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Exhausting attentional tracking resources with a single fast-moving object

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Highlights

- Attentional limits were assessed with wide spacing to avoid object interference.
- The speed limit for tracking two objects was much slower than for tracking one.
- Attentional resource theory of tracking was supported.
- At least two tracking resources, one in each hemisphere.
- At fast speeds, performance tracking two no better than predicted by capacity of one.

Abstract

Driving on a busy road, eluding a group of predators, or playing a team sport involves keeping track of multiple moving objects. In typical laboratory tasks, the number of visual targets that humans can track is about four. Three types of theories have been advanced to explain this limit. The fixed-limit theory posits a set number of attentional pointers available to follow objects. Spatial interference theory proposes that when targets are near each other, their attentional spotlights mutually interfere. Resource theory asserts that a limited resource is divided among targets, and performance reflects the amount available per target. Utilising widely separated objects to avoid spatial interference, the present experiments validated the predictions of resource theory. The fastest target speed at which two targets could be tracked was much slower than the fastest speed at which one target could be tracked. This speed limit for tracking two targets was approximately that predicted if at high speeds, only a single target could be tracked. This result cannot be accommodated by the fixed-limit or interference theories. Evidently a fast target, if it moves fast enough, can exhaust attentional resources.

Introduction

Attentional tracking allows one to stay abreast of the changing locations of objects of interest. The ability may also have broader importance. Zenon Pylyshyn (1989; 2007) has argued that tracking provides an indispensable link between cognition and perception, allowing cognition to select from the enormous amount of information available in the large array of perceptual processors that process the entire visual field in parallel.

Visual tracking is typically studied with the "multiple object tracking" paradigm (Pylyshyn & Storm, 1988). In the version that we use here, several identical discs are presented. Participants are required to keep their gaze on the center of the screen, so that tracking must be performed by attention rather than by the eyes. The discs begin moving and a variable number are designated as targets by highlighting them in white. The rest are red. After all move about for a brief interval, all become red, and as they continue moving the participant attempts to keep track of the formerly-white targets. The discs stop after some seconds, and the participant is asked to indicate which discs were the targets. The number of objects that can be successfully tracked is limited to about four for the stimulus parameters used in most of the literature.

The processes that impose the target number limitation are not understood. Pylyshyn (1989; 2007) proposed that tracking is implemented by a fixed set of discrete pointers or “slots”, and some subsequent authors have supported this idea (Pylyshyn & Storm, 1988; Yantis, 1992; Cavanagh & Alvarez, 2005).

Tracking ability might instead by conferred by a continuous resource, with poor performance resulting when that resource is depleted or spread too thinly among targets (Alvarez & Franconeri, 2007; Tombú & Seiffert, 2008). A target travelling at high speed or near a distracter may be more difficult to track (Tombu & Seiffert, 2010; Iordanescu, Grabowecki, & Suzuki 2009), and allocating additional tracking resource might compensate for the difficulty (Tombu & Seiffert, 2008).

A similar theoretical debate has arisen regarding the processing that encodes information into working memory, with some authors proposing a flexible resource (Shibuya & Bundesen, 1988; Bays et al. 2011; Alvarez & Cavanagh 2004; Wilken & Ma, 2004) and others suggesting a fixed limit or number of slots (Cowan, 2001; Pashler, 1988; Luck & Vogel, 1997).

A third theory of attending and tracking is that the limits on performance are imposed by spatial interference among attentional spotlights on targets (Franconeri et al., 2010; Shim, Alvarez, & Jiang, 2008) or crowding of target representations in cortex (Franconeri et al., 2008; Intriligator & Cavanagh, 2001). We will refer to this as “spatial interference theory”. The specific suggestion of Franconeri et al. (2010) was that the interference involves a field of suppression surrounding each attended target.

Note that the other theories do not deny that deleterious spatial interactions sometimes do occur—lateral interference among objects is well-established (Pelli & Tillman, 2008). The spatial interference theory of Franconeri et al. (2008; 2010) claims however that the cost of tracking additional items is always due to spatial interactions rather than depletion of a resource pool.

When making predictions from this theory, Franconeri has occasionally gone beyond its necessary implications, e.g. “This account correctly predicts that increasing the speed of the moving objects does not change performance, as long as it is done in way that does not change the number of object interactions” (Franconeri, in press, p.12). This cannot be true across all speeds because the visual system cannot represent objects moving at very high speeds as well as it can at low speeds (e.g. Burr & Ross, 1982), and elsewhere Franconeri's team has more accurately written: "there should be a constant upper limit on speed for each object" if interactions are avoided (Franconeri et al., 2010, p. 921). In other words, finding a decline of performance with speed cannot rule against the theory by itself (Tombú & Seiffert, 2010), instead one must find that the cost of speed is higher when more objects are tracked, even when spatial interference is avoided.

In this study, to preclude spatial interference we use widely spaced objects. According to the fixed-limit theory and spatial interference theories, adding a second target to be tracked should not reduce the speed limit for tracking the first target. Yet we find the second target has a substantial cost. Indeed, the speed limit for tracking two targets is similar to that predicted if at high speeds only one target can be tracked and the participant must guess regarding the other.

Experiment 1: The high cost of a second target

Method

Six participants (aged 29-37, four males, two authors) who reported normal or corrected-to-normal vision agreed to participate, following approval of the protocol by the University of Sydney's ethics committee. Two were the authors. All six had extensive experience fixating in laboratory experiments.

A 120 Hz CRT displayed four red discs (evoked by the red gun only, with Gaussian intensity profiles; visible diameter 1 deg; peak luminance 20 cd/m^2) and a white fixation point against a black background, at a distance of 57 cm from the eye. The discs traveled in two concentric circular trajectories centered on fixation (see Figure 1 and Figure 2, bottom panel). Two discs were placed on each trajectory, always opposite each other (180° apart). In this paper, "deg" will refer to degrees of visual angle, while the "°" symbol will be reserved for other angles.

The inner trajectory had a radius of 2 deg. In the small separation condition, the outer trajectory had a radius of 4 deg. In the large separation condition, the outer trajectory had a radius of 9 deg. Therefore, in the small separation condition the distance between any two blobs was always at least 2 deg.

