

# Effects of target enhancement and distractor suppression on multiple object tracking capacity

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Mounting evidence suggests that visual attention may be simultaneously deployed to multiple distinct object locations, but the constraints upon this multi-object attentional system are still debated. Results from multiple object tracking (MOT) experiments have been interpreted as revealing a fixed attentional capacity limit of 4 objects, while other evidence has suggested that attentional capacity may be more fluid. Here, we investigated the influence of target stimulus factors, such as speed and size, and of distractor filtering factors, such as number of distractors and screen density, on MOT performance. Each factor had significant effects on capacity, producing values that ranged from above 6 objects down to one object, depending on the task demands. Although our results support the view that crowding effects modulate the effective capacity of attention, we also find evidence that central processes related to distractor suppression and target enhancement modulate capacity.

Keywords: attention, capacity, vision, multiple object tracking, distractor filtering, target enhancement

Citation: Bettencourt, K. C., & Somers, D. C. (2009). Effects of target enhancement and distractor suppression on multiple object tracking capacity. *Journal of Vision*, 9(7):9, 1–11, <http://journalofvision.org/9/7/9/>, doi:10.1167/9.7.9.

## Introduction

Several lines of research have demonstrated that visual attention may be simultaneously deployed to more than a single region of space (Awh & Pashler, 2000; McMains & Somers, 2004; Müller, Bartelt, Donner, Villringer, & Brandt, 2003; Pylyshyn & Storm, 1988). However, “Multiple Spotlight” selection is limited to a relatively small number of object locations. Since the late 1980s, multiple object tracking (MOT) experiments have tended to show a limit of  $4 \pm 1$  object locations (Culham, Cavanagh, & Kanwisher, 2001; Pylyshyn & Storm, 1988; Scholl, Pylyshyn, & Feldman, 2001; Yantis, 1992). The consistency of this 4 object limit has led some to theorize that attentional selection has a fixed 4 slot capacity (Cowan, 2001; Xu & Chun, 2006), though others have suggested that capacity limits are flexible, spanning a range from 2 to 8 objects (Alvarez & Franconeri, 2007; Horowitz et al., 2007), with the precise limit dependent upon the task demands and subject experience. Thus, many questions still remain regarding the mechanisms that limit the simultaneous selection of multiple objects.

Prior work has demonstrated that multiple object tracking capacity is affected by several aspects of the stimuli and by task demands. Both temporal (Verstraten, Cavanagh, & Labianca, 2000) and spatial (Intriligator &

Cavanagh, 2001) resolution limits of attention have been found. Below these limits capacity drops off sharply. However, these limits might reflect data-limited rather than resource-limited processes (Norman & Bobrow, 1975). Different attentional capacities have also been seen when target stimuli are separated into different quadrants or hemifields (Alvarez & Cavanagh, 2005; Carlson, Alvarez, & Cavanagh, 2007), but hemispheric split of capacity could be realized in both fixed and flexible models. Horowitz et al. (2007) found that when complex stimuli are used, capacity can drop below 4 objects; however, fixed slots proponents have argued that complex stimuli might require more than one slot (Zhang & Luck, 2008). Horowitz et al. (2007) also found that capacity appears to be hindered by distractors, such that capacity measurements were closer to 4 objects with fewer distractors; other work has found attentional selection of static objects appears to be impaired by increased screen density (Franconeri, Alvarez, & Enns, 2007). Both of these sets of findings could be explained by crowding effects, rather than by distractor suppression per se, and are potentially consistent with either fixed slot or flexible resource models. One recent study stands out as particularly compelling evidence that attentional capacity is governed by the limitations of a continuous pool of resources rather than a fixed discrete limit on the number of objects. Alvarez and Franconeri (2007) reported MOT capacities of up to 8 objects when then the objects

moved slowly and that capacity differences at higher speeds could not be attributed to error rates or data limitations.

If attentional capacity is governed by a continuous pool of resources, then one would expect that multi-element tracking capacity would be modulated by any factor that draws on the central resource pool. Two broad classes of attentional mechanisms have been proposed to enhance targets while diminishing the influence of distractors. “Push-only” mechanisms suggest that attentional effects are intentionally directed only toward targets and not toward distractors (Alvarez & Franconeri, 2007; Pylyshyn & Storm, 1988). This view suggests that attention works to amplify target processing, leaving distractors unprocessed unless they impinge upon a target selection window. In contrast, “Push-pull” mechanisms suggest that attention enhances target representations and suppresses distractor representations (Pinsk, Doniger, & Kastner, 2004; Posner, Snyder, & Davidson, 1980; Somers, Dale, Seiffert, & Tootell, 1999; Yi, Woodman, Widders, Marois, & Chun, 2004). This view suggests that distractors exogenously grab attention and may diminish target processing even if the distractors do not enter a target selection window. Active and/or passive processes may “pull” attention from distractors.

One compelling version of “push” models states that flexible changes in attentional capacity are a direct reflection of the spatial resolution necessary to accomplish the task at hand. Research has shown that subjects are more prone to errors when targets and distractors get closer. These errors are due to the distractor entering the target’s attentional spotlight, causing subjects to either lose the target or swap the target and distractor (Alvarez & Franconeri, 2007; Intriligator & Cavanagh, 2001; Oksama & Hyönä, 2004; Pylyshyn, 2004; Sears & Pylyshyn, 2000). In order to overcome these sorts of local, crowding-related errors, the spatial resolution model, or FLEX model, states that the attentional spotlight must shrink and become more precise in order to prevent distractors from entering the spotlight. However, this increased precision comes at a cost, taxing the resource pool such that fewer targets can be tracked.

We suggest that, as in the active filtering push-pull model, the task demands of target enhancement and distractor suppression draw on the resource pool that supports tracking, and thus, should impact capacity. In the present set of MOT studies we have investigated a variety of different factors, including speed, size, and number of distractors, in order to examine the role that “push” and “pull” mechanisms may have in attentional capacity. Task demands were modulated to examine both positive and negative effects on capacity. Although we found evidence to support a significant role for crowding, we also found that capacity was significantly affected by attentional demands related to target enhancement and distractor suppression that could not be attributed to crowding. A range of capacities both above and below the putative four object limit was found, supporting the flexible resource

theory and suggesting that attention may be better thought of as being actively deployed in a push-pull manner based on task demands.

