Resource demands of object tracking and differential allocation of the resource

Wei-Ying Chen · Piers D. Howe · Alex O. Holcombe

Abstract The attentional processes for tracking moving objects may be largely hemisphere-specific. Indeed, in our first two experiments the maximum object speed (speed limit) for tracking targets in one visual hemifield (left or right) was not significantly affected by a requirement to track additional targets in the other hemifield. When the additional targets instead occupied the same hemifield as the original targets, the speed limit was reduced. At slow target speeds, however, adding a second target to the same hemifield had little effect. At high target speeds, the cost of adding a same-hemifield second target was approximately as large as would occur if observers could only track one of the targets. This shows that performance with a fast-moving target is very sensitive to the amount of resource allocated. In a third experiment, we investigated whether the resources for tracking can be distributed unequally between two targets. The speed limit for a given target was higher if the second target was slow rather than fast, suggesting that more resource was allocated to the faster of the two targets. This finding was statistically significant only for targets presented in the same hemifield, consistent with the theory of independent resources in the two hemifields. Some limited evidence was also found for resource sharing across hemifields, suggesting that attentional tracking resources may not be entirely hemifield-specific. Together, these experiments indicate that the largely hemisphere-specific tracking resource can be differentially allocated to faster targets.

Keywords Cognitive and attentional control · Divided attention · Object tracking

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Playing a team sport, eluding a group of predators, or taking children to the beach benefits from maintaining attention on multiple moving objects. The multiple-object tracking (MOT) task (Pylyshyn & Storm, 1988) has been widely used to study this process (Cavanagh & Alvarez, 2005; Scholl, 2009). In this task, a number of identical objects are presented and a target subset to be tracked is cued for a few seconds. The cues then disappear, so that the targets are identical to the nontargets, and all objects move about the screen for several seconds. At the end of the trial, all of the objects stop moving, and observers must indicate which objects were the targets. With commonly used display parameters, people typically succeed at tracking up to four or five targets (Alvarez & Cavanagh, 2005; Pylyshyn & Storm, 1988; Yantis, 1992).

The number of objects that people can track varies with the circumstances, and various theories have been proposed to explain the varying limits. Franconeri and his collaborators suggested that spatial interference is the *only* factor that limits the number of targets that can be tracked, writing that "barring object-spacing constraints, people could reliably track an unlimited number of objects as fast as they could track a single object" (Franconeri, Jonathan & Scimeca, 2010, p. 924). Decreases in tracking performance with additional targets were proposed to be due to the cortical representations of two nearby targets interfering with each other (Franconeri, 2013). Specifically, when two targets are close to each other, a suppressive surround of one target may overlap with the spotlight of attention focused on the other target, and vice versa, inducing worse tracking performance for both targets (Franconeri, 2013; Franconeri, Lin, Pylyshyn, Fisher & Enns,

2008). Spatial interference undoubtedly can contribute to the capacity limit when traditional MOT displays are used, because in those displays objects pass very close to each other, which can cause crowding (Intriligator & Cavanagh, 2001; Pelli & Tillman, 2008).

Evidence from widely spaced target configurations has indicated a second reason for the decrease in performance with increasing target loads. Specifically, tracking a target requires allocating some process or entity, of which the brain has a finite amount or number. We will use the term *resource theory* broadly to refer to any such theory positing that tracking targets reduces the process available for other targets. This is in contrast to the spatial-interference theory of Franconeri and colleagues (Franconeri et al., 2010; Franconeri et al., 2008).

The spatial-interference theory of Franconeri et al. (2008) proposes that each target is tracked equally well, regardless of the number of targets, provided that the targets are all sufficiently well separated. The limitation on the number of targets that can be tracked arises due to target–target interactions. These cannot be avoided when there is not enough space in the visual field to keep all of the targets widely spaced.

The "resource" of resource theories may be a finite set of discrete pointers (sometimes called "slots") that are assigned to the targets (Horowitz & Cohen, 2010; Pylyshyn & Storm, 1988) or a continuous pool of mental resource that is divided among the targets (Alvarez & Franconeri, 2007). For the continuous models, there are a number of possibilities for how reducing the resource per target (by increasing the number of targets that one must track) impairs performance. One possibility is that allocating less resource to a target reduces the temporal precision with which each target is tracked. That theory is consistent with the results of Holcombe and Chen (2013), who found that temporal frequency or speed limits on tracking decreased in a situation in which the targets never crossed the paths of the other targets.

Such evidence rules against a Franconeri-style non-resource theory, whereby temporal limits occurred only due to suppression that endures at each location that a target visits, impairing the tracking of targets that enter the area subsequently. Instead, the Holcombe and Chen (2013) finding is more consistent with a resource account.

Another theory that for present purposes is termed a *resource theory* is the serial-switching theory. According to this account, only one slot or spotlight is available to track targets, and it must be rapidly switched among targets for tracking to succeed (Holcombe & Chen, 2013; Tripathy & Howard, 2012; Tripathy, Öğmen & Narasimhan, 2011; but see Howe, Cohen, Pinto & Horowitz, 2010). When more targets are present, then, each target receives proportionally less processing time.

The important point that these resource theories have in common is that adding targets reduces the performance per

target, even if no interactions among targets—creating spatial or temporal interference—occur. In our first two experiments, we validated this prediction of resource theories. We avoided spatial interference among targets by spacing the targets widely, and avoided temporal interference by not allowing the targets to cross paths. We found that performance nonetheless decreased with tracking loads. Evidence for this had already been provided by Holcombe and Chen (2012, 2013), but here we performed additional tests using a display configuration that allowed us to go on and test the possibility of differential allocation of the putative tracking resource.

Under resource theories, it is conceivable that different targets, presented simultaneously, may be allocated different amounts of the resource. With the slot theory, for example, if the resource comprises four discrete tracking slots and two targets are presented, three slots could be devoted to the more-demanding target, with just one slot devoted to the less-demanding one. If the resource is instead a continuously divisible pool, then the more-demanding target might be allocated 75 % of the resource, and the less-demanding target only 25 %. If the resource is instead a unitary focus of attention that is time-shared among the targets, it might visit the more-demanding target more often. In summary, a flexible resource may be differentially allocable among targets, rather than split evenly between them. In our third experiment, we found evidence that this was so.

Previous evidence for variable resource allocation

Although numerous studies have found evidence for an attentional-resource component to tracking, little evidence is available that speaks to the possibility of differential resource allocation. For example, Tombu and Seiffert (2008) found evidence that tracking depends on an attentional resource that is also required when performing auditory tone discrimination. They also found evidence that tracking demands more of this resource when the targets are moving quickly. However, they did not investigate whether one can allocate more of the resource to one target (or one task) than to another.

Indirect support for differential resource allocation was found by Liu et al. (2005). In one of their experiments, half of the targets moved at 1 deg/s, and the other half moved at 6 deg/s. They found that tracking accuracy was the same for both kinds of targets, even though one would expect that if both received equal resources, accuracy would be poorer for the faster targets. This was a null result, however, and one they did not discuss or follow up.

Experiments by Iordanescu, Grabowecky and Suzuki (2009) also yielded some data that were interpreted as supporting differential resource allocation. Their observers

viewed a number of moving discs and were asked to track a subset of them. All of the discs were colored, and each target was a different color. The objects moved about randomly, and at the end of the trial, all of the discs disappeared and the observers were asked to indicate the final location of a particular target (e.g., the red one). Observers were more accurate at indicating the final location of a target when it was located near distractors. Iordanescu et al. suggested that this occurred because more resource is devoted to targets when they are near distractors. But because they did not directly manipulate proximity, but rather relied on random movements, other display characteristics may have differed when the targets and distractors were near. Furthermore, two other studies have failed to replicate this finding (Howard & Holcombe, 2008; Howard, Masom & Holcombe, 2011). The reasons for these failures to replicate are unclear, particularly as the experiments by Howard et al. (2011) used a stimulus paradigm very similar to that employed by Iordanescu et al.