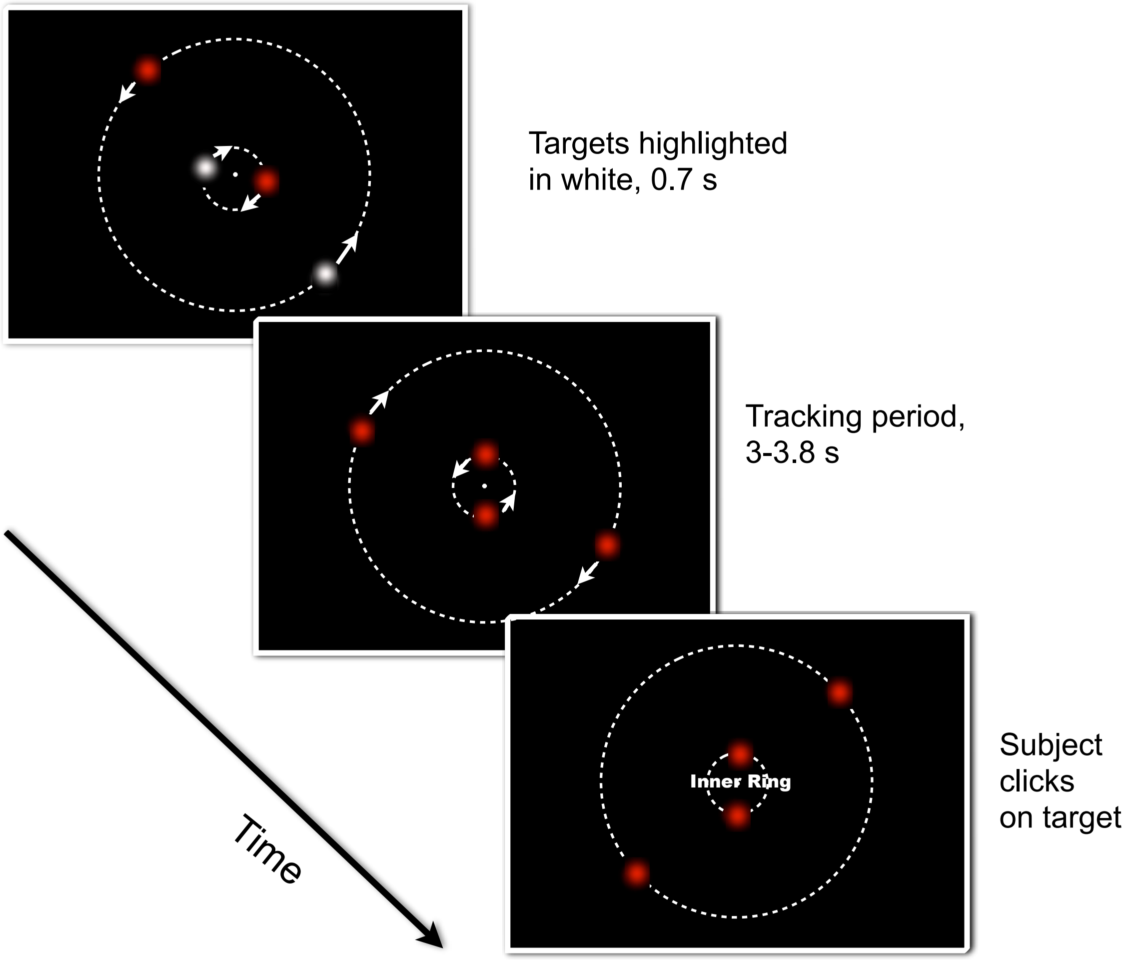


Figure 1. **The trial sequence. After the targets are highlighted in white, all discs become red and revolve about the fixation point. During this interval, the pair of discs on each trajectory occasionally reverses movement direction, at random times independent of the other pair. After 3 to 3.8 s the discs stop, one ring is indicated by presenting text next to it, and the participant clicks on one disc of that ring.**

Studies of lateral interference have shown that crowding normally occurs only when a target object is separated by less than half its eccentricity from another, whether the objects are stationary (Bouma, 1970; Pelli & Tillman, 2008; for the exception that occurred with masked targets, see Vickery et al., 2009) or moving (Bex, Dakin, & Simmers, 2003). Based on those findings, with the outer discs at 4 degrees and the inner at 2 degrees in the small-separation condition, it is possible that the inner disc might crowd the outer. The large-separation condition was designed to eliminate the possibility of crowding. The closest approach of the inner disc and outer disc is 7 deg, far from the expected 4.5 deg crowding zone for the outer disc.

Both pairs of discs began at random points in their trajectories, with the outer discs revolving about fixation initially in the opposite direction from those in the inner trajectory. Targets were indicated by showing the discs as white when the motion began. They gradually became red over the next 0.7s, via a linear ramp through RGB space. The pairs of blobs occasionally reversed direction—each pair was independently assigned reversal times that succeeded each other at random intervals between 1.2 and 2 s. The total tracking interval varied randomly between 3.0 and 3.8 s.

In one condition, participants tracked one disc (either in the inner or outer trajectory, chosen randomly on each trial) and in the other, they tracked two, one in each trajectory. At the end of the trial, participants used the mouse to indicate which blob was a target. In the two-targets condition, in half of trials participants were prompted to indicate the target in the inner trajectory, in half of trials the outer trajectory.

All objects revolved about fixation at the same rate. Five rotation rates (0.7, 1.0, 1.3, 1.6, and 1.9 rps) were used, which were presented in pseudorandom order and fully crossed with the one-target versus two-targets conditions.

Data analysis

Plots of speed versus proportion correct were fit by logistic regression modified to span from 99.5% correct asymptotically at low speeds (which corresponds to a 1% lapse rate) to 50% correct performance (chance rate) at high speeds, allowing estimation of the "speed limit"—the rate at which performance fell to 68% correct. This speed limit was estimated separately for each participant and condition.

Calculating the predictions of a one-target capacity limit

To put any findings of speed limit differences in perspective, we calculated the predictions of an extreme scenario- that participants can only track one object, and must guess on the half of trials for which they track the wrong target. On this model, for the half of trials where a participant tracks the target that is subsequently queried, predicted performance for that speed is provided by the one-target logistic curve fit. On the other half of trials, participants perform at chance- 50%. Because according to this model participants guess on half of trials, performance never exceeds 75% correct. Actual performance is higher than this at slow speeds, showing that the model is wrong. Nevertheless, the speed limit (68% threshold) that it predicts is useful as it puts the empirical results in perspective, allowing comparison to the limit that would occur if participants only tracked one object on each trial.

Results and discussion

For every participant, the speed limit (68% threshold) for tracking one object was better than for tracking two objects. It was significantly higher for tracking one target across participants in both the small separation (paired $t(5) = 3.23$, p=0.023) and large separation (paired $t(5) = 4.93$, p=0.004) conditions (Figure 2). This speed limit cost for tracking a second target depended little or not at all on separation—two-factor ANOVA F (1,5)=0.002, p=0.968.

When the two authors were excluded from the data, the speed limit difference between tracking one and tracking two was still statistically significant for the large separation condition (paired $t(3) = 3.95$, $p = .029$), but no longer so for the small separation condition (paired $t(3) = 2.52$, $p = .086$).