## Experiment 1

Alvarez and Franconeri (2007) recently reported that manipulations of object speed can strongly affect attentional capacity, producing large variations in attentional capacity, with up to eight objects successfully tracked. However, a variety of speeds have been used across other MOT experiments, and yet they have generally all reported capacity measurements of four objects (Alvarez and Cavanagh, 2005; Pylyshyn & Storm, 1988; Scholl et al., 2001; Yantis, 1992). Why then were Alvarez and Franconeri (2007) able to show such a strong variation across speeds, and such a high capacity? One main difference is the extreme slowness at which their discs moved in the track 8 condition. The discs moved on the order of 0.5°/s, for 5 s, and thus the discs only traveled approximately 2.5° in each trial. With this small displacement, the task may have devolved into more of a short-term memory task than an attentional tracking task. Subjects could have simply grouped the discs into shapes and stored this in memory, thereby inflating the actual capacity.

Therefore, the aim of [Experiment 1](#) was to re-examine the effect of speed on attentional capacity and to attempt to replicate Alvarez and Franconeri’s (2007) findings under conditions that decrease the opportunity for subjects to rely on spatial short-term memory strategies. Tracking time was doubled in order to increase the net displacement between the start and end locations of each target. Our preliminary experiments suggested that subjects had significant difficulty tracking eight objects, creating highly variable performances that could unduly obscure any effects of speed on capacity. In response to this, we decided to simplify the experiment and ask subjects to track only five of ten discs. Although this necessarily created a ceiling on capacity, it permitted us to unambiguously examine the change in capacity across the higher range of speeds. However, to overcome this self-imposed ceiling limit, we ran two additional conditions at slower speeds, in which subjects also were asked to track 7 of 14 or 8 of 16 balls. All speeds were below the limit of about 50°/s at which subjects become unable to attend and track even one object (Verstraten et al., 2000) and ranged across the speeds commonly used in MOT paradigms. This range of speeds should allow us to see whether changes in disc speed had any effect, detrimental or beneficial, on attentional capacity.

## Methods

Eight undergraduate students participated in the first set of conditions in [Experiment 1](#), an additional eight participated in the second and third conditions. The

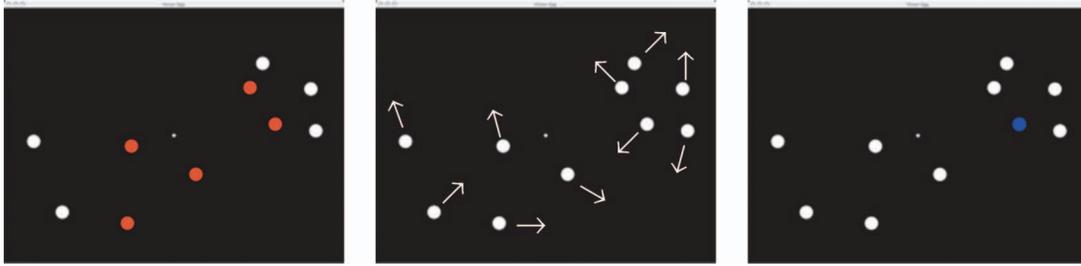


Figure 1. MOT task. Target discs were cued (in red, 1 s) for each trial. The cues disappeared and the discs moved around the display for 10 s, avoiding other discs and the fixation cross. One disc was then cued (in blue, 2 s) and subjects reported (yes/no) whether the cued disc was in the original target set.

display (see [Figure 1](#)) consisted of ten white discs (diameter =  $1.2^\circ$ ) on a black screen ( $32.5^\circ \times 24.0^\circ$ ), with a small fixation cross in the center of the screen. At the beginning of each trial five discs were highlighted in red for 1 s, and subjects were instructed to remember the highlighted discs and to track them without moving their eyes. Eye movements were not recorded as they have been shown to not strongly influence tracking performance (Scholl et al., 2001; however, see Fehd & Seiffert, 2008). The cues disappeared, and all ten discs moved in random directions across the screen at one of five constant speeds: 1, 4, 8, 10, or  $13^\circ/\text{s}$  for ten seconds. Speed was varied across blocks and block order was randomly determined. The discs were controlled by a repulsion algorithm that aggregated the distance (as measured from the center of each disc) between each disc, the fixation cross, and the walls to determine the direction movement, such that as a disc came closer to any of these objects, it was more likely to be directed away. This caused each disc to repulse off each other, the walls, and the fixation cross to prevent any overlap. When the discs stopped, one disc was highlighted in blue for 2 s. Subjects indicated whether the probed disc was one of the targets. Subjects completed a total of 150 trials, 30 in each condition. The second and third conditions used the same basic stimuli and methods as the first, but instead of tracking five out of ten discs, in the second condition subjects had to track seven out of 14 moving at  $1^\circ/\text{s}$  for ten seconds, and in the third they tracked eight out of 16 moving at  $0.5^\circ/\text{s}$ . In both of these conditions the discs were slightly decreased in size (diameter =  $0.9^\circ$  instead of  $1.2^\circ$ ) in order to better allow all the discs to fit on the screen.

K score was calculated as

$$K = (H + CR - 1.0) * n, \quad (1)$$

where H is hit rate, CR is correct rejection rate, and n is number of discs tracked.

Prior to this experiment and all following experiments, subjects completed one or more practice blocks of 18 trials, in which they tracked one, two, or three discs each trial. Subjects practiced until reaching at least 80% correct performance.

## Results and discussion

The results are shown in [Figure 2](#) (See [Supplemental Figure 1](#) for performance data). Varying the speed of the discs significantly influenced performance ( $F(4,39) = 7.86$ ,  $p = 0.0001$ ) (see [Figure 2](#)), partially verifying Alvarez and Franconeri's (2007) findings.