Howe et al. (2010, Exp. 8) performed a more direct test of whether the tracking resource could be differentially reallocated between targets during tracking. In their displays, each object would repeatedly pause, so that it was moving for only half of the tracking period. In the simultaneous condition, all of the objects moved and paused simultaneously (i.e., synchronously). In the sequential condition, the objects were divided into two groups, each with an equal number of targets, and the two groups moved in alternation. When the objects in one group were moving, those in the other group were stationary. The rationale was that when an object was not moving, it would require less tracking resource (Alvarez & Franconeri, 2007; Bettencourt & Somers, 2009), and more resource could thus be allocated to the moving objects. Since fewer objects were moving at any one time in the sequential condition than in the simultaneous condition, it was expected that tracking performance would be greater in the sequential condition. In fact, the tracking performance was equal for the two conditions, suggesting that the tracking resource could not be dynamically reallocated between the targets. But, to benefit performance in the Howe et al. study, any unequal distribution of resources would have to be reversed at the rate of the movement alternation. Perhaps participants *could* allocate a resource unequally but could not change this resource allocation rapidly. Using a constant difference in speed, our Experiment 3 tested for the possibility of allocating more resource to the faster target.

Hemisphere specificity

The factors that limit tracking, such as target speed and number, appear to operate largely independently in the left and right visual fields, suggesting that if a resource does mediate tracking, then two independent pools exist, one in each cortical hemisphere. Alvarez and 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 was not significantly affected when the second target was presented in the opposite hemifield. This suggests that the resource consumed by additional targets is hemisphere-specific.

A concern with the Alvarez and Cavanagh (2005) finding is that some or all of the decrease in performance with additional targets may have reflected spatial interference rather than resource depletion. In the Alvarez and Cavanagh study, the objects could pass very close to each other. Since spatial interference (crowding) is known to be greater when objects are presented unilaterally rather than split across hemifields (Liu, Jiang, Sun & He, 2009), the observed decrease in tracking performance when the targets were presented unilaterally might have been due to spatial interference.

Holcombe and Chen (2012) addressed this issue by using a display in which the objects were kept widely separated to avoid crowding. After finding the maximum speed at which observers could track one target, the researchers tested how this speed limit was affected when observers were asked to track an additional target. The speed limit decreased substantially if both targets occupied the same hemifield. If the second target was instead placed in the opposite hemifield, however, little decrement in the speed limit occurred. This supports the original claim of attentional resources that are independent in each hemisphere. Here we investigated whether the hemisphere-specific resource can be differentially allocated, by comparing the effects of targets of differing speeds placed in the same hemifield or in opposite hemifields.

The resource-versus-performance function

If tracking does require an attentional resource, how much resource is needed for successful tracking of a single target? Answering this question fully would mean quantifying the function that maps the proportion of the resource allocated to a target onto percentage correct. This resource-versus-performance function (Fig. 1) relates the proportion of attentional resource devoted to a target to the likelihood of getting it correct (Norman & Bobrow, 1975).

Ideally, we would measure the resource-versus-performance function by asking participants on different trials to allocate different proportions of their attention to each of two targets—90 %:10 %, 80 %:20 %, 70 %:30 %, and so forth. While that may be a valid method for simple judgments regarding briefly presented stimuli (Bonnel & Miller, 1994; Lee, Koch & Braun, 1999; Pastukhov, Fischer & Braun, 2008), we believe it would
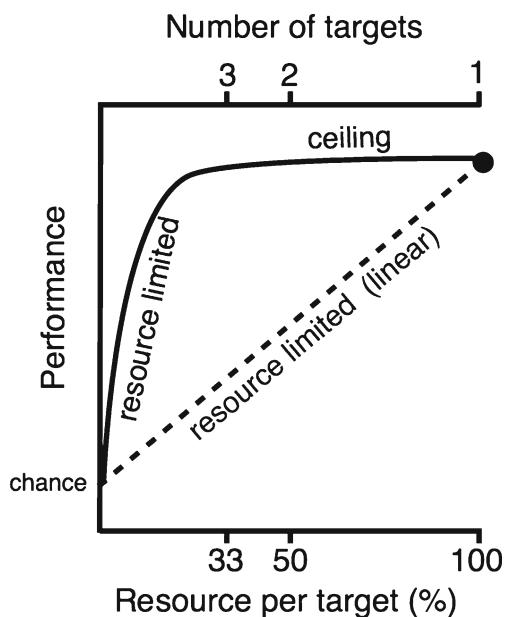
Fig. 1 Hypothetical performance-versus-tracking-resource functions. The dashed line shows a linear function relating the proportion of the tracking resource (and the corresponding number of targets, top axis) to performance. This is a candidate function based on our results for fast speeds, but for slow speeds the function is believed to be more like the solid curve. The relatively flat right portion of the solid curve indicates that when attention is divided among a few targets, there is little cost for performance, as has been documented by ourselves and others. Only when many targets are tracked (leftmost, steep part of the curve) do additional targets impose a significant cost for performance

be difficult to induce participants to allocate a particular proportion of attention to two targets throughout a tracking trial.

Participants commonly report that they know when they fail to maintain their attention on a particular target for tracking. These reports are validated by the empirical success of the method of adjustment in tracking studies (Verstraten, Cavanagh & Labianca, 2000; Vul, Frank, Tenenbaum & Alvarez, 2009), which requires that participants recognize when they succeed or fail to track the designated targets. Using this knowledge, during a trial, participants may shift the resource formerly used for a lost target to one of the other targets. It seems unlikely that, even if they were explicitly instructed to allocate (say) 30 % of their resources to a target, that upon losing the other target the participant would leave 70 % of their resources thereafter unused. In a further complication, toward the beginning of a trial, participants may recognize that the targets' speeds are too fast for all of them to be tracked, and then shift all of the attentional resource toward a subset of the targets. These possibilities of strategic allocation and reallocation depending on the characteristics of targets may make it difficult to enforce a particular allocation proportion.

We can nevertheless glean some limited information regarding the resource-versus-performance function. Two

points on the function are already specified by the definition of resource theory. When only one target is tracked, 100 % of the resource is devoted to it and performance is at maximum. When no resource is available per target (effectively, when a very large number of targets are specified), performance should be at or very near chance.

The simplest possible resource-versus-performance function would then connect these two points with a straight line, which we will refer to as the *linear resource function* (see Fig. 1). This linear function then predicts that when two targets are tracked (50 % resource is allocated to each target), performance will be approximately halfway between the one-target level and chance.

In the literature on simple psychophysical judgments of briefly presented stimuli, data supporting an approximately linear performance-versus-resource function was found for several concurrent-discrimination tasks by Braun and colleagues (Lee et al., 1999; Pastukhov et al., 2008).

A different resource function for tracking was proposed by Horowitz and Cohen (2010). Horowitz and Cohen assessed participants' ability to report, after the display had stopped, the direction that tracked targets had been moving. They found evidence that performance matched the resource function predicted from a noisy independent-samples model of the resource. Specifically, the theory was that resource improves performance by improving the precision of tracking in the same way that increasing the number (n) of noisy samples taken from a distribution improves the precision (standard deviation) of the estimate of the mean. Specifically, the standard deviation improves with the square root of n. Note that the dependent variable in the Horowitz and Cohen analysis was the standard deviation of the reports of targets' final motion directions.

The relationship between precision and proportion correct in tracking targets is uncertain. If this relationship is linear, the noisy independent-samples theory predicts that proportion correct will increase with the square root of n, as schematized in Fig. 2. The corresponding curve (dashed line) in the graph is simply that for which performance grows in proportion to the square root of the resource, with the additional constraints that zero resource yields chance performance and 100 % resource yields the one-target performance. We do not favor this theory (see the General Discussion), but it usefully provides a competing possible resource-versus-performance function. Moreover, for a length discrimination task, some evidence for this linear relationship between proportion correct and the resource allocated was found by Bonnel and Miller (1994), and such a relationship was considered for short-term memory by Zhang and Luck (2008).

In this article, we will only be able to assess the performance-versus-resource function empirically at the 50 %-resource (two-target) point. We found that at slow speeds,
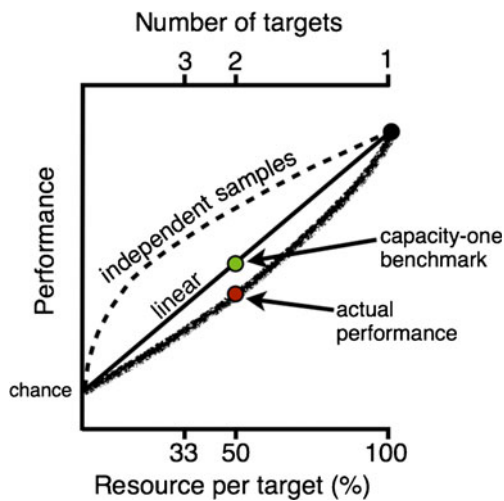
Fig. 2 Hypothetical performance-versus-tracking-resource functions for fast object speeds. Experiments suggest that for fast object speeds, there is always a cost of adding additional targets, and the curves shown here are all consistent with that finding. The dashed line shows a prediction based on an independent-samples idea, so that performance increases with the square root of the resource applied. Because at fast speeds we have found that performance falls at or below the capacity-one benchmark (results here and of Holcombe & Chen, 2012, 2013), the resource required for successful tracking is higher even than is shown by the linear resource function. The shape of the function is unknown, but one possibility is shown by the coarse fuzzy line

performance exceeded both the linear and independent-samples function, whereas the function was very different for fast speeds. For fast speeds, performance fell at or below the linear function (as schematized in Fig. 2). This implies that participants did no better at fast speeds than if they had tracked only one target and ignored the other, as we explain below.

