, then we would expect to see stronger correlations in the capacity limitations between visual attention and VSTM than was seen in Experiment 1, as well as correlations in how modulating distractor filtering demands affects these limits. However, if this impact is unrelated between the two tasks, this would suggest a separation between attention and VSTM resources and that any correlations seen in capacity limitations between tasks is due to some other confounding factor that is unrelated to the actual capacity limit mechanisms. The following experiment was designed to test this theory by using the same tasks that were only weakly correlated in Experiment 1 and matching them on distractor filtering requirements.

Methods

Thirty subjects that participated in Experiment 1 also participated in this experiment. The tasks were similar to those used in Experiment 1.

Attentional task

Subjects completed two MOT tasks, one identical to Experiment 1 (standard MOT task) and one in which the distractor load was varied but target set size was held constant. The second MOT task and display were similar to Experiment 1. Five targets (signified in red for 1 s) were chosen out of either 10 disks (low distractor condition) or 20 disks (high distractor condition). Subjects tracked these disks for 10 s while maintaining fixation, then reported whether the probed circle (highlighted in blue) was one of the original targets. Subjects completed 30 trials per condition in the attention task, for a total of 60 trials.

VSTM task

Subjects completed two VSTM tasks, one identical to Experiment 1 (standard VSTM task) and one in which the distractor load was varied but target set size was held constant. The second VSTM task and display were similar to Experiment 1; however, now, the display consisted of both target and distractor squares. During a cue period, 5 target locations were cued by white outlined squares (see Figure 2a). Subjects were told to remember only the squares that appeared in the cued locations. After the cue period, either 10 or 20 colored squares were displayed for 100 ms. After a brief delay (900 ms), subjects detected a color change (occurring 50% of the time) in the cued target squares. A change in either the target or distractor squares occurred in every trial to encourage subjects to encode only the target squares and suppress distractors; subjects were only to report a color change in the cued target squares. Subjects completed 50 trials per condition, for a total of 100 trials. In addition to the standard attention and VSTM task practice completed in Experiments 1 and 2, subjects also completed a practice block of 10 practice trials in which they were asked to remember 2 out of 10 squares for the distractor VSTM task. Subjects practiced until reaching at least 80% correct performance.

For the standard MOT and VSTM conditions, K score was calculated as in Experiment 1, where the maximal K score across set size was taken as the subject's capacity measurement, in order to replicate the analysis above. To explore the relationship between MOT and VSTM with distractors, we completed two analyses. In the first, we averaged the K score across the 5 of 10 and 5 of 20 conditions for MOT and VSTM separately in order to examine the correlation between these tasks when they were matched on both target and distractor number. Second, in order to explore the effect of increasing the number of distractors present on MOT and VSTM capacity measures, we measured the difference in K score between the minimum and maximum number of distractor conditions. In MOT, this represents the difference between the 5 of 10 and 5 of 20 conditions. In the VSTM task, however, the minimal number of distractors was zero (standard VSTM task), and as set size 5 was not present in the standard VSTM task, to calculate the difference score between the minimum and maximum number of distractors, we averaged the K scores measured at set sizes 4 and 6 with no distractors and then subtracted the K score for 5 of 20.

Results and discussion

The results are shown in Figures 2b and 2c. Whereas there was only a weak, non-significant correlation between K score in the standard MOT and VSTM tasks ($r(28) = 0.18$, $p = 0.34$), replicating Experiment 1, a significant correlation in capacity was found here when target and distractor number were matched (averaged across both distractor levels) in the two tasks ($r(28) = 0.44$, $p < 0.02$). While the correlation coefficients between the standard MOT and VSTM tasks and the distractor- and target-matched MOT and VSTM tasks do not significantly differ from each other ($p = 0.29$), the change in capacity as distractor number was increased was significantly corre-