Our results generally confirm Alvarez and Franconeri's (2007) finding that speed dramatically affects capacity, such that at slower speeds more targets could be tracked (see [Figure 2](#) for a comparison between the two experiments). At the fastest speed, subjects could reliably track only 1.1 objects, while at the slowest speed, subjects' capacity tracking 5 of 10 discs was 4.9 objects, showing a decrease of 3.9 objects over the range of speeds. Since subjects were at ceiling in the slowest speed, we asked subjects to track 7 out of 14 discs at  $1^\circ/\text{s}$  and 8 of 16 discs at  $0.5^\circ/\text{s}$ . At  $1^\circ/\text{s}$  average capacity was 5.8 with two of the eight subjects at ceiling (7.0 for both), while 6 did not (6.1, 5.6, 5.6, 4.2, 3.3, 2.8). At  $0.5^\circ/\text{s}$  average capacity was 6.0 objects. Again two subjects approached ceiling (7.5 for both) while the other six did not (6.4, 5.9, 5.9, 5.9, 4.3, 4.3).

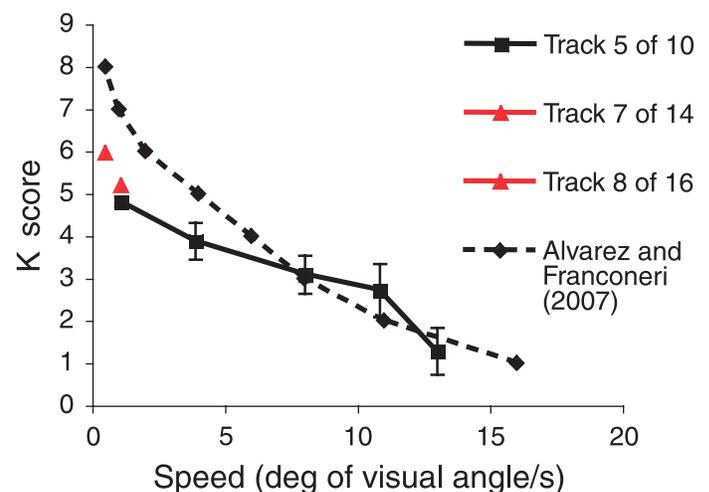


Figure 2. The graph shows the K score as a function of disc speed. Our speed results are plotted against Alvarez and Franconeri's (2007) speed findings.

Our results thus bolster the primary findings of Alvarez and Franconeri (2007). Although our subjects, on average, were not able to successfully track 8 objects, two subjects approached this level and our group results were far above the  $4 \pm 1$  limit that has been proposed in the fixed slot theory. The drop in capacity observed at faster speeds occurs well below the speeds at which data limitations occur (Verstraten et al., 2000), thus the speed effects must reflect resource limitations. Thus, our findings qualitatively support their findings of a flexible deployment of attention such that as speed increases, the overall the amount of attention needed for each object increases. The differences that we observed may be due to the longer tracking times employed, which increases the opportunity for errors to occur. We also note that the ceiling effects observed for two subjects may have reduced the group average.

Alvarez and Franconeri (2007) argued that the variable capacity observed across speeds was due to modulations in the spatial resolution of attention. As speed increases, the spatial uncertainty of the disc also increases, causing the size of the attentional window to become coarser allowing distractors to more easily enter. This idea has been expanded on to suggest that the primary change caused by the increased speed is an increased effect of crowding (Franconeri, Lin, Pylyshyn, Fisher, & Enns, 2008). Thus, the increased attentional demands of the tighter spatial attentional window reduce the overall number of targets that can be attended.

Since our experiments employed twice the tracking time of that used by Alvarez and Franconeri (2007), the increased number of crowding events in our experiments may contribute to the capacity differences observed at the slowest speeds. Another possibility is that the increase in the overall distance traveled by each disc in our experiments relative to theirs may have diminished spatial memory effects that may have contributed to their capacity observations. At moderate and fast speeds, on the other hand, our capacity measurements were very similar to theirs, suggesting the number of crowding events may not have been a large factor. Instead, as MOT mechanisms have been shown to monitor and use speed information to assist in tracking (Iordanescu, Grabowecky, & Suzuki, 2009), it may be that the demands of the stimuli, such as the higher demand on attentionally updating location information at faster speeds, play a role in attentional capacity. To investigate this possibility, in the next experiment we varied another stimulus factor, size.

## Experiment 2

Attention has been shown to enhance weak bottom-up input of targets (Carrasco, Ling, & Read, 2004; Chun & Marois, 2002; Kastner & Ungerleider, 2000). However, it is unclear how stimulus strength is related to attentional

resource allocation; there are conflicting reports as to whether target enhancement plays any role in MOT. Some studies suggest that there are weak or no target enhancement effects in MOT (Pylyshyn, 2006), but that instead, performance is mostly due to distractor suppression, while others have shown moderate target enhancement effects and no distractor suppression effects (Drew, McCollough, Horowitz, & Vogel, 2009), suggesting that changes in the saliency of the stimulus will have no effect on capacity. On the other hand, it is possible that as stimuli become less salient, for example by decreasing the size of the stimuli, target enhancement may need to be increased in order to keep target processing at a high enough level to allow for task completion. This increase of target enhancement would require more attentional resources, which if drawn from a shared resource pool, would reduce capacity.

Alternately, if crowding plays a determining role in capacity, and if crowding is driven by the attentional requirements of the task, as suggested by Tripathy and Cavanagh (2002) and Intriligator and Cavanagh (2001), then decreasing the saliency of stimuli may increase performance by decreasing the strength of the crowding effects that the distractors can generate. There is some support for the idea that stimulus visibility plays a role in crowding strength (Chung, Levi, & Legge, 2001; Pöder, 2006; Tripathy & Cavanagh, 2002), though the results are mixed. The FLEX model appears to predict that if crowding pressure is decreased, the attentional window will not have to be modified, reducing task demands and increasing overall attentional capacity. If, however, decreasing the saliency of the targets and distractors in conjunction has no effect on crowding pressures, then at worst, we should expect to see no effect of stimuli strength, as compared to the negative effect produced by target enhancement. Manipulations in target saliency can produce data as well as resource limitations, but since stimulus location is the only task-relevant factor in the MOT paradigm, as long as the stimuli are visible and non-overlapping this should not be a factor. Moreover, if subjects can track a single disc, we can conclude that their performance was not data-limited.

Thus, the goal of [Experiment 2](#) was to examine possible target enhancement effects on attentional capacity by varying the bottom-up perceptual strength of the stimuli by changing disc size. If capacity is driven primarily by the local errors caused by crowding, we should see an increase in performance and capacity as saliency decreases. A decrease in capacity as saliency decreases, on the other hand, would indicate a role for target enhancement in determining attentional capacity.

