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Spatial separation between targets constrains maintenance of attention on multiple objects

Won Mok Shim
Harvard University, Cambridge, Massachusetts
and Massachusetts Institute of Technology, Cambridge, Massachusetts

George A. Alvarez
Massachusetts Institute of Technology, Cambridge, Massachusetts

and

Yuhong V. Jiang
Harvard University, Cambridge, Massachusetts
and University of Minnesota, Minneapolis, Minnesota

Humans are limited in their ability to maintain multiple attentional foci. In attentive tracking of moving objects, performance declines as the number of tracked targets increases. Previous studies have interpreted such reduction in terms of a limit in the number of attentional foci. However, increasing the number of targets usually reduces spatial separation among different targets. In this study, we examine the role of target spatial separation in maintaining multiple attentional foci. Results from a multiple-object tracking task show that tracking accuracy deteriorates as the spatial separation between targets decreases. We propose that local interaction between nearby attentional foci modulates the resolution of attention, and that capacity limitation from attentive tracking originates in part from limitations in maintaining critical spacing among multiple attentional foci. These findings are consistent with the hypothesis that tracking performance is limited not primarily by a number of locations, but by factors such as the spacing and speed of the targets and distractors.

The human visual system is constantly confronted with an overwhelming amount of information, only a subset of which is selected for detailed processing. Unlike overt selection by eye movement, covert attention can sample multiple objects at once (Awh & Pashler, 2000). The maintenance of multiple attentional foci, however, is limited in capacity. For instance, when observers track a subset of moving objects with attention, accuracy declines as the number of tracked targets increases (Pylyshyn & Storm, 1988). Previous studies have interpreted this decline in terms of a limit in the *number* of attentional foci. However, when objects move in a restricted visual field, increasing the number of targets often results in a decrease in the spatial separation among targets. If attention is limited in maintaining close spacing among multiple foci, tracking accuracy should decline as tracked targets are spaced more tightly.

Indeed, visual attention is limited in its resolution to distinguish targets from nontargets. Attentive tracking is impaired when nontargets fall close to the targets (Intriligator & Cavanagh, 2001). Furthermore, in target identification tasks involving static displays, performance is impaired when nontargets are located near the target, showing "crowding" (Bouma, 1970; Pelli, Cavanagh, Desimone, Tjan, & Treisman, 2007). But is attention also limited in its ability to "resolve" closely spaced targets?

Using identification tasks, Bahcall and Kowler (1999) found that the identification of two targets among nontargets improved when the targets were farther apart. They suggest that local suppressive interactions among targets impair identification at close target distances (see also Cutzu & Tsotsos, 2003). This impairment, however, can originate from processes preceding attentional selection. An identification task entails presentation of objects with various features. Compulsory pooling of features within a local area or local contour interactions may impair processing before attentional selection (Parkes, Lund, Angelucci, Solomon, & Morgan, 2001; Pelli, Palomares, & Majaj, 2004). Whether target spacing directly influences attentional deployment remains unanswered.

This study directly measures spatial interaction among multiple attentional foci. We asked observers to track a designated subset of moving objects (Pylyshyn & Storm, 1988). This task does not require target identification; it only requires individuation of targets from otherwise identical distractors based on their motion trajectories. We parametrically manipulated the spacing between targets while holding the number of targets constant in Experi-

W. M. Shim, wshim@mit.edu; Y. V. Jiang, jiang166@umn.edu

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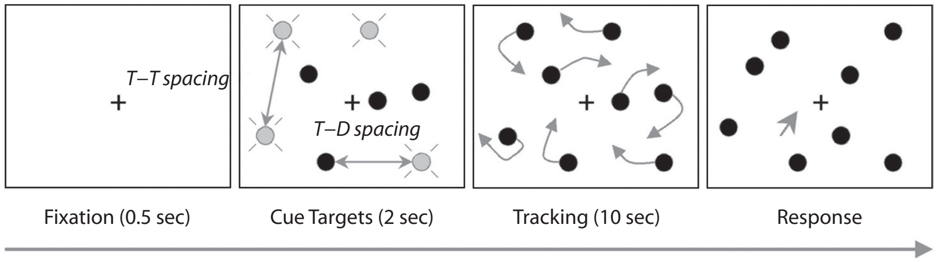