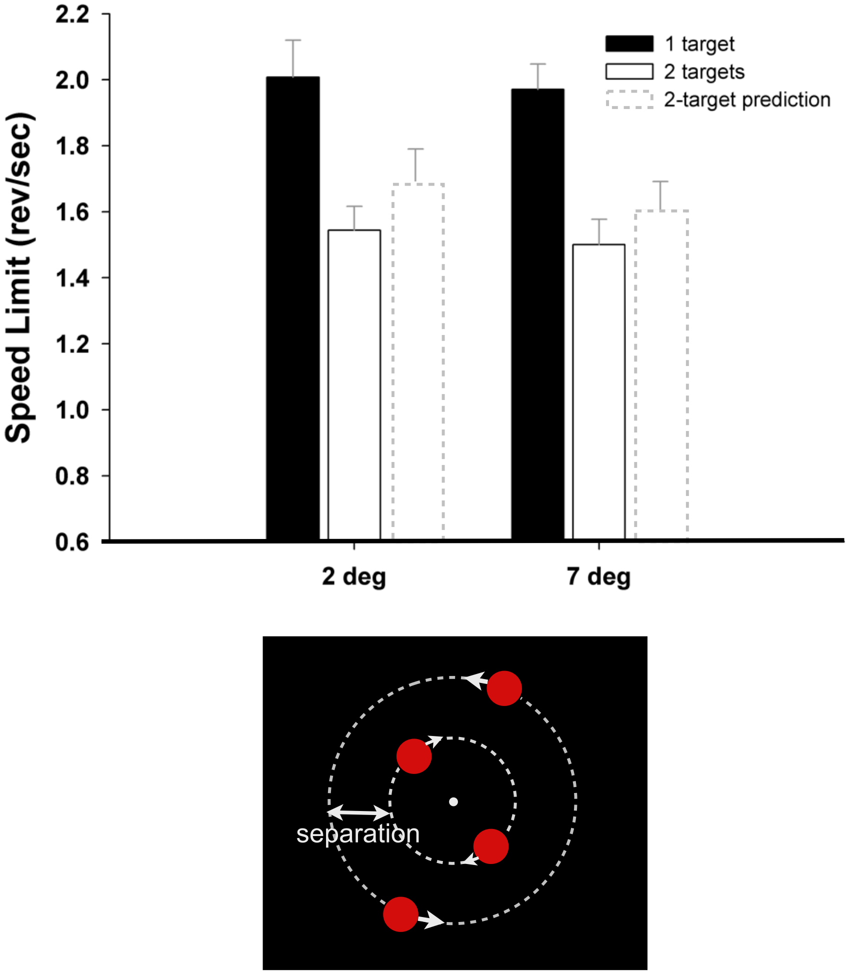


Figure 2. *Bottom panel*. The stimulus arrangement for Experiment 1. *Top panel*. The mean speed limits (68% thresholds), n=6. The speed limit for tracking two targets is substantially worse than the speed limit for tracking one, and is similar to that predicted by a one-target capacity limit (dashed bars). Error bars show 1 standard error.

The average speed limit penalty for tracking a second object, 0.46 rps, is severe. As shown in Figure 2, it is approximately the size predicted if the participants can only track one object, and must guess on the half of trials for which they track the wrong target. On this model (also described in the methods above), for the half of trials where a participant tracks the target that is subsequently queried, predicted performance for that speed is provided by the one-target curve fit. On the other half of trials, participants perform at chance—50%. Because according to this model participants guess on half of trials, performance can never rise above 75%, which for slow speeds is clearly disproved by the data—see the psychophysical curves shown in Figure 3. This shows that at slow speeds participants can track more than one object, as has been demonstrated before (Pylyshyn & Storm, 1988).

At high speeds, performance is closer to that of the one-object capacity model and the predicted speed limits (dashed bars of Figure 2) are not statistically significantly different from the actual, both for the small spacing ($t(5)=-1.008$, $p=0.360$) and large spacing ($t(5)=-1.015$, $p=0.357$) conditions. The non-significant trend is for even worse performance than the model, and this was unchanged when the two authors were excluded from the analysis. Worse performance than the model can occur if observers, although only able to track one target accurately at high speed, nevertheless allocate some resources to the second target. By having insufficient resources devoted to either target, both would be lost.

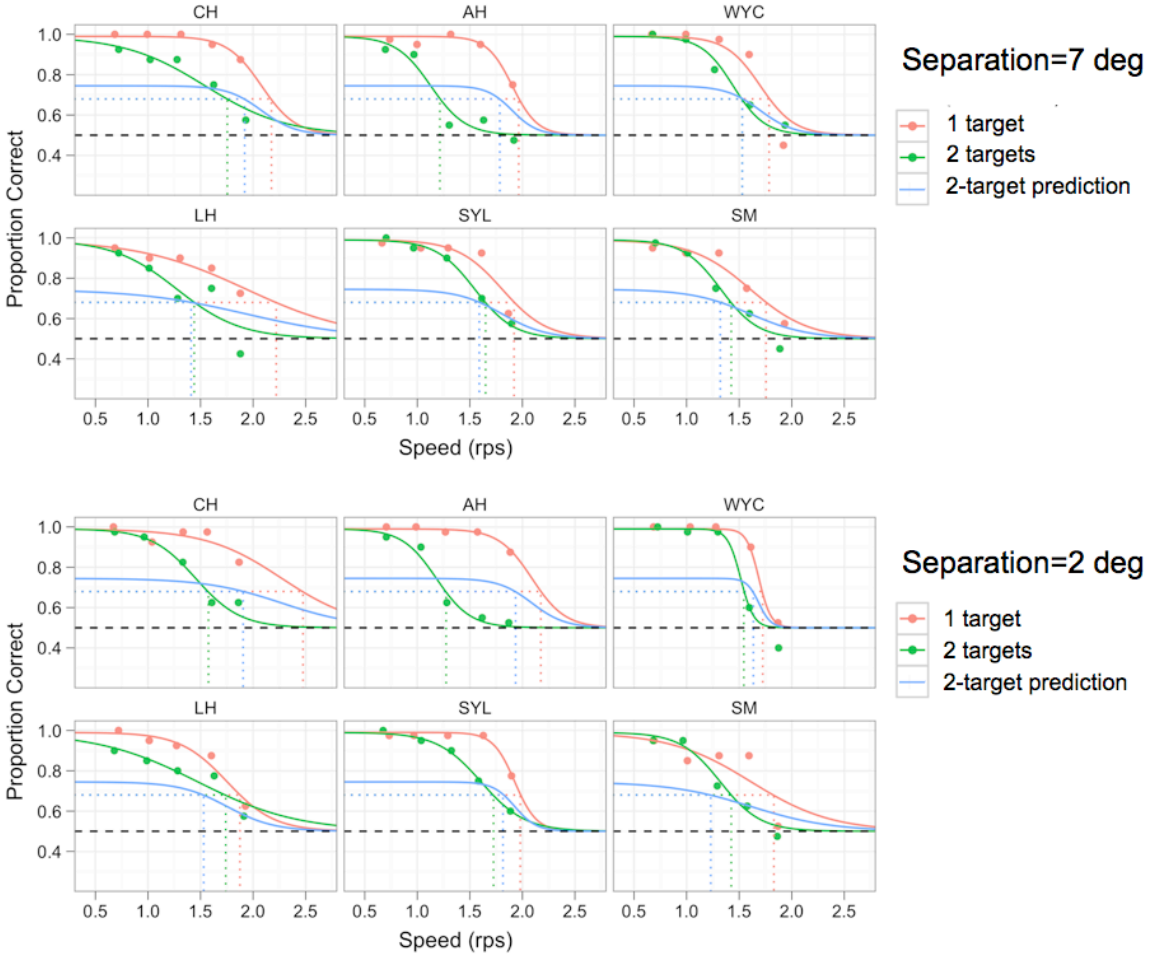


Figure 3. For each participant in Experiment 1, proportion correct is shown for each speed, for the one-target and two-target conditions. Also shown is the prediction for the two-target condition if the participant had a capacity limit of one target. Dotted lines show the 68% thresholds.

We were concerned that the difference in speed limit between the one-object and two-object conditions might be caused partly by greater forgetting of the answer in the two-object condition. If participants forgot which object was the target in more trials in the two-object condition, then the psychometric function would saturate at a lower ceiling. A "forgetting factor" like this would thus have the same effect on the psychometric function as an increase in the lapse rate used in psychophysics. In psychometric fits not shown here the lapse rate was allowed to vary for each subject and condition. No evidence was found for a higher lapse rate in the two-object condition, indeed the estimated trend was in the opposite direction, and compensating for that would only increase the already-large estimated speed limit difference between the one-object and two-object conditions.