## Methods

Fourteen Boston University undergraduate students participated in [Experiment 2](#). The stimuli and procedure

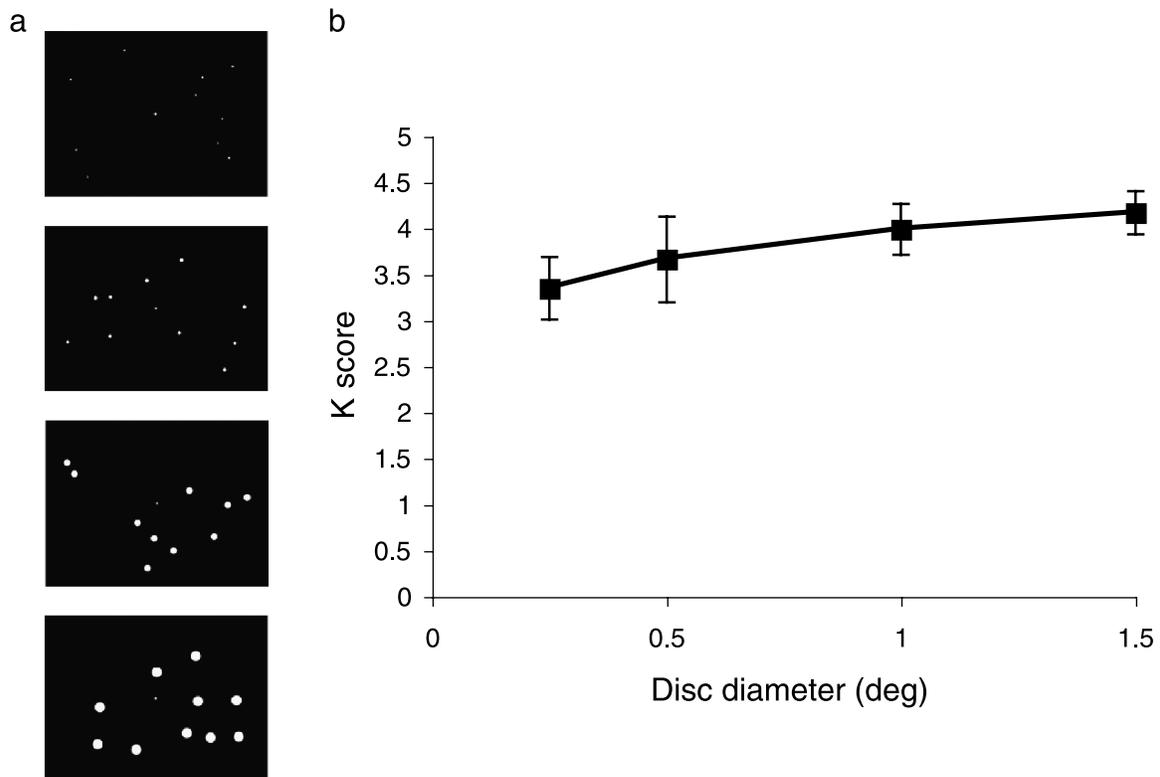


Figure 3. Stimuli (a) and results (b) for [Experiment 2](#). K score as a function disc size (a). As size decreased, capacity also decreased.

were the same as in [Experiment 1](#), except that speed was kept constant at 4.8°/s, and the size of the discs varied across four sizes: 0.25°, 0.5°, 1.0°, 1.25° in diameter (see [Figure 3a](#)). The range of sizes used encompasses those normally seen in MOT research. Block order was randomized. To ensure performance on the smallest sized discs was not due to a data-limited lack of visibility, six additional subjects tracked one out of ten discs at the smallest and largest size conditions. Subject's eye movements were tracked using an eye camera to ensure that they maintained fixation and did not track the disc with their eyes, as visibility is impaired in the periphery, relative to the fovea. Average performance was above 95% for both disc sizes, thus ruling out data-limitations.

## Results and discussion

[Figure 3](#) depicts the results. There was a significant main effect of size ( $F(3,55) = 2.93$ ,  $p < 0.05$ ). As size decreased, performance decreased. At the largest size capacity was 4.2 objects, while at the smallest size it was 3.4, a loss of 0.8 objects. This decrease was not due to data limitation as subjects performed above 95% correct tracking 1 target in both the smallest and largest size conditions. Thus, this effect, though not as large as the

effect observed in [Experiment 1](#), does indicate that, as more attention is required to enhance smaller targets, capacity decreases. One would expect, if crowding is the determining factor in MOT, as advocated by the FLEX model, that we would have found the opposite result or a null result. Decreasing size causes the distractors to appear further apart and/or less salient, which should have decreased crowding effects, and thus increasing attentional capacity. Our results run counter to this prediction. Thus, we conclude that the detriment we see for the smaller discs must be due to a factor other than crowding or spatial resolution.

Our measurements may actually underestimate the demands on attention created by target enhancement. Though we see a modest overall decrease in capacity, this may reflect only the net effect of opposing target enhancement and crowding factors. The decreased salience may very well create both a detrimental effect on capacity due to the increased attention required to enhance and maintain the lower salience targets and a beneficial effect due to decreased crowding pressures from the less salient distractors. The increased demands due to target enhancement would thus be partly masked by the decreasing attentional demands from the distractors, creating a small net effect on capacity. This could also account for the negative findings of [Tripathy and Cavanagh \(2002\)](#) who kept visibility/salience constant across size manipulations.

This issue prompted us to take another look at the role of crowding by examining the role it may or may not play in distractor suppression.