Figure 1. Sample trial sequence used in Experiment 1. Targets are illustrated in gray on the cue display.

ment 1, and varied both target spacing and target number in Experiments 2 and 3. Results demonstrated significant interference from closely spaced targets. Our study adds an important constraint on the capacity limitation in tracking multiple objects.

EXPERIMENT 1

Using an attentive tracking task in Experiment 1, we varied the minimal spacing allowed between one target and another and between targets and distractors (Figure 1). Because attention is limited in resolving targets from nontargets, we expect accuracy to decline as target–distractor distance reduces. Of interest is whether target–target distance also affects tracking. There are three possibilities. If tracking is limited solely by target number, then performance should be comparable for different target–target distances. Alternatively, grouping of adjacent targets through proximity may enhance the segregation of targets from distractors. Because observers are required to differentiate targets from distractors but not targets from themselves, enhanced grouping of targets at closer target–target distances should facilitate performance. In a third competing hypothesis, adjacent attentional foci may suppress each other through local interactions, reducing the contrast between a suppressed target and nearby distractors. Consequently, performance may decline at closer target–target distances.

Method

Participants. Ten participants (18–35 years of age), including two authors (W.M.S. and Y.V.J.), completed Experiment 1 in a room with interior lighting. They had normal or corrected-to-normal visual acuity and normal color vision. Viewing distance was fixed at 87 cm by a chinrest.

Stimuli. Each trial started with a black fixation (0.45º) presented inside a gray presentation window (15.58º × 15.58º) for 500 msec. Subsequently, eight black disks (0.23º radius) were presented at random locations inside the presentation window. The spatial distribution of disks was comparable across all conditions during the cue period. Four disks blinked for 2 sec to signify their status as targets. Once the blinking stopped, all disks moved freely within the presentation window. They moved at a constant speed (specified below) and repelled one another when a minimal distance (specified below) was reached. Participants tracked targets while maintaining central fixation. The disks stopped moving after 10 sec, and participants clicked the four tracked targets. The actual targets then blinked for 1.6 sec. A trial's accuracy was calculated as the number of correct choices divided by 4.

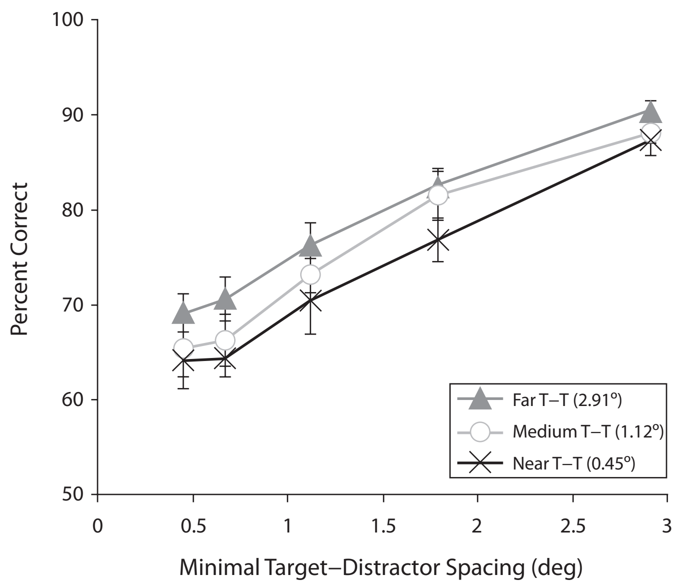


Figure 2. Experiment 1 results. Error bars represent ±1 *SE*.