The capacity-one performance benchmark

The capacity-one performance benchmark, first described by Holcombe and Chen (2012; which they termed the *capacity-one model*), calculates the performance level expected if participants track only one target and completely ignore the second. This puts any cost of splitting attention in perspective by comparing the cost to what would occur if participants could only track one object. The rationale is that if participants track only one object, then on half of the trials their performance will be the same as in the one-target condition, and on the other half of trials they will guess.

For the present experiments, the capacity-one performance benchmark yields the same performance level as the linear performance-versus-resource function (Fig. 2). Therefore, when empirical performance falls to this level (as we found for high target speeds), we cannot say whether it is because the linear function is correct or because participants only tracked a single target. It may be that at high

speeds the resource requirement for successful tracking is even greater than that indicated by the linear function, and participants switch to tracking only one target, as that yields better performance than attempting to track both.

The present experiments

In the first two experiments, we sought to confirm that with the present display configuration, a hemifield-specific resource mediated tracking. After finding support for this hypothesis, we then conducted an experiment to test whether more resource was allocated to the faster of two targets.

As we described in the Hemisphere Specificity section above, Holcombe and Chen (2012) found evidence for the hemisphere specificity of the resource in their Experiment 3. In that experiment, however, the durations of the trials did not differ for different speeds, meaning that for trials testing fast target speeds, the targets traveled much farther than they did on slow-speed trials. Franconeri et al. (2010) pointed out that with this type of design, high-speed trials may be associated with more spatial interference because the targets pass relatively near each other on more occasions. In the Holcombe and Chen (2012) display configuration, the objects were always far from each other, so this explanation seems unlikely, but nevertheless we sought to exclude it here. In Experiments 1 and 2, we therefore equated the distance traveled across speeds. The results supported the hemifield-specific resource theory, so in Experiment 3 we proceeded to investigate the possibility of differential allocation of the resource.

Experiment 1: Testing the hemifield specificity of the tracking resource

Holcombe and Chen (2012) in their Experiment 3 found that the maximum target speed that could be tracked (68 % threshold) with two targets in a hemifield was no better than would be expected if participants had ignored one of the targets and simply guessed whenever it was probed (the capacity-one performance benchmark). An alternative theory that makes the same prediction is that the resource-versus-performance function is linear. These explanations suggest that successful tracking (>68 % accuracy) at high speeds requires more than 50 % of the resource.

An alternative explanation is that performance was much worse for the two-target condition at high speeds because of spatial interference between the targets. The opportunity for spatial interactions may have been higher when the stimulus was presented at high speeds, as it traveled farther during the trial (Franconeri et al., 2010). If, instead, we were to equate the distance traveled for different speeds, the putative

spatial interference should not be higher at faster speeds. According to the spatial-interference theory, then, the two-target speed limit cost associated with additional targets should be much reduced or disappear.

Method

Five participants (four male, one female, 24–31 years of age) who reported normal or corrected-to-normal vision agreed to participate, following approval of the protocol by the University of Sydney's ethics committee. One of these participants was the first author. All had extensive experience fixating in laboratory experiments.

A 120-Hz CRT displayed eight 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 eyes. The spatial arrangement of the discs is schematized in Fig. 3. Four pairs of discs were presented in all conditions. Each pair moved on a circular trajectory centered in one of the four quadrants of the visual field. The circular trajectories were centered on points 6 deg from the vertical midline and 6 deg from the horizontal midline (representing the centers of the four quadrants). The radius of each trajectory was 2.5 deg of visual angle, and because the two discs on a trajectory were always diametrically opposed, the separation between them was always 5 deg of visual angle. These distances should be large enough to avoid crowding among the objects (Intriligator & Cavanagh, 2001; Pelli & Tillman, 2008).

To indicate which discs were targets, for the first 0.7 s of the motion interval, the color of the targets was white instead of red. Following this was the tracking period, during which all of the objects were red. To prevent participants from predicting the final target positions from their initial positions and speeds, the discs occasionally reversed direction. Each pair of discs was independently assigned a series of reversal times, which succeeded each other at random intervals between 1.2 and 2 s. This resulted in more reversals for trials that had slow speeds. At the end of the trial, one pair of discs was indicated, and the participants used the mouse to indicate which of the two discs was the target.

In the four-targets condition, one disc of each pair was designated as a target to be tracked. In the two-targets bilateral condition, the two target pairs were both above the fixation point in half of the trials and both below in the other half. In the two-targets unilateral condition, the two target pairs were either both to the left or both to the right of the fixation point (Fig. 3).

To avoid the possibility of more opportunities for spatial interference at higher speeds, the cumulative distance traveled by the discs was the same for all trials. This was achieved by setting the duration of the trial to a different value for each speed condition. All objects revolved about fixation at the same rate. Across trials, five rotation speeds (0.7, 1.0, 1.4, 1.7, and 2.2 revolutions per second) were used, and to achieve a constant distance traveled of 6.6 revolutions, this yielded five corresponding tracking durations (9.4, 6.6, 4.7, 3.9, and 3 s).

Each observer participated in 160 trials for each of the five rates, yielding 800 experimental trials in total, divided into five sessions. Conditions were mixed; each observer performed in no more than two sessions a day, and the observers had a minimum break between sessions of 5 min.

Fig. 3 Schematic of the displays in Experiments 1 and 2. Four pairs of red discs were presented in each condition. Each pair moved along a circular trajectory (dotted lines) centered in one quadrant and potentially included a target. The targets were presented in one of three conditions: two targets to the left or the right side of the vertical meridian (two-target unilateral), two above or below the vertical meridian (two-target bilateral), or four targets, with one in each quadrant (four-target). The targets were initially white, before becoming red like the distractors
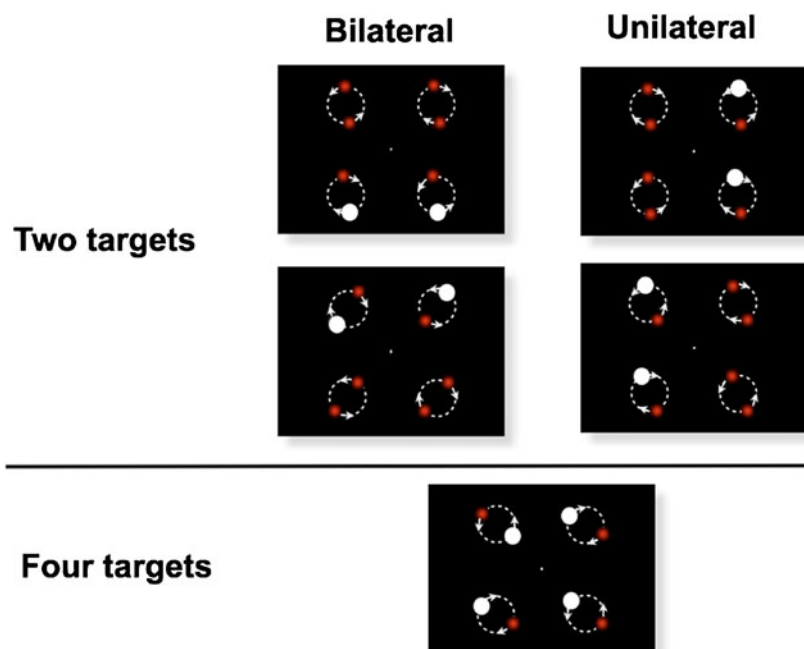
Data analysis Plots of speed versus proportion correct were fit by a logistic regression that spanned from chance (50 % accuracy) to a ceiling level of performance. The ceiling performance corresponded to the lapse rate, which in the fitting procedure was allowed to vary from 1 % to 10 % to get the best estimate. This estimated lapse rate for each condition is reported in the Results section. We refer to the speed at which performance was estimated by the regression to fall to 68 % correct as the "speed limit." The regression was fit separately for each participant and condition in order to estimate the speed limits.