## Experiment 3

In MOT, distractors and targets are identical to each other, and so, attention must work to hold onto targets while filtering out distractors (Chun & Marois, 2002; Desimone & Duncan, 1995). Distractor stimuli, by definition, have the potential to interfere with the effective processing of target stimuli, however, it is unclear what relationship distractor suppression has to attentional capacity. Attention may act to diminish the influence of distractors in either a “push-only” fashion in which attention is directed only toward targets, passively leaving distractors unprocessed, unless they impinge upon a target selection window (e.g., crowding); or via a “push-pull” mechanism, in which attention enhances (pushes) target representations and actively suppresses (pulls) distractor representations to prevent distractors from exogenously grabbing attention and interfering even outside the target selection window. These two mechanisms predict two very different outcomes in terms of attentional capacity as the number of distractors increase. In an active filtering “push-pull” mechanism, an increase in the number of distractors would require additional attentional resources be employed to pull processing away from distractors and prevent the exogenous redeployment of attention. However, as in the FLEX model, “push-only” mechanisms would only require an increase in attentional resources if the attentional window needed to become more precise to prevent the increased distractors number from crowding any targets.

Reaction time and physiological evidence supports a push-pull model in which attention is withdrawn from distractors and directed to targets (e.g., Pinsky et al., 2004; Posner et al., 1980; Somers et al., 1999; Yi et al., 2004). Moreover, it has been shown that inhibition of nontargets plays a strong (if not primary) role in MOT and that the inhibition is highly localized to the distractors (Pylyshyn, 2006, but see Drew et al., 2009). Prior work has also indicated that increasing the number of distractors decreases performance (Horowitz et al., 2007; Oksama & Hyönä, 2004). However, it remains unclear whether this influence of distractors on performance merely results from an increase in crowding effects or whether the number of stimuli to be filtered out explicitly plays a role. Thus, to tease apart the role of crowding from that of distractor inhibition, we first ran an experiment (3a) in which the number of distractors was increased. This was compared with another experiment (3b) in which we varied the screen size without changing the number of stimuli to create the same densities seen in experiment 3a. This allowed us to

determine whether crowding accounted for any of the effects seen in experiment 3a. Since the density changes of experiment 3b were centered on the fovea, it is possible that this experiment might underestimate the effects of crowding, which are lessened at the fovea (Levi, Hariharan, & Klein, 2002). Therefore, a third experiment (3c) repeated this size-density analysis but divided the screen (and targets and distractors) into two areas, each with a peripheral center of focus. This allowed us to directly compare the effects of crowding and distractor number in the periphery across the same subjects.

## Methods

Eight Boston University undergraduate students participated in experiment 3a; seven participated in experiment 3b, and seven participated in experiment 3c. The stimuli were the same as in the second experiment in speed, but in experiment 3a there were 10, 14, 20, 28, or 40 white discs (diameter =  $0.9^\circ$ ) (see Figure 4a). In experiment 3b, there were always ten discs and density was matched to experiment 3a. The densities used were 0.013, 0.018, 0.026, 0.036, 0.051 discs/ $^\circ$ . This translated into screen sizes of  $32.5^\circ \times 24.0^\circ$ ,  $27.5^\circ \times 20.3^\circ$ ,  $23.0^\circ \times 17.0^\circ$ ,  $19.4^\circ \times 14.3^\circ$ , and  $16.3^\circ \times 12.0^\circ$ , respectively. The entire monitor screen area was black to prevent background distractions in the smaller screen conditions, but the active screen area, in which the discs could travel, was outlined in gray (see Figure 4a). In experiment 3c, the screen was split into two active areas (one left, one right), outlined in gray, with the rest of the monitor screen black as in experiment 3b. Subjects track four white discs (two in each screen area). In three of the five blocks, each screen area was  $16.2^\circ \times 24.0^\circ$ , and the number of white discs was either 10, 20, or 40 (diameter =  $0.9^\circ$ ). In the other two blocks density was matched to the 20 and 40 disc conditions (0.026 and 0.051 discs/ $^\circ$ ). In these blocks, there were always ten white discs (diameter =  $0.9^\circ$ ) and each screen area was  $11.6^\circ \times 17.0^\circ$  or  $8.2^\circ \times 12.0^\circ$  (see Figure 4c). The procedure was similar to Experiment 1. Trial types were blocked, and block order was randomized to control for order effects.

## Results and discussion

The results are shown in Figure 4. In experiment 3a, there was a significant main effect of number of distractors ( $F(4,39) = 13.79$ ,  $p < 0.0001$ ). As the number of distractors increased, performance decreased. A capacity of 4.0 objects was seen for tracking five out of ten discs, but when subjects had to track five out of 40 discs, capacity was only 0.8 objects, suggesting that not even one disc could be tracked reliably. This low capacity is remarkable, given that tracking was not data-limited.