Table 1
Average Target–Target Distances (T–T) and Target Eccentricity in Experiment 1

	Minimal T–T					
	Near (0.45º)		Medium (1.12º)		Far (2.91º)	
	M	*SE*	*M*	*SE*	*M*	*SE*
Average T–T*	7.91	.06	7.99	.06	8.37	.05
Target eccentricity*	5.54	.03	5.59	.03	5.84	.03

Note—*SE* was calculated for each observer and averaged. $^*p < .0001$.

Table 2
Average Target–Distractor Distances (T–D) in Experiment 1

	Minimal T–D									
	0.45º		0.67º		1.12º		1.79º		2.91º	
	M	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*
Average T–D*	7.87	.03	7.91	.03	8.01	.03	8.15	.04	8.46	.03

Note—*SE* was calculated for each observer and averaged. $^*p < .0001$.

Procedure. Because individuals varied in their ability to track fast-moving targets, each participant completed a preliminary session to determine appropriate speed. Here, the minimal distance allowed between any two disks was 2.91º. The motion speed varied in seven even steps between 2.87º/sec and 19.86º/sec for 84 preliminary trials. From these psychometric data, we estimated the speed at which performance was 87.5%.

In the main experiment, items moved at the individually tailored speed (range: 10.1º/sec to 16.35º/sec). We manipulated the minimal distance between targets (T–T spacing: 0.45º, 1.12º, or 2.91º) and the minimal distance between targets and distractors (T–D spacing: 0.45º, 0.67º, 1.12º, 1.79º, or 2.91º). In all conditions, disks traversed all possible locations of the field. Each participant completed 180 trials (3 T–T spacing × 5 T–D spacing × 12 trials in random order). Note that only minimal distance was manipulated. The disks were usually much farther apart. Average T–T and T–D distances are listed in Tables 1 and 2.

Results

Accuracy declined when distractors were allowed to get closer to the targets [$F(4,36) = 58.98$, $p < .001$; see Figure 2], consistent with the idea that attention is limited in resolving targets from nontargets (Intriligator & Cavanagh, 2001). Accuracy progressively improved as minimal T–D spacing increased, except from the closest to the second-closest distance ($F < 1$; other Fs > 17.82, ps $< .005$).

Critically, accuracy also declined when targets were allowed to get closer to one another [$F(2,18) = 13.92$, $p < .001$]. Accuracy rates in the two closest T–T spacing conditions were marginally different from each other [$F(1,9) = 4.24$, $p = .07$], and both were significantly worse than that in the farthest T–T spacing (Fs > 6.40, ps $< .03$). Effects of T–T spacing were comparable at all levels of T–D spacing, showing no interaction between the two factors ($F < 1$).

Discussion

Even though participants always tracked four out of eight moving objects, performance declined when nontargets were allowed to get closer to the targets and when targets were allowed to get closer to each other. This finding refutes the strong claim that target number is the sole source of attentional limitation. Attention is also limited in its resolution to differentiate targets from nontargets (Intriligator & Cavanagh, 2001). Furthermore, attentional resolution is modulated by target–target spacing. Although Bahcall and Kowler (1999) and others have shown reduced identification for closer targets, their results may originate from local contour interactions (Parkes et al., 2001; Pelli et al., 2004). By eliminating the need to identify different features, Experiment 1 convincingly showed that reducing target–target distance impairs the selection and maintenance of multiple attentional foci. Given that participants were not required to differentiate one target from another, reducing target–target distance must have impaired their ability to properly select targets from nontargets.

EXPERIMENT 2

In Experiment 1, we held the target number constant while varying minimally allowed distance among targets. However, the minimal distance was only occasionally reached, leading to possible underestimation of target distance effects. Experiment 1 was also uninformative about whether effects of target spacing hold when target number varies. To overcome these weaknesses, we varied target number and target spacing in a more constrained display in Experiment 2.