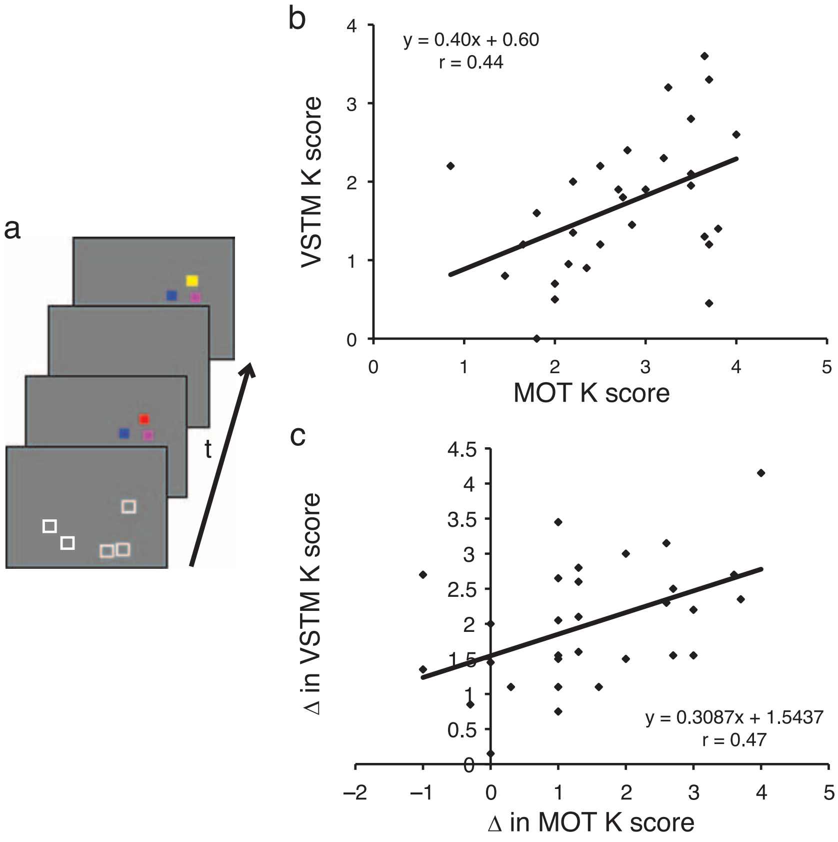

Figure 2. (a) Cued VSTM stimuli and (b) correlation results comparing MOT and VSTM when matched for number of targets and distractors and (c) change in capacity with addition of distractors, showing a correlation between VSTM and MOT (which were only weakly correlated in Experiment 1) when number of targets and number of distractors were matched (b). A significant correlation in the impact of distractors on capacity was also seen (c).

lated ($r(28) = 0.42$, $p < 0.02$), suggesting that distractor filtering in both tasks draws on capacity-limited resources in a similar manner. Along with the addition of distractors, the VSTM task was changed to include a cuing phase as well. It is likely that some of the increase in correlation between Experiment 1 and the distractor version presented here is due to the attentional selection process brought on by this cuing phase as well. However, as previous research has shown distractor suppression to have a much larger effect on capacity than target selection processes (Bettencourt & Somers, 2009; Pylyshyn, 2006; Vogel et al., 2005; Zanto & Gazzaley, 2009), and as the effect on capacity of increasing the number of distractors is correlated between VSTM and MOT tasks, we believe that the resources consumed by distractor suppression processes to underlie the majority of the correlations seen here.

The weak correlation seen in Experiment 1 suggested that attentional and VSTM capacity limitations are not due to a shared, fixed capacity buffer. Here, we see that the strength of the correlation between these capacity limits is driven by the degree to which the two share a common process, spatial filtering of distractors. This suggests that capacity limitations in both attentional and VSTM tasks are driven by underlying mechanisms that draws on a shared, limited resource pool. These results do not support a distinction between attention and VSTM but rather between the processes involved in both tasks.

General discussion

Overall, we found that VSTM and attentional capacities were related to each other but that the strength and significance of the relationship between tasks was related to the similarity in spatial filtering demands across tasks. Experiment 1 found that while attentional and VSTM capacities appeared related in other studies, they are, at best, weakly correlated in individual subject analyses, failing to support a common capacity-limited visual buffer. Experiment 2 showed that previously weakly related capacity limits can be made to more strongly correlate if the tasks used to measure them are changed to include similar processing requirements, such as distractor filtering. Moreover, increasing task difficulty by modulating the spatial precision demands impacted capacity limits in a similar manner across both tasks, suggesting that the demands of underlying processes on a shared resource pool play a large role in determining capacity limits.

Some researchers have suggested that attention is simply an emergent property of VSTM (Courtney, 2004) and vice versa (Postle, 2006). However, our results support the view that both attentional and VSTM capacity limits appear to be simply the outcome of the resource demands of various underlying processes, in this case, primarily distractor filtering, common in both tasks. Previously, it has been suggested that there may be one, general, visual processing capacity-limited buffer that dictates the capacity limitations seen in both visual attention and VSTM (Cowan, 2001). This model would predict that attention and VSTM capacities would be related, regardless of the particular task used to measure the capacity limit. Contrary to this, in Experiment 1, we failed to observe a significant correlation between two commonly used capacity measurement tasks, MOT and change detection, and what correlation did exist was rather weak. Our results also do not support the idea of complete independence between attention and VSTM capacity-limited buffers as the results of Experiment 2 showed significant correlations between capacities when resources were taxed by distractor filtering processing in both tasks.