Holcombe and Chen (2012) calculated the expected effect on speed limits of increasing the number of targets, under the seemingly worst-case assumption that observers could track only one target per hemifield and had to guess on the trials in which they were queried about the untracked target. In fact, this capacity-one performance benchmark is not the worst-case scenario, because the resource-versus-performance function might fall below the linear function (Fig. 2). In that case, if participants were to attempt to track both targets, performance would fall below the capacity-one benchmark.

Calculation of the prediction of the hemisphere-specific capacity-one performance benchmark in the present circumstances proceeded as follows. In each visual hemifield, it was assumed that the observer would track only one target. Thus, in half of the trials the observer would by chance have tracked the target in the pair that was queried. For these trials, the performance for that speed was provided by the bilateral two-target logistic curve fit, as this corresponds to the situation in which there is only one target in each hemifield. On the other half of the trials, the observer would have been queried about one of the pairs that he had not tracked. Consequently, the observer would be forced to guess which of the two discs was the target, and therefore would perform at chance (50 %). From the resulting psychometric function, we can extract the benchmark's speed limit (68 % threshold) for the four-target condition. This benchmark speed limit is shown as the upper dashed bar at the bottom of Fig. 4.

For slow target speeds, the actual performance for tracking two targets was higher than the capacity-one benchmark, in the present data as well as in those of Holcombe and Chen (2012, 2013). This shows that at slow speeds, participants can track more than one target in each visual hemifield. At high speeds, however, actual performance was similar to the benchmark. In their previous assessment of the speed at which performance fell to the "speed-limit" level of performance (68 % correct), Holcombe and Chen (2012) found that the capacity-one benchmark speed limit was not significantly different from that of the humans. This indicates that participants did no better than they would have if they had tracked just a single target in each visual hemifield.

If anything, the observed speed limits here were even worse than those of the capacity-one benchmark (this

statistically nonsignificant trend was also observed by Holcombe & Chen, 2012, and Holcombe & Chen, 2013). This indicates that devoting half of the resource to a target yields only very poor performance for each target. If dividing one's resource between the targets frequently results in failure to successfully track any of them, one would be better off attempting to track only one, which might be the strategy that participants sometimes adopted.

An alternative, and unlikely, hypothesis, but an instructive one for the contrasting prediction that it makes, is that observers track objects independently in the upper and lower visual hemifields (UVF and LVF, respectively), and can only track one in each. For this UVF/LVF capacity-one benchmark, in the four-target condition, performance on half of the trials would be given by the unilateral two-target condition, and by the chance level on the other half of trials. This benchmark's speed limit is shown by the lower dashed bar at the bottom of Fig. 4.

Results and discussion

The data and fitted curves are shown for each participant in the top panel of Fig. 4, with the associated speed limits (68 % thresholds) shown in the bottom panel. For two targets, consistent with the hemisphere-specific resource theory, the speed limit was better in the bilateral arrangement (2.05 revolutions per second [rps], 32.21 deg/s) than in the unilateral arrangement (1.59 rps, 24.98 deg/s). This difference was statistically significant according to a paired t test, $t(4) = 3.557$, $p = 0.024$, Cohen's $d = 2.572$.

Also as predicted by the hemisphere-specific resource theory, as compared to the speed limit for tracking two targets in a single hemifield, adding two more targets in the opposite hemisphere had no significant effect on the speed limit (1.59 vs. 1.50 rps), $t(4) = 1.85$, $p = 0.138$, Cohen's $d = 0.888$.

Relative to having one target in both the left and right hemifields, tracking a second target in each hemifield was expected to halve the resource available per target, reducing performance. Consistent with this prediction, the requirement to track an additional target significantly reduced the speed limit. The speed limit decreased from 2.05 rps (32.21 deg/s) to 1.50 rps (23.57 deg/s), $t(4) = 3.329$, $p = 0.029$, Cohen's $d = 1.702$. This cost (0.5 rps, 7.86 deg/s) was significantly larger than the (nonsignificant) cost of adding targets in the opposite hemisphere described in the previous paragraph (0.09 rps, 1.41 deg/s), as indicated by a paired t test on the speed limit differences, $t(4) = 3.557$, $p = 0.024$, Cohen's $d = 2.572$.

The nonsignificant trend for a poorer speed limit in the four-target condition (1.50 rps) than in the unilateral two-target condition (1.59 rps) suggests that in the latter condition, both the ipsilateral and contralateral hemispheres might have contributed to tracking the targets. A similar nonsignificant effect was observed in Experiment 3 of Holcombe
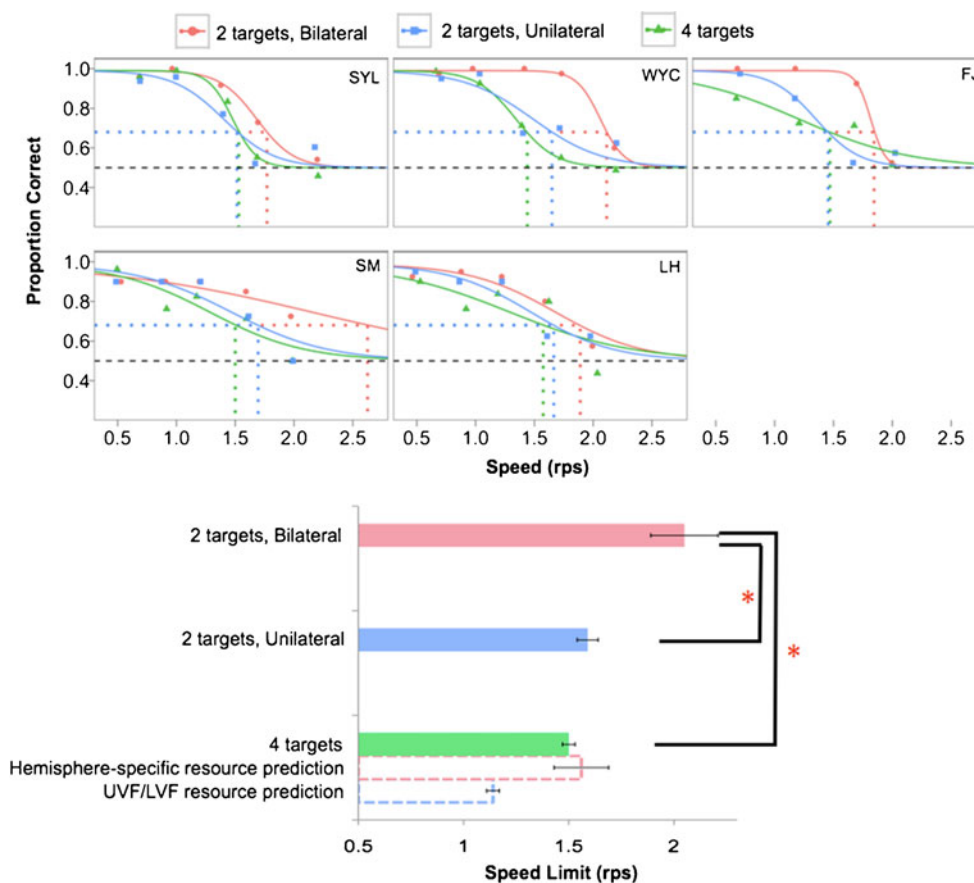
Fig. 4 Results of Experiment 1. (Top) For each participant, proportions correct are shown for each speed in the two-target bilateral (red), two-target unilateral (blue), and four-target (green) conditions. Dotted lines show the 68 % thresholds (speed limit). (Bottom) Empirical speed limits for tracking two and four objects are shown as solid bars, and the capacity-one model predictions for four targets are shown as dashed bars. At slow speeds, performance exceeds the 75 %-correct performance of the hemisphere-specific capacity-one benchmark. A high speeds (the speed limit), the data are consistent with participants being able to track only one target in each hemifield and having to guess on the other (the hemisphere-specific capacity-one benchmark, red dashed bar). In contrast, the data are not consistent with the prediction of the upper- and lower-visual-hemifield (UVF/LVF)-specific resource capacity-one performance benchmark (blue dashed bar). Error bars show one standard error across participants

and Chen (2012). These nonsignificant trends suggest that the tracking resource may not be 100 % hemisphere-specific.