Figure 3 illustrates the display setup. On each trial, 16 bouncy disks were evenly distributed in four visual quadrants. Participants were cued to track 1 target (*track-1*); track 2 targets from a single quadrant (*track-2-near*); or track 2 targets, 1 in each of two separate quadrants (*track-2-far*). It is of critical importance that we constrained the disk motion so that the disks could not move out of their original quadrant. This ensured that the target–target distance was always closer in track-2-near than in track-2-far.

There are three possible outcomes. First, if attentive tracking is constrained only by target number, performance should be equivalent for track-2-near and track-2-far. Whether these conditions would be better than track-1 depends on when capacity is reached. If one assumes that attentional capacity is 4, then all conditions should yield ceiling performance. If one assumes that attentional capacity is graded depending on motion speed, then performance in track-2 conditions should be worse than in track-1 at fast speeds. Alternatively, performance in the track-2-far condition may be worse than in track-2-near, because there were six nontargets within target quadrants in track-2-far and only two nontargets within target quadrants in track-2-near. Finally, if attentive tracking is limited by maintaining close target spacing, performance should be worse in track-2-near than in track-2-far. In addition, track-2-far may not incur a significant cost over track-1.

Method

Participants. Six observers, including W.M.S. and Y.V.J., completed Experiment 2. Other participant characteristics were similar to Experiment 1's.

Stimuli and Procedure. On each trial, 16 black disks (0.34º radius) were presented, 4 in each quadrant (6.71º × 6.71º). Quadrant borders were separated from the midlines by 1.43º. Disks moved freely within a quadrant but could not move outside of the starting

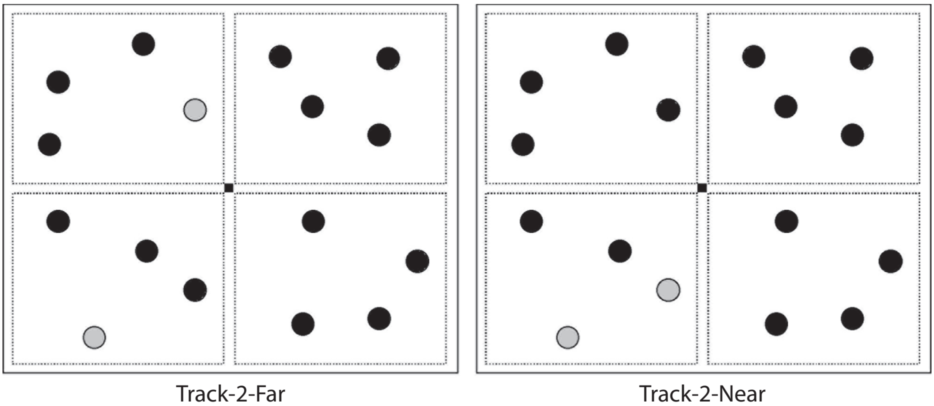


Figure 3. Two of the conditions tested in Experiment 2. Targets are illustrated in gray. Dotted lines are shown for illustrative purposes only.

quadrant. Disks in one quadrant moved independently of disks in other quadrants. Within a quadrant, the minimal spacing between any 2 disks was 1.61º.

Participants were cued to track one target; two targets within a single quadrant; or two targets, one in each of two vertically or horizontally adjacent quadrants. During the cue period, the target disk(s) changed from black to red (or to green for half of the participants) for 1 sec before changing back to black for another second. Then all disks started moving within their home quadrants for 8 sec. Motion speed was constant within a trial, but varied on different trials (5.73º/sec, 7.16º/sec, 8.58º/sec, 10.01º/sec, or 11.43º/sec). Once motion stopped, a randomly selected disk from one of the tracked quadrants was highlighted for 1 sec; participants pressed a key to indicate whether it was a tracked target. The likelihood that the probed disk was a target was 50% in all conditions. Accuracy feedback was displayed after each response.

Each participant completed 240 trials (3 tracking conditions × 5 motion speeds × 16 trials, in random order). Other aspects of the experiment were the same as in Experiment 1.