If the effect of speed were due to a fixed limitation of the tracking mechanism, unaffected by availability of resources, then it should be unchanged by the number of targets to track. Our results contradict this. When a target travels faster or a second is present, each apparently receives a smaller share of the resource, to the extent that at high speeds, only approximately one object can be tracked.

An incidental result was a trend for tracking speed limit (in revolutions per second) to decrease with eccentricity. After averaging the inner ring's speed limits across the two separation conditions, an ANOVA was conducted with number (tracking 1 or tracking 2) and eccentricity (2, 4, or 9 deg) as factors. Eccentricity was nearly significant ($F(1,5)=3.710$, $p=0.072$), with average speed limit for a single target 2.0 rps at 2 deg, 1.92 rps at 4 deg, and 1.74 rps at 9 deg. This apparent decline conflicts with the report of Verstraten, Cavanagh, & Labianca (2000) regarding tracking one bar of a two-cycle circular grating: "an informal test showed… the maximum tracking rate was unaffected by eccentricity" (p.3660). But the non-significant decrease we found was small enough that the speed limit is captured much better by revolutions per second than by linear speed. Converting the rps for each eccentricity into linear speed gives 25, 48, and 98 deg per sec, as if the speed limit increases dramatically with eccentricity. More likely is that the limit is largely set by a limit of revolutions per second.

One concern about our result of an effect of target number is that if participants pursued a target with their eyes, greatly reducing the speed of the first target, this could yield the faster speed limit for tracking one, even without a resource limit. Participants, who were all highly experienced with fixating during laboratory experiments, reported that they did not pursue a target with their eyes. But it's still possible that some did, so in the next experiment an eyetracker was used.

Experiment 2: Constant travel distance and eyetracking

To avoid spatial interference, Experiment 1 included a large separation of 7 deg between target trajectories. Although according to previous studies of visual interference, this should ensure that no spatial interference occurred (Pelli & Tillman, 2008), it is conceivable that the interactions in attentional tracking span a much larger range than those suggested by conventional studies of crowding. If so, then the poorer performance at higher speeds when tracking two might be caused by a greater number of spatial interactions.

The opportunity for a greater number of spatial interactions arises at higher speeds because the distance travelled by the objects was greater at high speeds, so that they pass relatively near each other more times. To avoid this, in Experiment 2 we adopt the approach introduced by Franconeri et al. (2010) of equating the total distance travelled for different speeds. As Franconeri et al. pointed out, this should equate the number of opportunities for spatial interactions across speeds. As a result, according to the interference theory the effect of speed should be greatly reduced.

To enforce fixation, here we used an eyetracker to discard trials where participants moved their eyes by more than 1.5 deg from the fixation point.

Methods

2.1. Participants

Of six participants (4 male, aged 29-37) five also participated in Experiment 1.

2.2. Stimulus

The stimuli were identical to those in Experiment 1 except for a few changes described here. Whereas in Experiment 1 each of the two circular trajectories contained two discs, here in Experiment 2 each contained three blobs, equally spaced about the trajectory (Figure 4). Using three discs lowered the guessing rate to 33%. The inner circular trajectory had a radius of 2.5 deg of visual angle and the radius of the outer circular trajectory was 5.5 deg, outside the crowding zone (Bouma, 1970; Pelli & Tillman, 2008).

The cumulative distance traveled by the blobs was 3.6 revolutions on every trial, achieved by setting the duration of the trial to a different value for each speed. Five speeds were used. After the 0.7s target-cuing interval, the blobs changed direction at random succeeding intervals of between 1.2s and 2s, as in experiment

1. The direction changes for each ring were determined randomly and independently of those for the other ring, as in experiment 1.

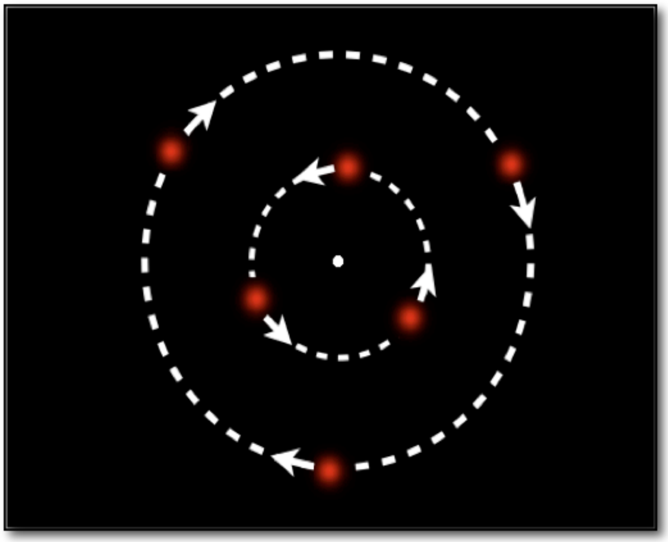


Figure 4. Display of Experiment 2. The "discs" (Gaussian blobs) traveled in two concentric circular trajectories that were centered on the fixation point. Three discs were in each ring, presented 120° of separated from the others. The radius was 2.5 deg of visual angle for the inner ring, 5.5 deg for the outer ring.

2.3 Eye movement monitoring

Eye movements were monitored using an SR Research EyeLink 1000 eye tracker and analyzed with the associated Eyelink 1000 version 1.5.2 software. At the beginning of each session, the eye-tracking system was calibrated and validated using the standard 5-point calibration. The experimenter monitored the video image of the participant's eye at the beginning of each trial to ensure the participant fixated and the eye tracker continued to report this correctly. The eye tracker was recalibrated if, during the interval before the trial, it registered the participant's eye location as away from fixation even though the participant reported fixating. If the eye tracker reported that the participant moved their eye by more than 1.5 deg of visual angle from the fixation point, the trial was discarded.

2.4 Procedure

The sequence of events on a given trial was identical to that of Experiment 1. Five rotation rates (0.6, 0.9, 1.2, 1.5, and 1.8 rps) were used, which to achieve a constant distance traveled of 3.6 revolutions, yielded 5 corresponding tracking durations (6, 4, 3, 2.4, 2 seconds). Each observer participated in 48 trials for each of the five rates. Observers were presented with 240 experimental trials in total, divided into two sessions run on different days.

2.5 Data analysis

The curves were fit as in Experiment 1, adjusted for the lower 33% chance rate of the present experiment. The prediction from the one-target capacity limit premise was also adjusted accordingly, spanning 33.33% correct performance to 66.25%. The threshold accuracy considered the speed limit was set to 57%, the equivalent point on the psychometric curve as the 68% point in Experiment 1.

Result:

The criterion of eye movement greater than 1.5 deg from fixation led to exclusion of 8.8% of trials (SD = 3.5% across participants). The eyetracker was less reliable for the three participants who wore glasses—not counting them, only 3.2% of trials were excluded. A repeated measures ANOVA found no significant effect of speed (F(1,5)=1.11, p=0.379) or target number (F(1,5)=2.373, p=0.184) on eye movements greater than 1.5 deg.