So far, we have considered only the simple qualitative prediction of hemisphere-specific resource theory—that adding targets to the opposite hemifield will have no effect, whereas adding targets to the same hemifield impairs performance. Given that same-hemifield targets appear to load on the same resource, the question arises of how much resource is needed to accurately track a target. This cannot be measured directly, but we can compare performance to the prediction of the linear resource-versus-performance function (the linear function in Fig. 2). The capacity-one performance benchmark makes the same prediction for the cost of adding a second target, that performance will fall halfway to chance.

At low target speeds, performance is clearly much better than the capacity-one performance benchmark. Indeed, at very low speeds participants' performance is near 100 % correct. The estimated lapse rate for the four-target condition is 0.04, suggesting that the psychometric function saturates at 96 %. If participants could only track one object in each hemifield (the capacity-one performance benchmark), performance should never exceed 75 % correct for four targets. This indicates that participants are capable of tracking all four objects when they move slowly.

Assuming that they did not ignore any of the targets, the performance level provides some information about the performance-versus-resource function. Reducing the resource available for a target from 100 % (one target per hemifield) to 50 % (two targets per hemifield) has little effect on performance. The first reaction of many expert readers may be that this is a ceiling effect. That is our point. At slow speeds, tracking is very accurate (near ceiling), whether 50 % or 100 % of the resource is used (flat resource-vs.-performance function in this domain).

For high target speeds, we suspected that tracking would be resource-intensive, meaning that adding a target to each hemifield would be costly. To put any speed limit cost in perspective, we calculated the speed limit of the capacity-one performance benchmark. This hemisphere-specific capacity-one benchmark speed limit is shown by the upper dashed bar at the bottom of Fig. 4. The measured speed limit for tracking four targets (1.50 rps, 23.57 deg/s) was not significantly different from the benchmark (1.57 rps, 24.67 deg/s), as was revealed by a paired t test, $t(4) = 0.398$, $p = 0.711$, Cohen's $d = −0.182$. Performance at these high speeds then was as bad as if participants simply ignored the second target in each hemifield.

We cannot tell whether participants indeed only attended to a single target in each hemifield or instead attempted to track both and had a linear resource-versus-performance function. These results do suggest, however, that the true resource-versus-performance function is linear or lies below the linear function. The reason is that, presumably, participants would not act against the instructions and ignore the additional target unless tracking was so resource-intensive that devoting only 50 % of the resource to a target yielded worse performance than tracking only one.

The large speed limit cost of the additional target in each hemifield does not particularly support the spatial-interference theory described in the introduction. Because the objects were always widely spaced, it seems that spatial-interference theory would predict only a small effect on speed limit, if any.

As a further validation of the hemisphere-specific resource theory and the resemblance of the results to the capacity-one performance benchmark, we document here how discrepant the results are from the alternative assumption that observers tracked objects independently in the upper and lower hemifields, and within each only one target could be tracked. We call this the *UVF/LVF resource capacity-one performance benchmark* (lower dashed bar in Fig. 4). As we described in the Method section, this amounted to calculating a benchmark four-target speed limit using the performance in the two-target unilateral arrangement and combining it with guessing on half of the trials. As is shown in Fig. 4, this UVF/LVF resource benchmark's speed limit (1.14 rps, 17.91 deg/s) was significantly lower than the measured four-target speed limit (1.50 rps, 23.57 deg/s), paired $t(4) = 8.506$, $p = 0.001$, Cohen's $d = 3.804$, suggesting that the tracking resources are not specific to the UVF and LVF.

According to spatial-interference theory (Franconeri et al., 2010; Franconeri et al., 2008), the detrimental effects of additional targets should be equivalent across speeds if the total distance traveled by the objects is constant. Therefore, performance should be worse even at slow speeds in the four-target condition than in the two-target bilateral condition. This would manifest as an increase in the

lapse rate parameter in our psychometric function fit. This parameter represents the ceiling performance level. If spatial interference among targets impairs tracking, it should reduce accuracy more for conditions with higher numbers of targets, thus inflating their lapse rates relative to those conditions with fewer targets.

A repeated measures analysis of variance (ANOVA) was conducted, with conditions and subjects as the independent variables and lapse rate the dependent variable. We found no significant differences among the three conditions: two-target bilateral (lapse rate = 0.04), two-target unilateral (lapse rate = 0.05), and four-target (lapse rate = 0.03), $F(2, 8) = 0.288$, $p = 0.757$, $\eta_p^2 = 0.067$. These results argue against significantly greater spatial interference when more targets are tracked.

Hemifield independence was also tested by Experiment 3 of Holcombe and Chen (2012), but the lapse rates were not reported, as the article was a brief report. For completeness, we report them here. Contrary to what would be expected according to spatial interference, the lapse rate was higher in one of the one-target conditions than in either of the two-target conditions. In a repeated measures ANOVA, we found a significant effect of target number [$F(1, 7) = 6.462$, $p = 0.039$, $\eta_p^2 = 0.48$], but no significant effect of hemifield arrangement [$F(1, 7) = 4.036$, $p = 0.084$, $\eta_p^2 = 0.366$] and no interaction between target number and hemifield arrangement [$F(1, 7) = 1.194$, $p = 0.311$, $\eta_p^2 = 0.146$]. The significant effect of target number arose from slightly higher lapse rates in tracking one rather than two targets: one-target bilateral (lapse rate = 0.06), one-target unilateral (lapse rate = 0.03), two-target bilateral (lapse rate = 0.03), and two-target unilateral (lapse rate = 0.02).

Experiment 2: Eyetracking and constant number of reversals

This experiment was motivated primarily by a concern with Experiment 1: Participants may not have maintained accurate fixation on the fixation point. To address this concern, in the present experiment we recorded eye movements with an eyetracker.

A second point is that in Experiment 1, for trials with lower speeds, the number of reversals was greater. Therefore, it is uncertain to what extent the detrimental effect of increased speed was due to speed per se rather than to fewer reversals (if reversals might somehow have benefited performance). To resolve this issue, in Experiment 2 we equated the number of reversals across speeds.

Method

Six participants (four male, two female, 22–37 years of age) 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, and another three had also participated in Experiment 1.

The apparatus, stimuli, and procedure used were identical to those of Experiment 1, except for the addition of the eyetracker and the changes in the reversal times. During the 6.6 revolutions of cumulative distance traveled by the blobs after the target-cuing interval, the blobs changed direction at random successive points between 2.2 and 3 revolutions, resulting in two to three reversals per trial. The direction changes for each ring were determined randomly and independently of those for other rings. Each observer participated in 48 trials at each of the five speeds. This was fewer trials than in Experiment 1, to accommodate the eyetracker calibration and recalibration time. The speeds for individual observers were chosen on the basis of piloting. The tracking durations were set to achieve a constant distance traveled of 6.6 revolutions. Observers were presented with 240 experimental trials in total, divided into two sessions performed over two separate days.

Eye movements were monitored using an SR Research EyeLink 1000 eyetracker and analyzed with the EyeLink 1000 software, version 1.5.2. At the beginning of each session, the eyetracking system was calibrated and validated using the standard five-point calibration. The experimenter monitored the video image of the participant's eye at the beginning of each trial to ensure that the participant fixated and that the eyetracker continued to report this correctly. The eyetracker was recalibrated if, during the interval before the trial, it registered the participant's eye location as being away from fixation, even though the participant reported fixating. If the eyetracker indicated that the participant moved his or her eye by more than 2 deg of visual angle from the fixation point, the trial was discarded.

Results and discussion

The criterion of eye movement greater than 2 deg from fixation led to the exclusion of 8.3 % of the trials ($SD = 3.3$ % across participants). A repeated measures ANOVA revealed no significant difference in the numbers of these eye movements across the five speeds, $F(4, 20) = 2.146$, $p = 0.113$, $\eta_p^2 = 0.3$, or the three conditions (two-target bilateral, two-target unilateral, and four-target), $F(2, 10) = 1.677$, $p = 0.235$, $\eta_p^2 = 0.25$. The ANOVA also showed no significant interaction between speed and condition, $F(8, 40) = 0.539$, $p = 0.82$, $\eta_p^2 = 0.097$.