Results

Accuracy was determined primarily by target spacing (Figure 4). It was lower in track-2-near than in track-2-far [$F(1,5) = 40.53$, $p < .001$], even though there were more relevant nontargets in the latter condition. In contrast, accuracy was statistically equivalent for track-2-far and track-1 [$F(1,5) = 1.09$, $p > .30$], showing little decrement from the participants' having to track more targets. These results applied to all motion speeds except for the slowest when performance reached ceiling ($F < 1$ for the main effect of condition at the slowest speed). The interaction between tracking condition and motion speed was insignificant [$F(8,40) = 1.75$, $p > .10$]. The main effect of speed was significant; accuracy declined with increasing target speed [$F(4,20) = 8.19$, $p < .001$].

Consistent with previous findings (He, Cavanagh, & Intriligator, 1996), performance was better for tracking targets in the lower rather than in the upper visual field [$F(1,5) = 10.04$, $p < .05$]. The prominent difference between track-2-far and track-2-near targets was preserved in both the upper [$F(1,5) = 32.29$, $p < .005$] and the lower [$F(1,5) = 9.58$, $p < .05$] visual fields.

Is tracking accuracy better when targets occupy two hemifields rather than one, as suggested by Alvarez and Cavanagh (2005)? We divided data in the track-2-far

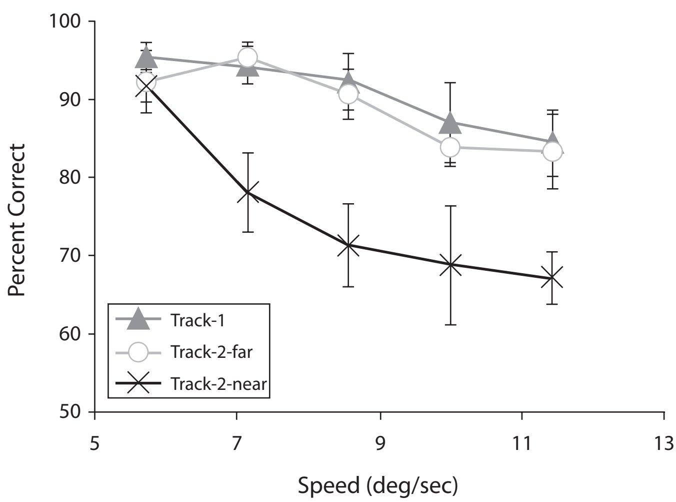


Figure 4. Experiment 2 results. Error bars represent ±1 *SE*.

Table 3
Average Target–Target Distances (T–T), Average Target–Distractor Distances (T–D), and Target Eccentricity (in Degrees) in Experiment 2

	Minimal T–T					
	Track-1		Track-2-Near		Track-2-Far	
	M	*SE*	*M*	*SE*	*M*	*SE*
Average T–T*	N/A	N/A	3.39	0.03	9.28	0.08
Average T–D***	3.40	0.01	3.40	0.01	3.40	0.01
Target eccentricity**	6.56	0.05	6.59	0.03	6.59	0.03

Note—*SE* was calculated for each observer and averaged. $^{*}p < .0001$. $^{**}p < .5$. $^{***}p < .7$.

condition based on whether the two targets occupied one or two hemifields. In both cases, performance was better than for track-2-near targets (Fs > 27.22, ps $< .005$). However, there was no statistical difference between the two conditions ($F < 1$). The discrepancy between our findings and Alvarez and Cavanagh's may be accounted for by differences in tracking load. Unlike in our study, where participants tracked two targets that were always far apart, observers in Alvarez and Cavanagh's study tracked four targets, and each of two pairs was placed in a single quadrant. Hemifield effects may be more prominent at higher tracking loads.