The effect of speed on proportion correct is plotted in Figure 5 (top panel), for tracking one and tracking two objects. A long-range spatial interference theory could accommodate overall lower performance when tracking two than when tracking one, but cannot account for performance falling off with speed at a lower range of speeds. It also predicts the effect of speed should be much smaller than in Experiment 1, because higher speeds are no longer associated with more spatial interactions.

It is evident from Figure 5 that the effect of speed was dramatic, just as it was in Experiment 1, even though spatial interference theory predicts much less effect of speed because the distance traveled here was the same for each speed, and consequently the opportunity for spatial interactions was equated across speed.

The effect of speed is quantified by the slope parameter of the logistic regression, although the estimates are sometimes unstable due to sparse sampling of speed in the steep performance region. This is obvious in the case of WYC for tracking two (see Figure 5). We exclude his data and, using t-tests, find no significant difference in slopes between the experiments. For tracking one, mean slope in E2 was -7.1 and -5.2 for E1's small separation condition (the most comparable condition), and for tracking two, mean slope in E2 was -5.0 against -4.6 in E1's small separation condition.

For every participant, the estimated speed limit (57% threshold) for tracking one target is better than for tracking two targets. The mean thresholds in each condition are plotted in Figure 5 (bottom panel). The average speed limit for tracking one object, 1.63 rps, was substantially higher than tracking two objects, 1.14 rps, paired $t(5)=6.252$, $p=0.002$. The difference in speed limit of 0.49 rps is similar to that found in the previous experiment- 0.46 rps. This is contrary to the expectation from spatial interference theory that the speed limit effect of a second target, if any, should be small. The two–target speed limit predicted by the one-object-limit was significantly higher than that of the actual data, paired $t(5)=-4.291$, $p=0.008$. Both these comparisons were also significant when the authors' data was excluded. The finding of poorer performance than the seemingly worst-case scenario of a one-object capacity limit may indicate that observers only have enough resource at high speeds to track one target, but continue to divide their resources among the two so that they cannot succeed with either of them.

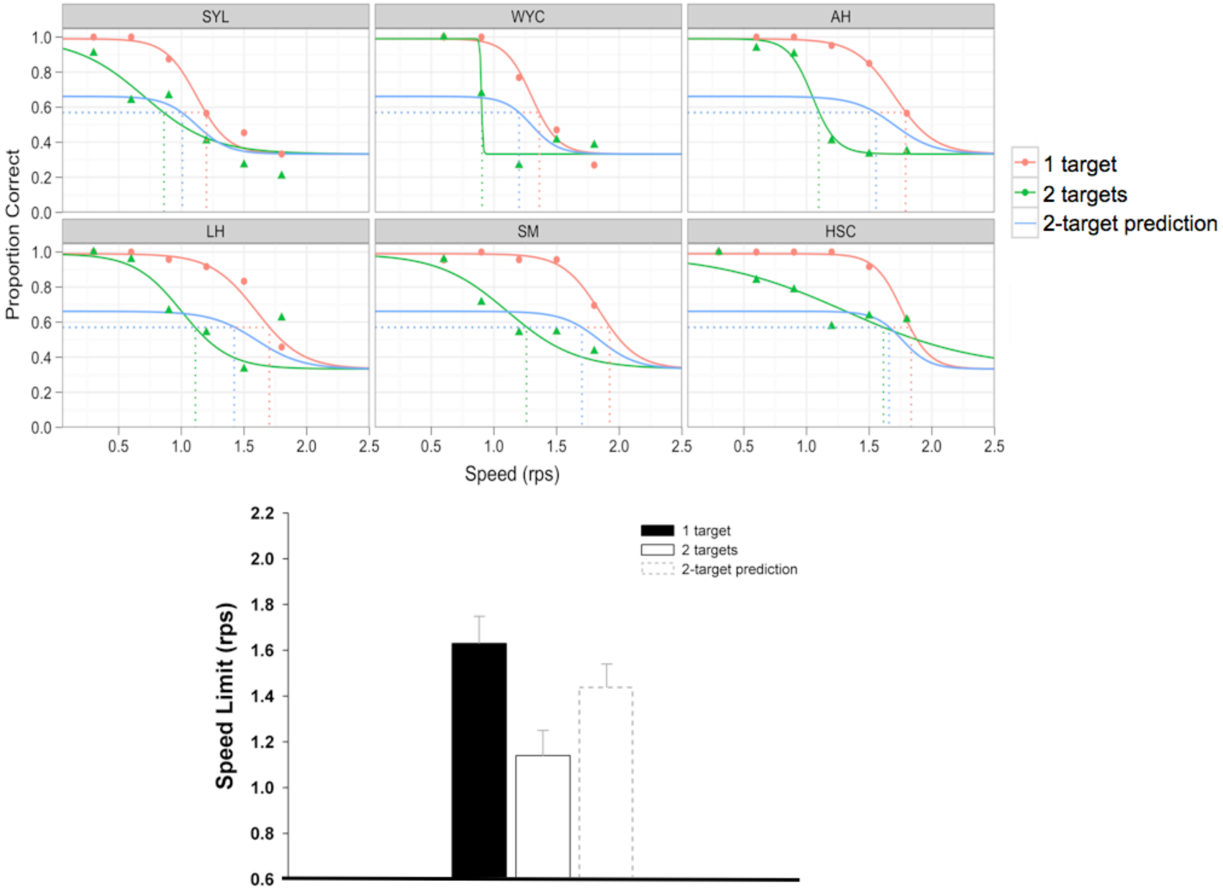


Figure 5. ***Top panel.*** Proportion correct is shown for each speed in the one-target (red) and two-target conditions (green) of Experiment 2 for each participant. Blue curve shows the prediction for the two-target condition if the participant had a capacity limit of one target. Dotted lines show the 57% thresholds. ***Bottom panel.*** Speed limits for tracking one and two objects and the speed limit predicted for two targets by the one-object capacity model. Error bars show one standard error across participants.

Experiment 3: Hemisphere specificity

The results of the first two experiments support the theory that a reduction of available resource reduces the tracking speed limit. The resource involved may be a general pool used by stimuli anywhere in the visual field. Alternatively, there may be multiple independent pools of this resource in the brain, potentially including one in the left hemisphere devoted to stimuli in the right visual hemifield and another in the right hemisphere devoted to stimuli in left visual hemifield.

In a seminal study of this topic, Alvarez & Cavanagh (2005) presented a target in one visual hemifield and tested the effect of adding another target in the same hemifield or in the opposite hemifield. Performance was much poorer when the additional target was presented in the same visual hemifield, but not affected much when the target was presented in the opposite hemifield.