The data and fitted curves are shown for each participant in the top panel of Fig. 5, with the associated speed limits (68 % thresholds) shown in the bottom panel. As in Experiment 1, the speed limit was considerably higher in the bilateral arrangement (1.89 rps, 29.69 deg/s) than in the unilateral arrangement (1.64 rps, 25.76 deg/s) for tracking two targets. This difference was statistically significant according to a paired t test, $t(5) = 4.233$, $p = 0.008$, Cohen's $d = 2.45$.

Consistent with the hemisphere-specific resource theory, as compared to the speed limit for tracking two targets in a single hemifield (two-target unilateral condition), adding two more targets in the opposite hemifield (four-target condition) had little to no effect on the speed limit (1.64 vs. 1.72 rps), paired t test $t(5) = -1.375$, $p = 0.228$, Cohen's $d = -1.17$. But, as compared to the speed limit in the two-target bilateral condition (1.89 rps, 29.69 deg/s), the speed limit for the four-target condition was significantly lower (1.72 rps, 27.02 deg/s), paired t test $t(5) = 8.307$, $p<0.001$, Cohen's $d = 3.784$.

The capacity-one performance benchmark puts these speed limit differences in perspective by calculating the result that would occur if participants only tracked one target in each hemifield and ignored the other. The ensuing capacity-one speed limit is shown by the upper dashed bar at the bottom of Fig. 5. As occurred in Experiment 1, the measured speed limit for tracking four targets (1.72 rps, 27.02 deg/s) was not significantly different from that of the capacity-one performance benchmark (1.74 rps, 27.34 deg/s), paired t test $t(5) = -0.603$, $p = 0.573$, Cohen's $d = -0.266$. This is consistent with the possibility that the tracking resource in each hemisphere was only sufficient to track one fast target in each hemifield.

As we did for Experiment 1, to further validate the hemisphere-specific resource theory, we document here how discrepant the results are from the alternative assumption that observers tracked objects independently in the upper and lower hemifields and that, within each, only one target could be tracked (UVF/LVF resource benchmark). Here we see the lone statistical difference from Experiment 1—the discrepancy of the observed speed limit (1.72 rps, 27.02 deg/s) from the prediction (1.52 rps, 23.88 deg/s) did not reach significance, although the effect was in the expected direction, paired $t(5) = 2.119$, $p = 0.088$, Cohen's $d = 1.414$ (Fig. 5). This may reflect the reduced power of this experiment—mainly because of the additional time demands of eyetracking, it included only 30 % as many trials per participant as had Experiment 1.

Experiment 3: Resource allocation between two targets of different speeds

According to resource theory, different amounts of resource might be allocated to different targets in a demand-based manner. This possibility was tested in Experiment 3 by comparing the speed limits at which observers could track a particular disc (the "critical target") under two conditions, in both of which the observer was required to track a total of two targets. In the "other-slow" condition, the second target

Fig. 5 Results of Experiment 2. (Top) For each participant, proportions correct are shown for the two-target bilateral (red), two-target unilateral (blue) and four-target (green) conditions. Dotted lines show the 68 % thresholds (speed limit). (Bottom) Empirical speed limits for tracking two and four objects are shown as solid bars, and capacity-one benchmark limits for four targets are shown as dashed bars. At slow speeds, performance exceeds the 75 %-correct performance of the hemisphere-specific capacity-one benchmark. At high speeds (the speed limit), the data are consistent with participants being able to track only one target in each hemifield and having to guess on the other (the hemisphere-specific capacity-one benchmark, red dashed bar). Error bars show one standard error across participants
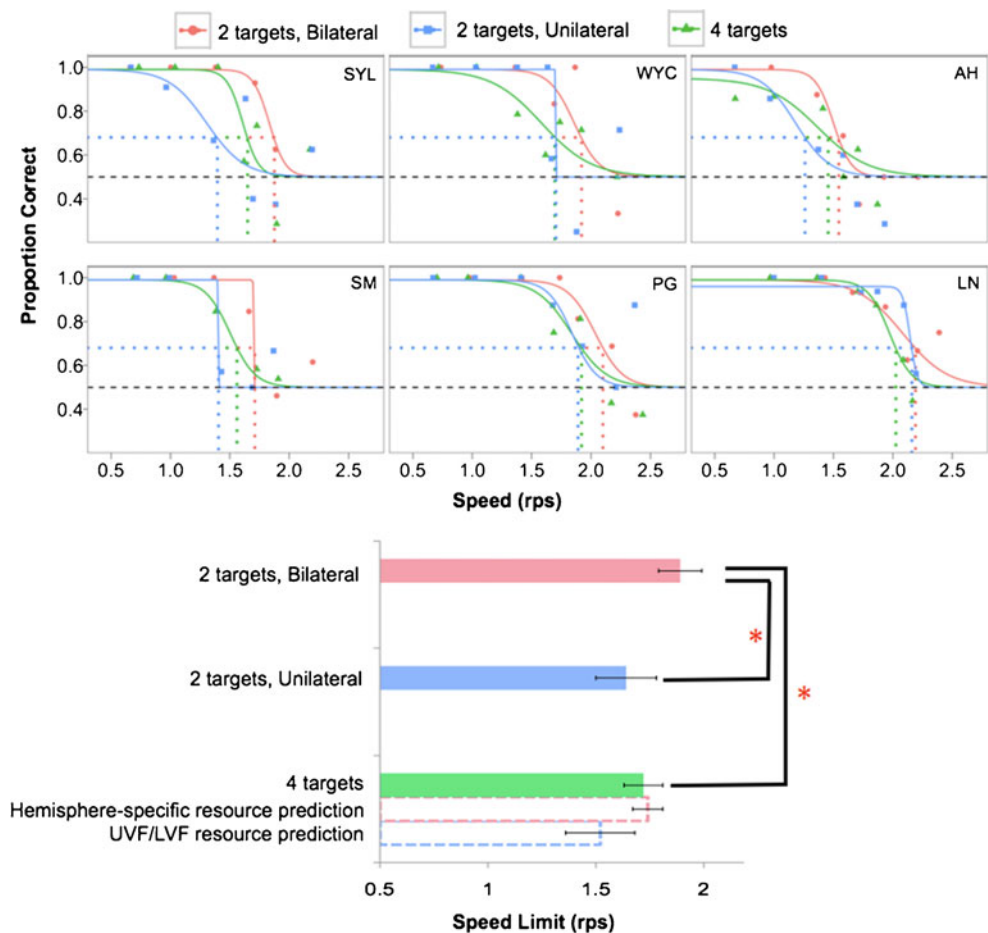
moved at a slow speed of 0.5 rps, whereas in the "same-speed" condition, the second target moved at the same speed as the critical target.

We reasoned that because in the other-slow condition the second target was slow, less resource would be needed to track it. This should leave more resource for the critical first target, allowing it to be tracked at a faster speed, provided that the attentional resource can be allocated unequally. Because the resource pools operate independently for the left and right visual hemifields, we predicted that an improved speed limit for the other-slow condition would only occur for the unilateral arrangement, not the bilateral arrangement.

Method

Seven participants (six male, one female, 27–32 years of age) who reported normal or corrected-to-normal vision agreed to participate in the protocol, which was approved by the University of Sydney's ethics committee. One of the participants was the first author.

The apparatus and stimuli used were identical to those of Experiment 1, except for a few changes described here. Whereas in Experiment 1 either two or four discs were cued as targets, here in Experiment 3, two discs were always

cued, one in each of two quadrants (Fig. 6). In the same-speed condition, the two targets moved with equal speeds,
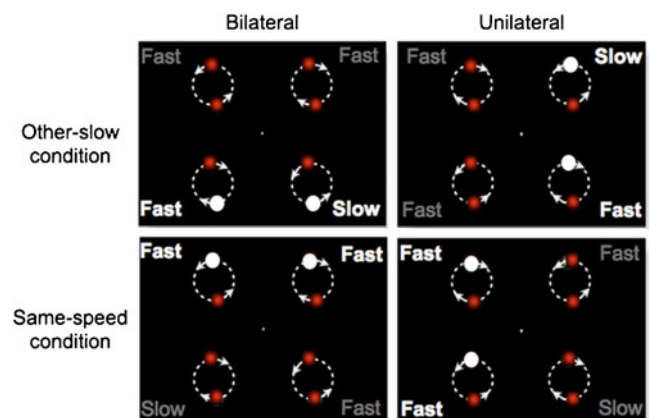

Fig. 6 In Experiment 3, four pairs of red discs (Gaussian blobs) were presented in each condition. Each pair moved along a circular trajectory (dotted lines) centered in one quadrant. A disc from each of two of the pairs was designated as a target. For the bilateral arrangement, the targets (cued in white) were both above or both below fixation, whereas for the unilateral arrangement, both targets were to the left or to the right. In the other-slow condition, one target always moved slowly (0.5 rps). In the same-speed condition, the two targets moved at the same speed (which varied across trials)

which varied across trials from 0.9 to 2.1 rps. In the other-slow condition, the critical target moved at a speed between 0.9 and 2.1 rps, and the slow target always moved at 0.5 rps. As in Experiment 1, at the end of the trial one pair of discs was indicated, and the participants used the mouse to indicate which of the two discs was the target. Both targets were equally likely to be queried.