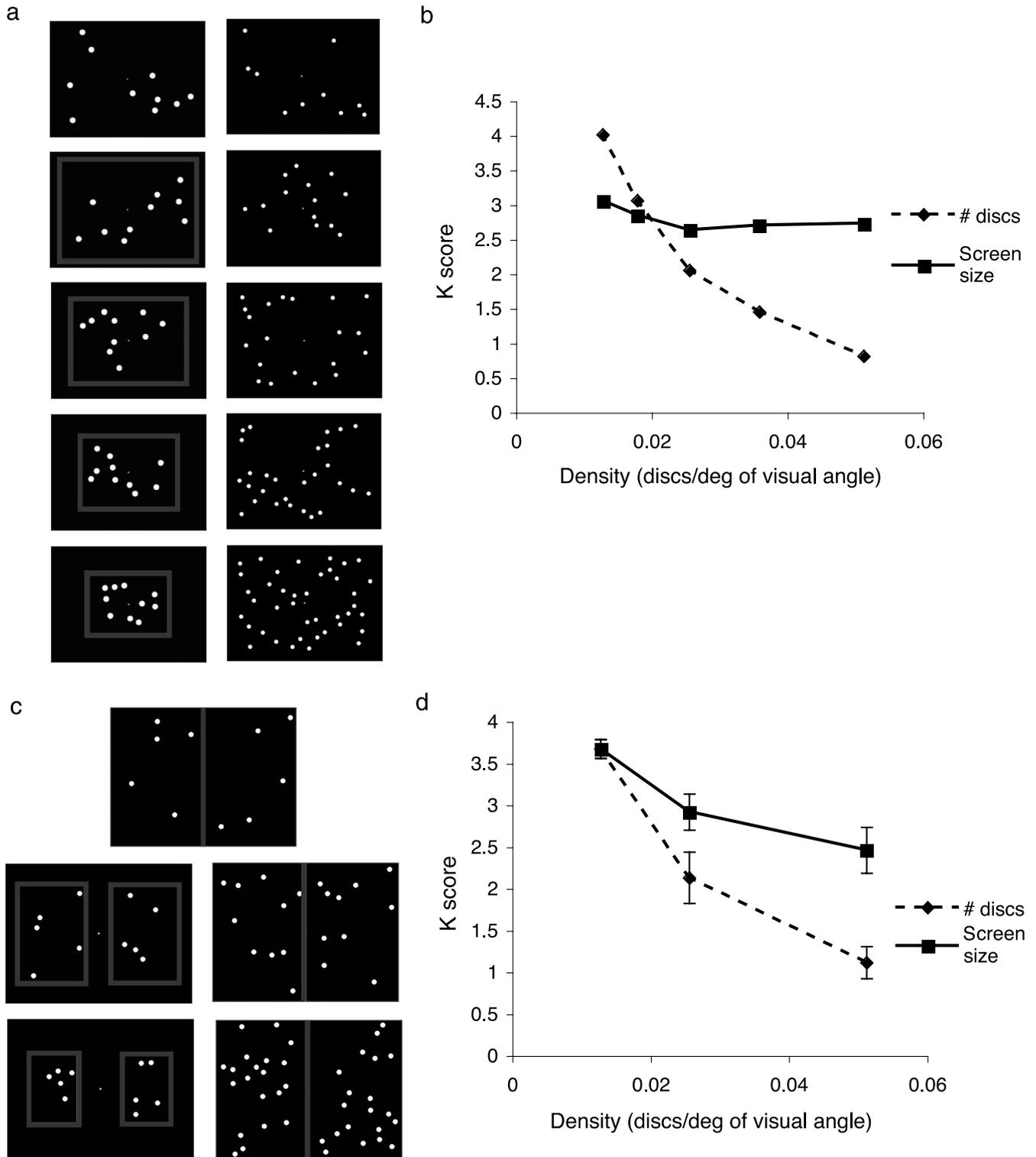


Figure 4. Stimuli (a, c) and results (b, d) for Experiment 3. Graph b shows mean K score for experiment 3a (number of distractors, stimuli on right in (a)) and experiment 3b (screen size, stimuli on left in (a)) as a function of screen density. The dashed line in graph b shows as the number of distractors was increased, capacity decreased, however, for density matched controls decreasing the screen size to match the amount of crowding present, had no effect on capacity. Graph d shows mean K score for experiment 3c as a function of screen density, stimuli depicted in (c). Both the number of distractor (dashed line) and screen size (solid line) manipulations caused significant impairments in attentional capacity, however, for density matched conditions, number of distractors showed a stronger effect.

Capacity had a maximal decrease of 3.2 objects as the filtering demands on attention were increased.

The first density control task (3b) showed no significant differences between densities ( $F(4,34) = 0.20, p = 0.94$ ). As density decreased, performance and capacity stayed constant, further corroborating Intriligator and Cavanagh's (2001) finding that densities at this level do not have an effect on attentional capacity. However, the periphery density experiment (3c) showed both a significant effect of number of distractors ( $F(2,20) = 34.49, p < 0.0001$ ) and of density ( $F(2,20) = 8.29, p = 0.003$ ). As both increased, capacity levels decreased. However,  $t$ -tests revealed that both the 0.026 and 0.051 discs/° density matched conditions differed significantly from each other ( $t(6) = 2.95, p = 0.026$  and  $t(6) = 3.97, p = 0.007$  respectively). In the 0.026 discs/° comparison, subjects showed an additional capacity loss of 0.8 discs for the distractor condition as compared with the density condition, and for the 0.051 discs/° comparison, an additional loss of 1.3 discs.

These results suggest that, while crowding, especially in the periphery, does play a role in the attentional capacity as more distractors are added, there is an additional large effect of filtering that cannot be explained by crowding effects. At least half of the effect seen in our distractor manipulation (3a) is due solely to the increase in number of stimuli, and not to the concurrent increase in crowding. Two factors may explain this decrease in capacity due to number of distractors. First, it may be that distractors exogenously attract attention, reducing the amount left in the central pool. Second, it may be that distractor suppression is more of an active process, as theorized by Pylyshyn (2006), rather than a passive withdrawal of attention. Our results cannot distinguish between these two explanations; however, we note that these mechanisms are not mutually exclusive and it is plausible that both of these factors are playing a role in decreasing the overall attentional capacity, such that fewer objects can be actively attended to when more distractors are present.

## General discussion

Overall, we found a high degree of variation in capacity measurements, ranging a low of 0.8 objects to a high of 6.3 objects, depending on task demands in MOT. Two competing models, the “flexible resource pool” and the “fixed-slot” models, have been previously proposed to explain capacity limits in attentive tracking of multiple objects. The broad range of tracking capacities observed in the present study are most consistent with the view that attention works as a continuous, flexibly deployed resource. Experiment 1 qualitatively replicated the findings of Alvarez and Franconeri (2007), showing that as speed decreases, capacity, as measured by  $k$ -score, increases. At the slowest speed, our subjects were able

to track, on average, 6.3 items. This is less than the eight seen by Alvarez and Franconeri (2007), though still more than the  $4 \pm 1$  limit imposed by the fixed slot model. Experiment 2 showed that the intrinsic stimulus factor of size significantly impacted performance. These performance differences cannot be attributed to stimulus complexity (Awh, Barton, & Vogel, 2007) or to data-limitations of the stimuli (Norman & Bobrow, 1975) and run counter to those expected by crowding effects. This supports the view that target enhancement processes other than those linked to crowding prevention draw upon shared resources and flexibly alter capacity. Experiment 3 demonstrated that, while crowding does play a significant role in MOT and capacity measurements, as has previously been suggested (e.g., Franconeri et al., 2008; Intriligator & Cavanagh, 2001; Pylyshyn, 2004), there is a large effect caused by the presence of distractors that cannot be attributed to crowding. These capacity changes may be attributed to the attentional demands of suppressing the representations of distractors. Each of these experiments showed a decrease in capacity that can be attributed to an increased draw on central attentional resources. Depending on task demands, attentional resources can either be prioritized onto a smaller number of targets to enhance their processing, focused on distractor suppression, or used to modify the attentional resolution to prevent target-distractor swaps. This differential prioritization causes a variable number of attentional “slots” (both above and below the fixed slot model's four object limit) to be created to allow for optimal task performance.