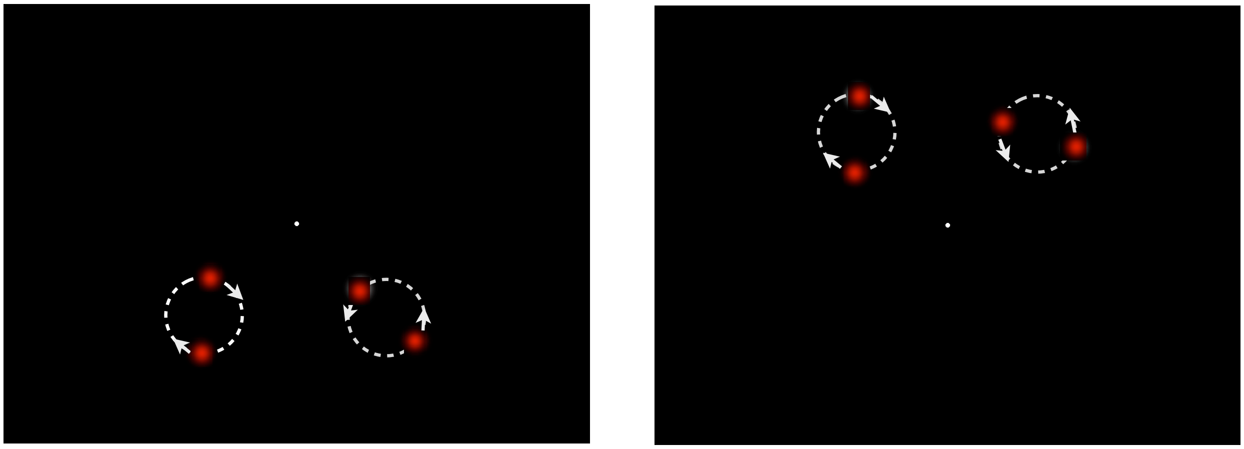
This finding of Alvarez & Cavanagh (2005) does not necessarily imply that the tracking resource is hemifield and hemisphere-specific. In their experiment, the objects could come very close to each other and therefore crowding may well have occurred. Spatial interference theory can therefore account for the finding with the proposal that spatial interactions are very weak or absent across the vertical midline. Liu et al. (2009) found that crowding was weaker when target and flankers were presented bilaterally rather than unilaterally.

To investigate whether the resource that manifestly consumes speed is indeed hemisphere-specific, in uncrowded conditions we tested whether bilateral performance is better than than a unilateral arrangement.

Method

Eight people (six male, aged 29-36) who reported normal or corrected-to-normal vision agreed to participate, including six who also participated in Experiment 1. Two were the authors.

Bilateral Conditions



Unilateral Conditions

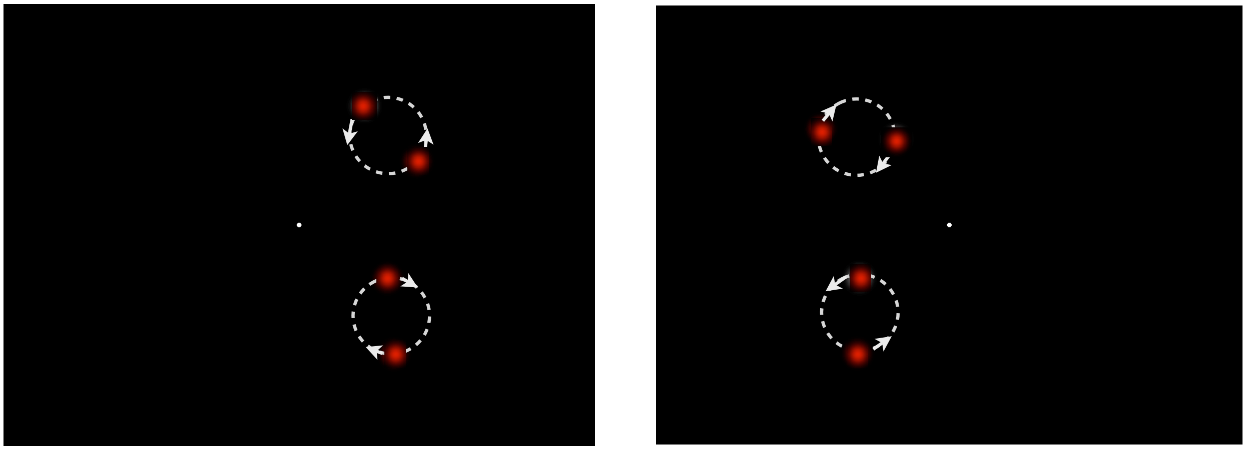


Figure 6. In Experiment 3, two pairs of discs were presented in each condition. Each pair moved along a circular trajectory (dotted lines) and was centered in one quadrant. They were presented in one of four conditions: unilaterally, at the left or right side of the vertical meridian, or bilaterally, above or below fixation. A disc from one or both pairs were designated as targets.

The spatial arrangement of the objects is schematized in Figure 6. Two pairs of discs were presented in all conditions. Each pair moved on a circular trajectory that was centered in one of the four quadrants of the visual field. The two pairs of discs were placed in either the same hemifield (unilateral condition) or opposite hemifields (bilateral condition). Each circular trajectory was centered on a point 6 deg from the vertical midline and 6 deg from the horizontal midline (representing one of the four quadrants). The radius of each trajectory was 2.5 deg. These distances are large enough to avoid crowding among the objects (Pelli & Tilman 2008; Levi 2008). For the unilateral condition, in half of trials the two pairs were placed in the left visual field and in half of trials in the right visual field and for the bilateral condition, in half of trials the two pairs were placed in the upper visual field and in half of trials in the lower visual field.

The speeds used were adjusted based on the results of Experiment 1 for each participant. For example, the speed limit of observer LH in Experiment 1 was 1.78 rps, leading us to use object speeds of 0.8, 1.2, 1.6, 1.8, and 2.0 rps here. Each observer participated in 192 trials for each of five speeds, yielding 960 experimental trials in total, divided into six sessions. Each participant did no more than two sessions a day and observers had a minimum break between sessions of 5 minutes.