As in Experiment 1, both bilateral and unilateral arrangements were used (Fig. 6). For the bilateral arrangement, in half of the trials the targets were both above the fixation point, and in the other half, both were below the fixation point. For the unilateral arrangement, in half of the trials the targets were both to the left of the fixation point, and in the other half, both were to the right of the fixation point.

The sequence of events was identical to that of Experiment 1, but there was a difference in how the duration of the trials was set. The total tracking interval varied randomly between 3.0 and 3.8 s. Because the targets during the same trial could have different speeds, their travel distances were necessarily different. At the end of a trial, one pair of discs was indicated by a central arrow, and participants were prompted to use the mouse to indicate which was the target. Each observer participated in 128 trials for each of the five speeds. Observers were

presented with 640 experimental trials in total, divided into four sessions. Each participant performed no more than two sessions a day and had a minimum break between sessions of 5 min. The data were analyzed as in Experiment 1, with speed limits (68 % thresholds) extracted from the psychometric curve fit.

Results and discussion

For each participant, the data and the associated psychometric curves are shown in Fig. 7 for the same-speed versus the other-slow condition and for the unilateral versus bilateral arrangements. When the participants tracked two moving targets with equal speeds (same-speed condition), performance was better for the bilateral arrangement than for the unilateral arrangement. In a paired t test for the same-speed condition, we found that across the seven participants, the speed limit for the bilateral arrangement (1.98 rps, 31.11 deg/s) was significantly higher than that for the unilateral arrangement (1.62 rps, 25.45 deg/s) [$t(6) = 4.549$, $p = 0.004$, Cohen's $d = 1.897$; see the bottom right panel of Fig. 7], further supporting the hemisphere-specific resource theory.
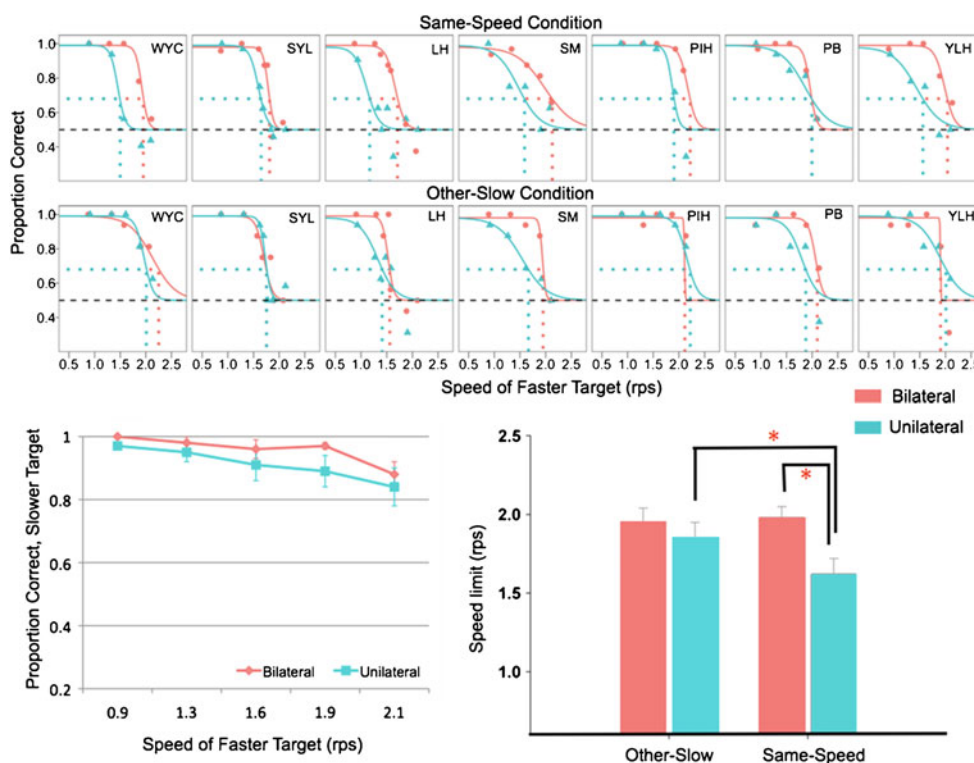

Fig. 7 (Top) For each participant, proportions correct are shown for each speed in the two-target bilateral (red) and two-target unilateral (blue) arrangements. The top row shows performance in the same-speed condition, averaged across both targets. The bottom row shows performance in the other-slow condition for the critical, faster target. Dotted lines show the speed limits (68 % thresholds). (Bottom left) Tracking accuracy for the slow target (mean across participants) is

shown for the other-slow condition, as a function of the speed of the fast target. (Bottom right) Red bars show the speed limits for the bilateral arrangements in the same-speed and other-slow (faster target only) conditions. The blue bars show the speed limit for the unilateral arrangements in the same-speed and other-slow (faster target only) conditions. Error bars show one standard error across participants, and stars indicate statistically significant differences, $p < 0.05$

With the unilateral arrangement, most participants had higher performance for the fast target when the second target moved slowly (other-slow condition) than when it moved at the same speed, paired t test $t(6) = 2.68$, $p = 0.037$, Cohen's $d = 1.014$. This is the critical finding, supporting the theory that with the unilateral arrangement, each target was allocated different portions of the hemifield-specific resource, depending on its speed.

The results of the bilateral condition suggest that tracking resources cannot be shared across the vertical hemifield boundary to the extent that they can within a hemifield—with the bilateral arrangement, there was no significant difference between the speed limits for the faster targets in the same-speed and the other-slow conditions, $t(6) = 0.489$, $p = 0.642$, Cohen's $d = 0.194$. This difference between the unilateral and bilateral arrangements was confirmed by a significant interaction between hemifield arrangement and speed found in a repeated measures ANOVA, $F(1, 6) = 7.034$, $p = 0.038$, $\eta_p^2 = 0.54$.

In order to understand in more detail how tracking performance was affected by the speed difference of the targets, the performance for tracking the slow target (in the other-slow condition) is plotted in the bottom left panel of Fig. 7. It shows proportions correct for the slow target as a function of the speed of the faster target.

For the slow target, a downward trend in tracking accuracy was observed as the speed of the fast target increased. This result was analyzed with a linear regression in the unilateral arrangement ($b = -0.106$, $r^2 = 0.161$, $p = 0.017$) and in the bilateral arrangement ($b = -0.058$, $r^2 = 0.132$, $p = 0.032$). The drop was significantly larger for the unilateral than for the bilateral arrangement, according to a paired t test comparing the slopes of the two conditions, $t(6) = 2.512$, $p = 0.046$, Cohen's $d = 1.105$. This difference was not significant, however, in the alternative analysis of a repeated measures ANOVA, in which it would have manifest as an interaction between speed and hemifield arrangement, $F(4, 24) = 0.898$, $p = 0.481$, $\eta_p^2 = 0.13$. The ANOVA did show a significant speed effect, $F(4, 24) = 3.361$, $p = 0.026$, $\eta_p^2 = 0.359$, and a marginally significant hemifield arrangement effect, $F(1, 6) = 5.161$, $p = 0.064$, $\eta_p^2 = 0.462$. A significant decrease in performance regardless of the hemifield of the speedier target would suggest that the resource is not 100 % hemisphere-specific. More data would be needed to be confident of this interpretation.