Discussion

To date, most attentive tracking studies have attributed attentional limitation to the number of target objects. Experiment 2 constrains this idea by showing that attention is also limited in maintaining close target spacing. Tracking two targets is not significantly more difficult than tracking one, provided that the two targets are sufficiently far apart. Once targets fall closer, performance declines, revealing interaction between closely spaced attentional foci.

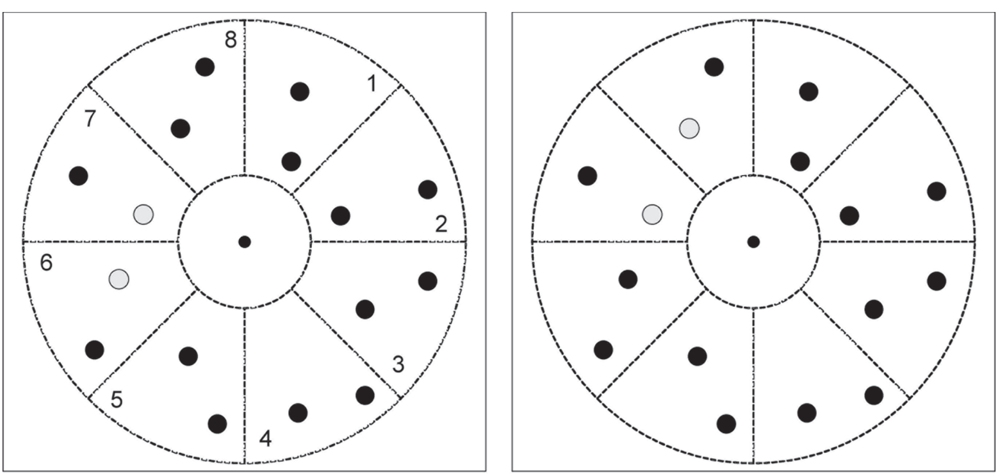
The effect of target spacing was stronger in Experiment 2 than in Experiment 1, possibly due to a stronger manipulation of T–T spacing (Table 3). This revealed a dramatic effect of target spacing on attentive tracking. Target number had negligible effects on performance across a wide range of motion speed. It is tempting to conclude that attentive tracking is not constrained by target number, but this conclusion is unwarranted. Because we only tested tracking of one or two targets, it remains possible that, at higher set sizes, target number affects performance over and above its effect on target spacing. At higher set sizes, it becomes increasingly difficult to establish far target–target distances unless one enlarges the motion field, which unfortunately places items at more peripheral locations. Future studies are needed to test whether target number contributes to attentional limitation over and above its effect on target spacing.

EXPERIMENT 3

Experiment 2 showed that accuracy was much higher in track-2-far than in track-2-near. But did the difference reflect an effect of target spacing, as we have claimed earlier, or did it reflect an effect of quadrant-based attentional limitation? After all, the two targets in track-2-far fell within two separate quadrants, whereas the two targets in track-2-near fell in a single quadrant. If attentional limitation is quadrant-based, then competition between targets in separate quadrants may be weaker than that in the same quadrant (Carlson, Alvarez, & Cavanagh, 2007; Kastner et al., 2001).

Experiment 3 was designed to dissociate competition from target spacing from quadrant-based attention. We placed 16 bouncy disks in a circular disk evenly divided into eight slices. Each slice contained 2 disks that always moved in their original slice.

With this display (Figure 5), we cued participants to track one disk (track-1) or track two disks with three possible arrangements. In the track-2-near/same-quadrant condition, the two targets were taken from two adjacent



Track-2-near/different-quadrant Track-2-near/same-quadrant

Figure 5. An illustration of two conditions used in Experiment 3. Targets are shown in gray. The dotted lines are for illustrative purposes only.