This flexible deployment is in line with findings in other attentional research. Inattention and change blindness studies have shown that under low attentional demands, attention spreads to include distractors, while under high demand, attention is utterly consumed by the targets, allowing even salient distractors, such as a gorilla, to go unseen (Chun & Marois, 2002; Simons & Chabris, 1999). Additionally, other recent studies also have suggested roles for both target enhancement (Drew et al., 2009), and distractor suppression (Pylyshyn, 2006). This view differs considerably from the fixed slot theory, in which  $4 \pm 1$  items are selected, regardless of task demands. Fixed slot proponents have suggested that some of the flexibility seen in our study, as well as others, may be due, not to the loss of slots, but rather to data limitations or poorer performance in each slot (Awh et al., 2007). However, our stimuli were very simple in nature, requiring only location to be attended to, all well above the perceptual and attentional resolution limits, and did not differ in target-probe similarity across manipulations. Additionally, Alvarez and Franconeri (2007) have shown that performance is not impaired as speed increases (performance was 94% in all conditions), only capacity is. Finally, the relatively high capacities seen in the track 8 of 16 condition of Experiment 1 (group average of 6.3, individual highs of 7.5) are significantly beyond the fixed slot theory's four item limit. Thus, the findings present in

this paper are more parsimoniously accounted for by the flexible resource model and the view that the task demands of target enhancement, crowding, and distractor suppression modulate attentional capacity by drawing on a shared pool of resources via an active filtering push-pull attentional mechanism.

The FLEX model (Alvarez & Franconeri, 2007) provides an account of how a limited central resource can govern performance in the MOT task – as more targets are tracked, the attentional resources per target diminish, causing a widening of the effective attentional window, thus making targets increasingly susceptible to interference from crowding. Our findings are largely supportive of this model, but also point to an additional component of the attentional tracking system. We suggest that there is a central mechanism that actively governs the moment-to-moment allocation of attention to multiple targets, not only updating the position but also rebalancing the attentional resources across targets. At any given time, the attention required to maintain tracking is not equal for all targets. Targets approaching a crowding event have a greater need for attention. A system that could actively redeploy and balance attention across targets has the potential to most efficiently utilize attentional resources. Recent work by Iordanescu et al. (2009) supports this model of active redeployment and rebalancing of attentional resources. Under high crowding conditions, they found that subjects showed higher precision in target localization, as predicted by the FLEX model, however this level of precision was not identical across targets, such that only the more crowded target showed an increase in precision, less crowded targets were less well localized. Although we are inclined to view this as a parallel or multifocal mechanism, this idea of dynamic attentional allocation could be implemented in a serial framework by modulating attentional dwell times for each target to match its immediate attentional needs or by modulating the precision of the stored representation as suggested by Iordanescu et al. (2009).

This model highlights that some tracking failures might be attributed to failures in the redeployment of attention. The FLEX model provides a framework for understanding how a central constraint can cause local tracking errors, via crowding interference. In contrast, we suggest that a local constraint can cause central tracking errors. Specifically, the attentional network may adapt to an impending crowding event at one target by increasing the attentional resources to that target; however, this redeployment could also withdraw enough attention away from one or more other targets that their tracking is no longer maintained. We further suggest that this class of central failures may also be prevalent in the real world—unexpected events at one location cause us to rapidly shift our attentional resources to these events and withdraw from other events/locations. The rapid redeployment of attention can prevent failures at the enhanced location, but can also immediately result in failures at other locations where attentional

resources were suddenly withdrawn. Our results, which suggest the central pool of attentional resources is taxed both by the need to enhance the representation of targets and suppress the representation of distractors, require an explanation beyond simply a crowding mechanism and appear consistent with an active redeployment model. Further investigation will be required to better test this model.

## Acknowledgments

We thank Jascha Swisher, Mark Halko, Summer Sheremata, and Susan Mosher for helpful discussions and comments. This research was supported by National Science Foundation BCS-0236737 to DCS.

Commercial relationships: none.

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## References

- Alvarez, G. A., & Cavanagh, P. (2005). Independent resources for attentional tracking in the left and right visual hemifields. *Psychological Science*, *16*, 637–643. [PubMed]
- Alvarez, G. A., & Franconeri, S. L. (2007). How many objects can you track? Evidence for a resource-limited attentive tracking mechanisms. *Journal of Vision*, *7*(13):14, 1–10, <http://journalofvision.org/7/13/14/>, doi: 10.1167/7.13.14. [PubMed] [Article]
- Awh, E., Barton, B., & Vogel, E. K. (2007). Visual working memory represents a fixed number of items regardless of complexity. *Psychological Science*, *18*, 622–628. [PubMed]
- Awh, E., & Pashler, H. (2000). Evidence for split attentional foci. *Journal of Experimental Psychology: Human Perception and Performance*, *26*, 834–846. [PubMed]
- Carlson, T. A., Alvarez, G. A., & Cavanagh, P. (2007). Quadratic deficit reveals anatomical constraints on selection. *Proceedings of the National Academy of Sciences of the United States of America*, *104*, 13496–13500. [PubMed] [Article]
- Carrasco, M., Ling, S., & Read, S. (2004). Attention alters appearance. *Nature Neuroscience*, *7*, 308–313. [PubMed]
- Chun, M. M., & Marois, R. (2002). The dark side of visual attention. *Current Opinion Neurobiology*, *12*, 184–189. [PubMed]