Results and Discussion

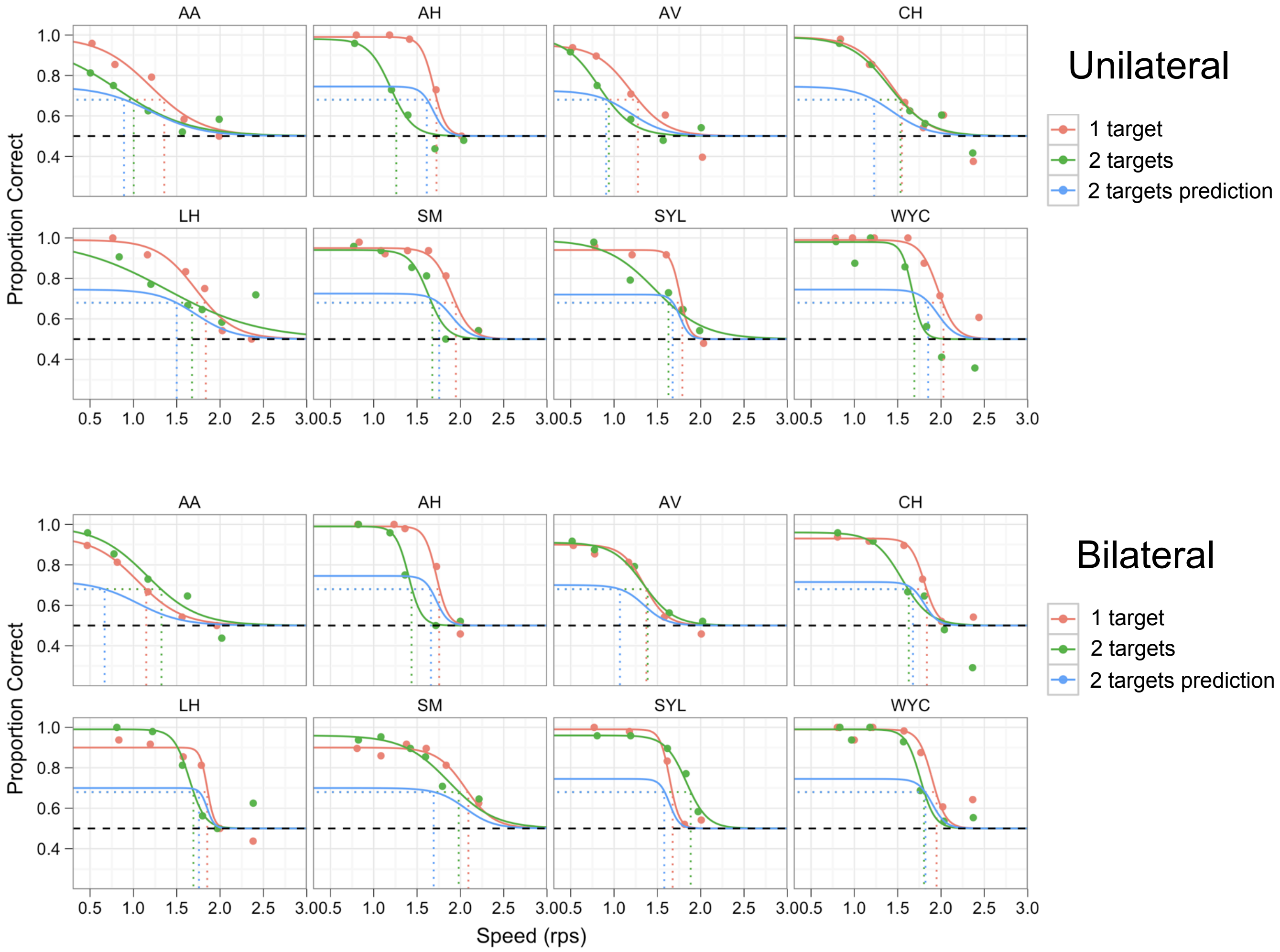


Figure 7. For each participant in Experiment 3, proportion correct is plotted against speed, for the bilateral and unilateral conditions, in the one-target (red) and two-target (green) conditions. The blue line shows the prediction for the two-target data based on the assumption that the participant could only track one target. Dotted lines show the speed limits (68% thresholds).

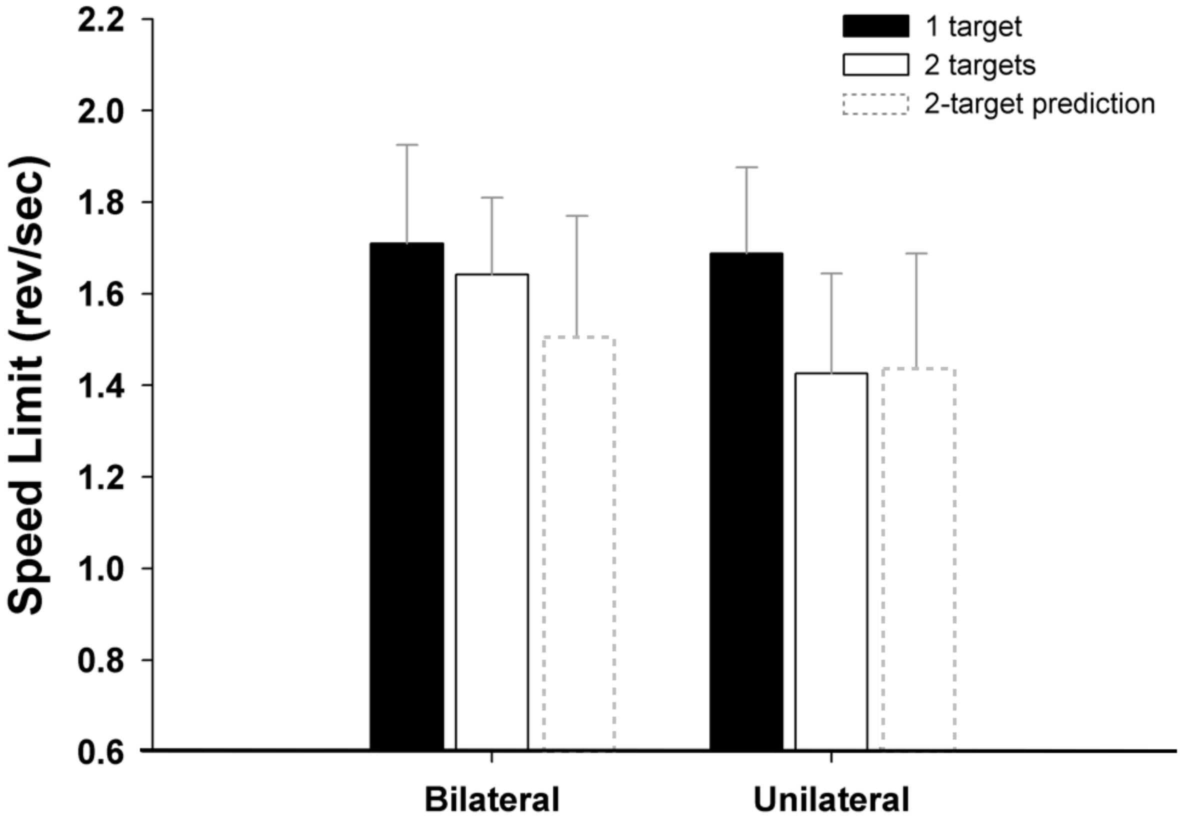


Figure 8. The mean speed limits (68% thresholds) for tracking one and tracking two objects, for the unilateral and bilateral condition of Experiment 3. The two-target cost is significantly greater in the unilateral condition than in the bilateral condition, indicating that the resource determining the speed limits is at least partially hemisphere-specific. Error bars show 1 standard error.

The data and fitted curves are shown for each participant in Figure 7, with associated speed limits (68% thresholds) shown in Figure 8.

The two-target cost was greater for the unilateral condition than for the bilateral condition, as shown by the significant interaction between number of targets and hemifield division in a 2 x 2 repeated-measures ANOVA, $F(1,7)=6.042$, $p=0.044$, partial $\eta^2=0.463$. Furthermore, a paired t-test indicated that performance was worse in the two-target unilateral condition than the two-target bilateral condition, $t(5) = 3.7$, $p=.014$. These results suggest that the tracking resource is, at least partially, hemisphere-specific.

The speed limit for the one-target condition was very similar whether the other pair of discs was in the same hemifield (1.69 rps) or the other hemifield (1.71 rps) and not significantly different (paired $t(7) = 1.37$, $p=0.72$). This suggests that in the one-target condition, there was no differential distracting or masking interference caused by the irrelevant pair of discs.

Our finding that speed limits were similar for two targets as for one target, when the two targets are in different hemifields, may appear to conflict with the findings of Shim, Alvarez, & Jiang (2008). When examining performance in a two-target condition, they found no significant benefit of placing them in different hemifields. As a result, they suggested that the hemifield independence documented by Alvarez & Cavanagh (2005) would only manifest when tracking load is greater than two. Their test however was probably less sensitive than ours, because performance in all the conditions involved in their comparison were greater than 85% correct, including many low speeds where performance was near ceiling (see their Figure 4). Like us, Shim et al. (2010) also found a bilateral advantage when tracking two targets. Their stimulus comprised four pinwheels, one in each quadrant. Performance tracking one "spoke" of two pinwheels was significantly higher when they were in opposite hemifields than when they were in the same hemifield.