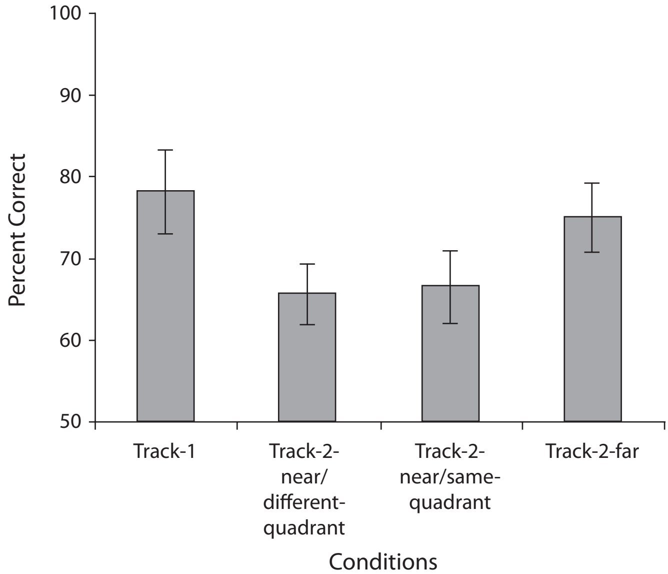


Figure 6. Experiment 3 results. Error bars represent ±1 *SE*.

slices that fell within a visual quadrant. In the track-2-near/different-quadrant condition, the two targets were from two adjacent slices that were separated by the horizontal or vertical midline. These two conditions were comparable in target–target distance, but differed in whether the targets fell within a single visual quadrant. Finally, in the track-2-far condition, the two targets were selected from two slices intervened by two other slices. The two targets were thus far apart and also fell in separate quadrants. Comparison across the four conditions allows us to dissociate quadrant-based attentional competition, target-spacing-based limitation, and target-number-based competition.

Method

Participants. Five observers from Experiment 2 and two new naive observers completed this experiment.

Stimuli and Procedure. Two black disks were presented in each of eight evenly divided slices in a circular arrangement (Figure 5; radius = 11º). Disks never moved out of the original slice during motion and could not move within 1.54º of fixation. Observers were cued to track one disk (track-1); track two disks from two adjacent slices that fell within a quadrant (track-2-near/same-quadrant; the disks could be from slices {1,2}, {3,4}, {5,6}, {7,8} of Figure 5); track two disks from two adjacent slices across the meridian (track-2-near/different-quadrant; the disks could be from slices {1,8}, {2,3}, {4,5}, {6,7} of Figure 5); or track two disks from two slices separated by two intervening slices (track-2-far; the disks could be from slices {1,4}, {2,7}, {3,6}, {5,8} of Figure 5). The disks moved at individually tailored speeds (range: 15.55º/sec to 25.92º/sec, across participants). Six observers completed two sessions of 64 trials each, and the remaining observer completed one session of 64 trials. Trials were divided randomly and evenly into the four different tracking conditions. Other aspects of the experiment were the same as those in Experiment 2. Table 4 shows the mean T–T and T–D distances.

Results

Tracking was significantly affected by condition (Figure 6) [$F(3,18) = 11.13$, $p < .001$]. Specifically, accuracy in the track-2-near/same-quadrant condition was not significantly different from that in the track-2-near/different-quadrant ($F < 1$), revealing no significant quadrant-based effect. Accuracy rates in both conditions were significantly worse than accuracy in track-2-far [$F(1,6)$s > 11.28, ps $< .02$] and significantly worse than accuracy in track-1 [$F(1,6)$s > 12.76, ps $< .02$]. The superior performance in track-2-far than that in track-2-near/different-quadrant revealed an effect of target spacing unconfounded with

Table 4
Average Target–Target Distances (T–T), Average Target–Distractor Distances (T–D), and Target Eccentricity (in Degrees) in Experiment 3

	Condition							
	Track 1		Track-2-Near/ Same-Quadrant		Track-2-Near/ Different-Quadrant		Track-2-Far/ Different-Quadrant	
	M	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*
Average T–T*	N/A	N/A	6.96	.09	6.96	.09	15.10	.19
Average T–D**	3.92	0.08	3.90	.07	3.88	.06	3.90	.05
Target eccentricity***	8.17	0.14	8.17	.09	8.19	.09	8.19	.10

Note—*SE* was calculated for each observer and averaged. *$p < .0001$. **$p < .5$. ***$p < .9$.

quadrant-based competition. Finally, accuracy in track-1 was not significantly better than that in track-2-far [$F(1,6) = 1.62$, $p > .25$], suggesting that target-number-based competition was weak.