- Chung, S. T. L., Levi, D. M., & Legge, G. E. (2001). Spatial-frequency and contrast properties of crowding. *Vision Research*, *41*, 1833–1850. [PubMed]
- Cowan, N. (2001). The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *Behavioral and Brain Sciences*, *24*, 87–114. [PubMed]
- Culham, J. C., Cavanagh, P., & Kanwisher, N. G. (2001). Attention response functions: Characterizing brain areas using fMRI activation during parametric variations of attentional load. *Neuron*, *32*, 737–745. [PubMed]
- Desimone, R., & Duncan, J. (1995). Neural mechanisms of selective visual attention. *Annual Review of Neuroscience*, *18*, 193–222. [PubMed]
- Drew, T., McCollough, A. W., Horowitz, T. S., & Vogel, E. K. (2009). Attentional enhancement during multiple object tracking. *Psychonomic Bulletin & Review*, *16*, 411–417. [PubMed]
- Fehd, H. M., & Seiffert, A. E. (2008). Eye movements during multiple object tracking: Where do participants look? *Cognition*, *108*, 201–209. [PubMed]
- Franconeri, S., Alvarez, G. A., & Enns, J. (2007). How many locations can you select at once? *Journal of Experimental Psychology: Human Perception and Performance*, *33*, 1003–1012. [PubMed]
- Franconeri, S. L., Lin, J. Y., Pylyshyn, Z. W., Fisher, B., & Enns, J. T. (2008). Evidence against a speed limit in multiple object tracking. *Psychonomic Bulletin & Review*, *15*, 802–808. [PubMed]
- Horowitz, T. S., Klieger, S. B., Fencsik, D. E., Yang, K. K., Alvarez, G. A., & Wolfe, J. M. (2007). Tracking unique objects. *Perception & Psychophysics*, *69*, 172–184. [PubMed]
- Intriligator, J., & Cavanagh, P. (2001). The spatial resolution of visual attention. *Cognitive Psychology*, *43*, 171–216. [PubMed]
- Iordanescu, L., Grabowecky, M., & Suzuki, (2009). Demand-based dynamic distribution of attention and monitoring of velocities during multiple-object tracking. *Journal of Vision*, *9*(4):1, 1–12, <http://journalofvision.org/9/4/1/>, doi: 10.1167/9.4.1. [Article]
- Kastner, S., & Ungerleider, L. G. (2000). Mechanisms of visual attention in the human cortex. *Annual Review of Neuroscience*, *23*, 315–341. [PubMed]
- Levi, D. M., Hariharan, S., & Klein, S. A. (2002). Suppressive and facilitatory spatial interactions in peripheral vision: Peripheral crowding is neither size invariant nor simple contrast masking. *Journal of Vision*, *2*(2):3, 167–177, <http://journalofvision.org/2/2/3/>, doi: 10.1167/2.2.3. [PubMed] [Article]
- McMains, S. A., & Somers, D. C. (2004). Multiple spotlights of attentional selection in human visual cortex. *Neuron*, *42*, 677–686. [PubMed] [Article]
- Müller, N. G., Bartelt, O. A., Donner, T. H., Villringer, A., & Brandt, S. A. (2003). A physiological correlate of the “Zoom Lens” of visual attention. *Journal of Neuroscience*, *23*, 3561–3565. [PubMed] [Article]
- Norman, D. A., & Bobrow, D. J. (1975). On data-limited and resource-limited processes. *Cognitive Psychology*, *7*, 44–64.
- Oksama, L., & Hyönä, J. (2004). Is multiple object tracking carried out automatically by an early vision mechanism independent of higher-order cognition? An individual difference approach. *Visual Cognition*, *11*, 631–671.
- Pinsk, M. A., Doniger, G. M., & Kastner, S. (2004). Push-pull mechanism of selective attention in human extrastriate cortex. *Journal of Neurophysiology*, *92*, 622–629. [PubMed] [Article]
- Pöder, E. (2006). Crowding, feature integration, and two kinds of “attention.” *Journal of Vision*, *6*(2):7, 163–169, <http://journalofvision.org/6/2/7/>, doi:10.1167/6.2.7. [PubMed] [Article]
- Posner, M. I., Snyder, C. R., & Davidson, B. J. (1980). Attention and the detection of signals. *Journal of Experimental Psychology*, *109*, 160–174. [PubMed]
- Pylyshyn, Z. W. (2004). Some puzzling findings in multiple object tracking: I. Tracking without keeping track of object identities. *Visual Cognition*, *11*, 801–822.
- Pylyshyn, Z. W. (2006). Some puzzling findings in multiple object tracking: II. Inhibition of moving nontargets. *Visual Cognition*, *14*, 175–198.
- Pylyshyn, Z. W., & Storm, R. W. (1988). Tracking multiple independent targets: Evidence for a parallel tracking mechanism. *Spatial Vision*, *3*, 179–197. [PubMed]
- Scholl, B. J., Pylyshyn, Z. W., & Feldman, J. (2001). What is a visual object? Evidence from target merging in multiple object tracking. *Cognition*, *80*, 159–177. [PubMed]
- Sears, C. R., & Pylyshyn, Z. W. (2000). Multiple object tracking and attentional processing. *Canadian Journal of Experimental Psychology*, *54*, 1–14. [PubMed]
- Simons, D. F., & Chabris, C. F. (1999). Gorillas in our midst: Sustained inattention blindness for dynamic events. *Perception*, *28*, 1059–1074. [PubMed]
- Somers, D. C., Dale, A. M., Seiffert, A. E., & Tootell, R. B. (1999). Functional MRI reveals spatially specific attentional modulation in human primary visual cortex. *Proceedings of the National Academy of Sciences of the United States of America*, *96*, 1663–1668. [PubMed] [Article]

- Tripathy, S. P., & Cavanagh, P. (2002). The extent of crowding in peripheral vision does not scale with target size. *Vision Research*, *42*, 2357–2369. [[PubMed](#)]
- Verstraten, F. A., Cavanagh, P., & Labianca, A. T. (2000). Limits of attentive tracking reveal temporal properties of attention. *Vision Research*, *40*, 3651–3664. [[PubMed](#)]
- Xu, Y., & Chun, M. M. (2006). Dissociable neural mechanisms supporting visual short-term memory for objects. *Nature*, *440*, 91–95. [[PubMed](#)]
- Yantis, S. (1992). Multielement visual tracking: Attention and perceptual organization. *Cognitive Psychology*, *24*, 295–340. [[PubMed](#)]
- Yi, D. J., Woodman, G. F., Widders, D., Marois, R., & Chun, M. M. (2004). Neural fate of ignored stimuli: Dissociable effects of perceptual and working memory load. *Nature Neuroscience*, *7*, 992–996. [[PubMed](#)]
- Zhang, W., & Luck, S. J. (2008). Discrete fixed-resolution representations in visual working memory. *Nature*, *453*, 233–235. [[PubMed](#)] [[Article](#)]