If the tracking resource were entirely hemisphere-specific, then performance would be exactly the same for tracking one and tracking two bilaterally. In our data, a non-significant trend was present suggesting poorer performance for tracking two compared to tracking one, even when the targets were in opposite hemifields (Figure 8). Because we were concerned the absence of a significant two-target decrement in our data might be a type 2 error (insufficient power), we conducted a simple additional experiment with two pairs of blobs. One pair was in a circular trajectory (2.5 deg radius) centered 6 deg directly to the left of fixation. The other pair was centered 6 deg directly to the right of fixation. Unlike in the main experiment, we equated the cumulative distance traveled (6.6 revolutions) across speeds. Six participants participated in approximately 120 trials each at speeds of 1.0, 1.2, 1.6, 1.9, and 2.2 rps. The average speed limit for tracking one object (1.98 rps) was not significantly different than that for tracking two targets (1.85

rps), paired *t*(5) = 1.46, *p*=0.20. The finding here, as with the main experiment, of a small non-significant effect of load supports our main conclusion of hemifield specificity of the resource. However, that both this additional experiment and the main experiment did find a (non-significant) decrease suggests that the resource may be only partially hemisphere-specific.

General Discussion

The large cost of a second target on tracking speed limit (E1 and E2), and the hemifield specificity of this effect (E3), support the resource theory of tracking. Both speed and target number deplete the tracking resource, so that at high speeds fewer targets can be tracked. Indeed, the demand of high speeds is so large that performance is similar to that expected if only one target could be tracked.

It is difficult to reconcile these results with the fixed-limit and spatial interference theories. According to the fixed-limit theory, the speed limit for tracking should not be affected by the number of targets. The fixed-limit theory could be modified to allow multiple pointers to be allocated to a single target, which would yield a prediction of lower performance for tracking two relative to tracking one. However, because according to this theory the pointers are independent, allocating multiple pointers to a target should provide only a small benefit (probability summation), and therefore cannot accommodate the very large effect of a second target documented here.

According to spatial interference theory, the speed limit for tracking can only be affected by the number of targets if the objects are sufficiently close to cause interference among their attentional spotlights and their associated surrounds. To avoid spatial interference, we used widely separated targets in Experiment 1. In the large-separation condition the two targets never came closer than 7 deg, much larger than the approximately half-eccentricity crowding zones of approximately 4.5 deg for the outer disc and 1 deg for the inner disc predicted by extensive previous work (Pelli & Tillman, 2008; Bouma, 1970). The distracter disc for each target was on the opposite side of the fovea, very far in cortical distance, and should not have caused any interference (Pelli, 2008).

Could spatial interference theory be salvaged with the proposition that the interference zones of the attentional spotlights are extraordinarily large? Not likely, for two reasons. First, the interference ought to increase with proximity (Shim, Alvarez, & Jiang, 2008), yet the speed limit cost of an additional target here was very similar at two very different separations (Figure 2). Second, in Experiment 2 we kept the opportunity for spatial interactions constant across speeds by equating total distance traveled (following the logic of Franconeri et al., 2010), yet still the second target was very costly for speed limits.

The resource documented in these experiments is likely to have implications for encoding information in other tasks. Here we studied only the tracking of object positions over time, but it is possible the findings apply to multiple object attention more generally. If so, this resource may also gate the entry of information into visual working memory, yielding phenomena such as the trade-off between number of items and precision of working memory (Bays et al., 2011).

Where in the brain is the resource?

Because the resource seems to be largely hemifield-specific (Experiment 3), it may be mediated by corresponding brain regions in opposite hemispheres that are lateralized in their processing of visual stimuli. The resource may reflect the action of a neural population that can assist in the processing of stimuli anywhere in a hemifield- in other words, a non-retinotopic brain region.

Neuroimaging studies of tracking have pointed to parietal regions, including those along the intraparietal sulcus and the posterior parietal cortex, as heavily involved in the attentive component of the task. At least three teams have found that multiple regions in parietal cortex monotonically increase in activity with the number of targets (Culham, Cavanagh, & Kanwisher, 2001; Jovicich et al., 2001; Shim, Alvarez, Vickery & Jiang, 2010). Potentially, the activity of neural populations in these areas might reflect the allocation of resource. However, Saygin & Sereno (2008) found evidence that some of these parietal areas are retinotopic, which seems inconsistent with the neurons constituting a resource that can be applied anywhere in the visual hemifield. However, the criteria for delineating regions in posterior parietal lobe is inconsistent across studies, so there may yet be a parietal region that is non-retinotopic yet lateralized and involved in tracking.

Only the Shim et al. (2010) study manipulated the speed of the targets. They found that although the BOLD signal was higher in posterior parietal cortex for tracking two targets than for tracking one, it did not increase with speed of the targets. Although we have already suggested that this region does not hold the tracking resource, to guide interpretation of future studies it is important to note that absence of a speed effect does not rule against a region’s activity comprising the resource. Our results suggest that regardless of speed, the entirety of the resource is applied to tracking, yielding higher performance at slow speeds than at fast speeds. This may even apply to attending to stationary targets. On the other hand, at stationary and slow speeds where behavioral performance is at ceiling, perhaps not all the resource is deployed. The uncertainty regarding this point makes it difficult to interpret an fMRI study that contrasted stationary with moving targets (Howe et al., 2009).

Although the hunt for attentional resources should go on, it may be simplistic to expect to find one or a few brain regions that respond in proportion to the amount of resource deployed. The deployment of attentional resources may instead reflect a complicated interaction among brain regions.

Serial or parallel?

A critical remaining issue for theories of tracking is whether multiple targets are processed entirely in parallel or instead their locations must be updated one by one (Tripathy, Ogmen, & Narasimhan, 2011; Howe, Cohen, & Horowitz, 2010). In terms of the current theoretical framework, serial processing can be considered a specific implementation of resource theory where the resource is time-shared among the targets. As the number of targets increases, each is processed proportionally less often by the serial process. The serial processing account specifically predicts that increasing tracking load will have a large effect on speed limits, because at higher speeds the targets travel farther between position updates by the serial tracker. Therefore, serial processing accounts are particularly compatible with the present findings. Serial accounts are undermined however by other results (Howe, Cohen, & Horowitz, 2010), so perhaps a parallel resource theory should be favored. Parallel resource theory explains our results with the proposition that even a single target can exhaust the tracking resource if presented at a high enough speed.

Supplementary material

Movie 1. Demonstration of a one-target trial of Experiment 1. The targets to track are initially red. Speed is nominally 2.1 rps, but will be slower on many computers. Due to the limitations of quicktime movie playback, on each frame the outer discs jump a large distance rather than travelling smoothly as they did in the actual experiment. Spatial dimensions are not to scale.

Movie 2. Demonstration of a two-target trial of Experiment 1. The targets to track are initially red. At high speeds, this was much more difficult than tracking one, for all our participants. Speed is nominally 2.1 rps, but will be slower on many computers. Due to the limitations of quicktime movie playback, on each frame the outer discs jump a large distance rather than travelling smoothly as they did in the actual experiment. Spatial dimensions are not to scale.

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