Discussion

Experiment 3 showed that multiple object tracking was severely constrained by target spacing. Quadrant-based or target number-based competition effects were nonsignificant, at least with this paradigm. The quadrant-based attentional competition effect that was recently reported by Carlson and colleagues (2007) may be sensitive to specific experimental parameters. Carlson et al. used a pinwheel-tracking task in which participants tracked a designated spoke in a rotating pinwheel. That task placed the distracting spokes tightly around the target spoke and may have been particularly sensitive to quadrant-based competition.

GENERAL DISCUSSION

Visual attention is a gateway for access to conscious perception and explicit memory. In what ways is visual attention limited? Conventional wisdom depicts the limit in terms of the number of independent attentional foci (Pylyshyn & Storm, 1988). Beyond a magical number, maintenance of attention on multiple objects breaks down. The concept of a fixed number of attentional foci is attractive because it captures limits in a range of processes, including attentive tracking (Pylyshyn & Storm, 1988), visual working memory (Luck & Vogel, 1997), and enumeration (Dehaene, 1997). This concept, however, is too simplistic. Attentive tracking, for example, is affected not only by target number, but also by target speed and target spatial arrangements (Alvarez & Cavanagh, 2005).

A complementary proposal is that attention is limited in spatial resolution (He et al., 1996; Intriligator & Cavanagh, 2001). When targets and nontargets are closely spaced (below the spatial resolution of attention), it becomes difficult to attend just to the targets. In the past, the concept of limited resolution has been discussed primarily in terms of target–nontarget distance, as most studies only required the selection of a single target. When multiple targets must be selected, as was the case in the present study, limitations in maintaining nearby foci become clear. This kind of limitation is partly anticipated by studies on visual crowding, yet, in crowding studies, it is notoriously difficult to identify whether crowding is an attentional limitation or a lower level perceptual limitation (Pelli et al., 2007). Multiple object tracking is not subject to this debate because it does not involve the presentation of multiple features for identification. In addition, confusion of adjacent target tags is inconsequential since the task does not require separation of one target from another. Using this task, we have provided compelling evidence that multiple attentional foci interact with one another.

We suggest that attention's resolution to distinguish targets from nontargets is modulated by local interaction between adjacent targets. When a single target is surrounded by multiple distractors, the target location is enhanced by attention, but nearby regions are suppressed (Müller, Mollenhauer, Rösler, & Kleinschmidt, 2005). The suppression increases the contrast between a target and its distractors, optimizing the spatial resolution of attention. When multiple attentional foci must be maintained, the spatial profile of each focus changes depending on the distance between adjacent foci. At longer distances, different attentional foci do not interact, so attentional resolution at each focus is comparable to that of a single attentional focus. At shorter distances, one target falls inside the "suppression zone" of another, which reduces attentional contrast between targets and nontargets. Eliminating suppression by encompassing both targets into a larger enhancing zone has the advantage of maintaining target activation, at the cost of enhancing nontargets as well, essentially reducing spatial resolution gained by having local suppression.

In this proposal, the suppressive interaction between targets is necessitated by the demand to filter out nontargets. The interaction may be less obvious when distractors are absent or when they are far away. Future studies are needed to elucidate the interaction between target–target spacing and target–distractor spacing.

In summary, this study argues against the idea that attention is primarily limited by the number of foci. We revealed strong interference between nearby attentional foci at close distances. This interference may contribute to attentional limitations, yielding a new insight into the source of capacity limitation in visual attention.

AUTHOR NOTE

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