Returning to the main results concerning speed limits, we have suggested that the lower speed limits in the unilateral arrangement were due to 50 % of the resource per target being insufficient to track accurately at high speeds. The lower speed limit might alternatively reflect greater difficulty that occurred regardless of relative disc speed, for example due to greater spatial interference. Such a general difficulty factor would cause the psychometric function to saturate at a lower ceiling in the unilateral condition. This is

not apparent in the plots, and we confirmed the lack of a significant effect by examining the lapse rates of the fits. The lapse rate sets the ceiling on performance. A repeated measures ANOVA showed no significant differences in lapse rates between the unilateral (0.03) and bilateral (0.02) conditions [$F(1, 6) = 0.948$, $p = 0.368$, $\eta_p^2 = 0.136$] and between the same-speed (0.03) and other-slow (0.02) conditions [$F(1, 6) = 0.203$, $p = 0.668$, $\eta_p^2 = 0.033$], and no significant interaction between the two hemifield arrangements and speed conditions [$F(1, 6) = 0.005$, $p = 0.944$, $\eta_p^2 = 0.001$]. Any speed-invariant difficulty difference was nonexistent or too small to be detected.

General discussion

These results provide new support for the theory that a largely hemisphere-specific resource mediates tracking, and that this resource can be differentially allocated to targets with different speeds. In the unilateral (same-hemifield) arrangement, pairing a target with a slower target rather than one of the same speed yielded better performance for the first target, presumably because slower targets are allocated less of the resource than are faster targets.

Hemisphere-specific resource theory

Experiments 1 and 2 showed that the speed limit for tracking four targets was substantially lower than that for tracking two targets bilaterally, but was similar to that for tracking two targets unilaterally. Previous studies had also found that tracking four targets spread across both visual hemifields had little or no additional cost over tracking two targets within a single hemifield (Alvarez & Cavanagh, 2005; Battelli, Alvarez, Carlson & Pascual-Leone, 2009). Our experiment shows that this result holds even when the objects are widely separated to avoid spatial interference and when the total distance traveled by the discs is held constant across trials. Holding travel distance constant was done to avoid a possible increase in spatial interactions with speed (Franconeri et al., 2010).

The similarity of the observed speed limits to the capacity-one performance benchmark is consistent with a linear performance-versus-resource function that is steeper than the independent-samples (square root) function (Horowitz & Cohen, 2010). It is also equivalent to what would occur if participants, realizing that 50 % of the resource was not enough to track each fast-moving target, gave up on one target in each hemifield and focused all of the resource on the other target. The consistent, although statistically nonsignificant, finding that performance actually fell below the benchmark (here and in Holcombe & Chen, 2012, 2013) suggests that the true resource-versus-performance function falls below the

linear function (e.g., the coarse line in Fig. 2). In other words, for fast targets, splitting the resource in two may yield performance that is worse than halfway toward chance from the one-target level. For example, more than half of the resource may be required to have any tracking success with fast targets, and therefore if the participants tried to track both in each hemifield, they would fail and have to guess regarding both, yielding performance even worse than the capacity-one performance benchmark.

Experiment 3 provided evidence that the resource can be differentially allocated to targets differing in speed, and that this ability is much greater within than across hemifields, which further supports the hemisphere-specific theory. We found that a target could be tracked at a faster speed when the other target within the same hemifield was moving relatively slowly. Across hemifields, that effect was not significant. For performance tracking the slow target, however, we found a significant though small effect of the speed of the target in the opposite hemifield, suggesting that the resource is largely but not entirely hemisphere-specific.

The conclusion from the differential-allocation evidence (Exp. 3) that the resource is largely hemisphere-specific is consistent with our primary measure of the speed limit cost for adding targets to the same or the opposite hemifield. Adding targets to the same hemifield yielded a much larger cost than did adding targets to the opposite hemifield. In support of the notion that a small amount of resource can be shared across hemifields, a nonsignificant trend for a cost of opposite-hemifield targets was found both here, in Experiments 1 and 2, and in Experiment 3 of Holcombe and Chen (2012), as well as in both relevant experiments of Alvarez and Cavanagh (2005). In the case of an experiment conducted by Hudson, Howe and Little (2012), the reduction in accuracy associated with adding targets in the opposite hemifield reached statistical significance (their Exp. 4).

Serial models and unequal time-sharing within a hemifield

Unequal allocation of the tracking resource is compatible with both parallel and serial models. According to a parallel account, all of the targets' positions are updated simultaneously, but devoting more resource to a target results in positions being updated more accurately. According to the serial account, target positions are updated one by one; the more targets there are, the less frequently their positions are updated (Howe et al., 2010; Oksama & Hyönä, 2008; Pylyshyn & Storm, 1988; Tripathy & Howard, 2012; Tripathy et al., 2011). At higher speeds, the targets travel farther between position updates, resulting in a greater speed limit cost for larger tracking loads (Holcombe & Chen, 2012, 2013). The findings of Experiments 1 and 2 are thus consistent with the theory that observers serially track multiple objects within one single hemifield but track independently (in

parallel) in the two hemifields. However, see Howe et al. (2010) for evidence counter to the possibility of serial switching within a hemifield.

Regarding the allocation issue, serial models have assumed that the positions of all targets are registered equally frequently. However, a serial model could allow for one target to receive a greater share of the tracking focus's time. This would accommodate our evidence for the flexibility of resource allocation.

Parallel models and differential resource allocation

The first theory ever proposed of MOT (Pylyshyn & Storm, 1988) was a "slots" or discrete model. According to it, targets are tracked in parallel, each by its own mental index (FINST) or slot. Because observers are assumed to have four to five FINSTs, the Pylyshyn and Storm slots theory explicitly predicts that tracking performance will not vary as the number of targets is increased until the number of targets exceeds the number of FINSTs that the observer has. Experiments 1 and 2 contradicted this prediction with the finding that the speed limit for tracking two targets bilaterally was substantially higher than that for tracking four targets. However, our results might be accommodated by a modified slot theory in which each target can be allocated more than one slot (Horowitz & Cohen, 2010). And under such a model, resource could be differentially allocated: Faster targets could be allocated more slots.

Alvarez and Franconeri (2007) and Vul et al. (2009) proposed continuous-resource theories to explain tracking limits. The original notion of continuous-resource theory was that the resource must be divided among targets, yielding less per target when more targets are tracked, and resulting in poorer performance. To explain the results of our Experiment 3, these theories could be elaborated to specify that more resource can be allocated to a fast than to a slow target.

An alternative to continuous-resource theory is the oscillatory, multilayer neural network model of Kazanovich and Borisyuk (2006). Because in that model each layer is responsible for tracking a single target, the amount of resource devoted to a target is not predicted to increase if the target moves faster than the other targets in the display. As such, this model is not expected to explain our finding that more resource is required to reach a particular performance level with fast than with slow targets. However, it could be modified to allow a single target to be tracked by more than one layer, and thereby accommodate our results.

Attention and the tracking resource

Theories of the tracking resource have been vague, in that they have not specified the resource-versus-performance functions that they entail. Horowitz and Cohen (2010) suggested

independent sampling, which involves a square-root increase in precision with resource. Unfortunately it is not clear whether the percentage of change in tracking accuracy would be linearly related to precision or have some other mapping. If it is linear, accuracy should increase with the square root of the resource (depicted in Fig. 2), but this has been ruled out by the present data. We instead found that for high-speed targets, the cost of dividing the resource was similar to what is suggested by the lower linear function. For slow targets, there was little cost of dividing the resource. What explains this change of the resource-versus-performance function with speed?

Perhaps the effect of increasing the resource devoted to a target is to increase tracking precision. Less temporal precision for instance may be more costly at higher speeds, because at high speeds the object will more often be far away from its last-registered location. Such ideas, however, will require theoretical development beyond the scope of this article.

What is the relationship of the tracking resource to the attentional processes required for other tasks? Possibly the hemifield-specific resource documented here is used solely for visual tracking and selection, and thus cannot be shared with other tasks. Alternatively, the resource that was differentially allocated in the experiments here may be a general (albeit hemisphere-specific) attentional resource required for many other tasks. Simultaneously performing visual search, having a telephone conversation, or discriminating auditory tones can reduce one's tracking ability (Alvarez, Horowitz, Arsenio, Dimase & Wolfe, 2005; Kunar, Carter, Cohen & Horowitz, 2008; Tombu & Seiffert, 2008). However, whether or not the resource shared with other tasks is hemifield-specific does not appear to have yet been tested. Here we found that the resource that could be differentially allocated among targets was largely hemifield-specific. More work must be done, especially testing of the hemifield specificity of nontracking tasks, to connect the present findings to those from other tasks.

This study provides the first evidence for differential allocation of the hemisphere-specific tracking resource between targets. Further work will be needed to determine whether the differential allocation is under strategic control and whether other tasks share this hemisphere-specific resource.

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