Instead, our results show strong evidence for a capacity-limiting role in both attention and VSTM related to spatial filtering demands. The manipulations of Experiment 2 induced correlations between the capacity limits of these two phenomena, and variations in the filtering demands, from low to high, impacted these limits in a correlated manner. This suggests that distractor filtering, and likely other processes, places similar demands on capacity stores in both VSTM and attention and that these demands drive how many objects can be successfully attended or remembered. This can explain why we found only a weak correlation in Experiment 1, as the standard MOT and VSTM tasks share only a minimal number of underlying processes. In such a case, we would expect to only see a weak relationship between capacity limits as each task is taxing the shared resource pool in a different manner and to different degrees. This explanation also accounts for the variations in capacity limits that have been observed across a wide range of factors, including object speed, spacing between objects, and stimuli complexity, in both attention and VSTM (Alvarez & Cavanagh, 2004; Alvarez & Franconeri, 2007; Bettencourt & Somers, 2009; Franconeri et al., 2007; Horowitz et al., 2007; Shim, Alvarez, & Jiang, 2008; Xu & Chun, 2006). Each of these modulations affects the amount of resources needed by an underlying task process, such as object individuation (for speed- and spacing-related modulations), object identification (for complexity-related modulations), and distractor filtering (for spacing and distractor number modulations). These increases in demand change the pattern of how resources are deployed. For example, as the number of distractors increases, distractor filtering processes consume more resources, pulling them away from target indexing mechanisms, which, in turn, decrease the overall number of objects that can be selected and encoded. Thus, capacity limits are not solely driven by a limited storage buffer, where the limitation is the number of slots available for storage, nor are they reflective of attention or VSTM as a whole. Instead, these limits reveal the resource use of underlying processes. The individual difference correlation-based approach that we have taken here to probe for shared mechanisms complements dual-task interference methods (e.g., Allen et al., 2006; Fougnie & Marois, 2006, 2009) and, indeed, are findings largely consistent with these prior observations.

If VSTM and MOT tasks are only weakly correlated on their face, then why have other researchers seen evidence for a relationship between these tasks? For example, previous work with ERPs has shown that the CDA in individual subjects reflects individual capacities for both MOT and VSTM tasks (Drew et al., 2011). However, in their task, they did not determine whether CDA activity correlated within individual subjects across the two types of tasks. Moreover, their VSTM task involved a distractor filtering component as they were to attend to stimuli presented in only one visual field. Additionally, they used a modified MOT task, in which subjects tracked items for only 1.5 s. This modification may have also shifted the focus of processing away from attentional maintenance of targets and, instead, emphasized the encoding of items, similar to VSTM. Thus, in a process-driven capacity limit model, we would expect to see a relationship between the capacities of these tasks and, thereby, a relationship between CDA measurements. In many other studies, the group-averaged nature of the comparison could obscure any individual differences that may exist. For example, while research has shown capacity-related IPS activity for both VSTM and MOT, no single study, to our knowledge, has determined whether the regions that appear to track capacity in these tasks intersect on an individual subject level. It may be that when capacities are correlated, similar regions would show capacity-related activity within IPS, but that as the capacities diverge, so might the neural activity. More research is necessary to understand the neural underpinnings of capacity limits.

While these results suggest a more primary role for capacity-limiting processes, we cannot rule out the idea of a general or distinct attention and VSTM-fixed capacity buffers. When the distractor filtering demands were reduced or eliminated all together, both VSTM and attention still showed limited capacities. However, our results do show that correlations between attention and VSTM are driven by the degree of similarity in these demands, reflecting strong support for the flexible resource use model. In particular, our results suggest that VSTM and MOT may share spatial indexing mechanisms, as suggested by work with ERPs and fMRI (Culham et al., 2001; Drew et al., 2011; Xu & Chun, 2006), but the demands of the tasks may impose different capacity limits on this indexing process. This suggests future avenues of research where the manner in which the processes involved in various tasks consume resources is modulated to examine the role these processes play in capacity limitations both behaviorally and in the brain, as well as to examine whether any processes differentially effect VSTM and attention, which could demonstrate a dissociation between the resource stores for these tasks.

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Corresponding author: Katherine C. Bettencourt.
Email: kcb@wjh.harvard.edu.
Address: 33 Kirkland St., 7th Floor, Vision Sciences Laboratory, Cambridge, MA 02138, USA.

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