Speed has an effect on multiple-object tracking independently of the number of close encounters between targets and distractors

Cary S. Feria

Attention, Perception, & Psychophysics

ISSN 1943-3921
Volume 75
Number 1

Atten Percept Psychophys (2013)
75:53-67
DOI 10.3758/s13414-012-0369-x

Springer

Atten Percept Psychophys (2013) 75:53–67
DOI 10.3758/s13414-012-0369-x

Speed has an effect on multiple-object tracking independently of the number of close encounters between targets and distractors

Cary S. Feria

Published online: 13 September 2012

Abstract Multiple-object tracking (MOT) studies have shown that tracking ability declines as object speed increases. However, this might be attributed solely to the increased number of times that target and distractor objects usually pass close to each other ("close encounters") when speed is increased, resulting in more target–distractor confusions. The present study investigates whether speed itself affects MOT ability by using displays in which the number of close encounters is held constant across speeds. Observers viewed several pairs of disks, and each pair rotated about the pair's midpoint and, also, about the center of the display at varying speeds. Results showed that even with the number of close encounters held constant across speeds, increased speed impairs tracking performance, and the effect of speed is greater when the number of targets to be tracked is large. Moreover, neither the effect of number of distractors nor the effect of target–distractor distance was dependent on speed, when speed was isolated from the typical concomitant increase in close encounters. These results imply that increased speed does not impair tracking solely by increasing close encounters. Rather, they support the view that speed affects MOT capacity by requiring more attentional resources to track at higher speeds.

Keywords Attention: object-based · Attention: selective · Attention: divided attention and inattention

An important task of the visual system is to track objects that are moving in the world around us. Automobile drivers tracking surrounding vehicles and athletes tracking opponents on the field demonstrate this ability. This capability is typically studied using the multiple-object tracking (MOT) paradigm originated by Pylyshyn and Storm (1988), in which observers track a subset of target items moving among identical distractors. Intuition tells us that tracking the vehicles surrounding a driver, for example, will become more difficult when the speed of the vehicles increases, the number of vehicles increases, or the vehicles become more crowded together. All of these intuitions have been evidenced by MOT studies, although the mechanisms by which these factors affect tracking are still a matter of debate.

It is well established that as the number of targets that need to be tracked increases, tracking performance declines (e.g., Pylyshyn & Storm, 1988; Yantis, 1992). While most studies have suggested that a maximum of about four or five objects can be tracked with high accuracy (e.g., Cavanagh & Alvarez, 2005; Pylyshyn & Storm, 1988; Yantis, 1992), some recent studies have shown that depending on task parameters, up to eight objects can be tracked (Alvarez & Franconeri, 2007; Howe, Cohen, Pinto, & Horowitz, 2010). This finding led to the proposal of the *flexible-resource model*, according to which there is a limited pool of resources for tracking that can be flexibly allocated to targets depending on task demands (Alvarez & Franconeri, 2007). As the resource demands to track each target increase, the number of targets that can be tracked decreases. Conversely, as the number of targets being tracked increases, the amount of resources that can be allotted to each target must decrease, causing a decline in tracking performance.

MOT performance also declines as the number of distractors increases (Bettencourt & Somers, 2009; Feria, 2012; Sears & Pylyshyn, 2000; Tombu & Seiffert, 2011). One reason that distractors interfere with tracking the targets is that when a distractor passes near a target, the observer may confuse the distractor with the target (Alvarez & Franconeri,

C. S. Feria (✉)
Department of Psychology, San Jose State University,
One Washington Square,
San Jose, CA 95192-0120, USA
e-mail: cary.feria@sjsu.edu

2007; Bae & Flombaum, 2012; Bettencourt & Somers, 2009; Feria, 2012; Horowitz et al., 2007; Intriligator & Cavanagh, 2001; Iordanescu, Grabowecky, & Suzuki, 2009; Oksama & Hyönä, 2004; Pylyshyn, 2004; Sears & Pylyshyn, 2000). It has also been proposed that distractors reduce tracking performance because they are physically salient and exogenously divert attention away from tracking the targets (Bettencourt & Somers, 2009; Feria, 2012; Störmer, Li, Heekeren, & Lindenberger, 2011).

Another factor that affects MOT ability is object proximity. When objects are closer together, MOT performance decreases (Alvarez & Franconeri, 2007; Intriligator & Cavanagh, 2001; Shim, Alvarez, & Jiang, 2008; Tombu & Seiffert, 2011). One reason that object proximity affects MOT is that the closer the distractors get to the targets, the more likely target–distractor confusions are to occur (Pylyshyn, 2004). The attentional focus on each target in MOT has a limited spatial resolution, and when the distance between a target and a distractor is smaller than the radius of the target's attentional selection window, it becomes difficult to individuate the target from the distractor (Intriligator & Cavanagh, 2001). According to the flexible-resource model, when fewer attentional resources are allocated to a target, its position is represented with poorer spatial resolution, and the size of the attentional window on the target increases, thus allowing more distractors to fall inside and get confused with the target. Moreover, when spacing between objects is close, a more narrow selection window is necessary, requiring more attention per target, and thus fewer targets can be tracked (Alvarez & Franconeri, 2007).

Several MOT studies have shown that tracking performance declines as the speed of the objects increases (e.g., Bettencourt & Somers, 2009; Fencsik, Urrea, Place, Wolfe, & Horowitz, 2006; Huff, Papenmeier, Jahn, & Hesse, 2010; Liu et al., 2005; Tombu & Seiffert, 2011). According to the flexible-resource model, the reason that speed affects MOT is that when objects are moving at fast speeds, more attention must be allocated to each target, and thus fewer targets can be tracked. Also, the faster the objects move, the wider the attentional selection window on each target is, which allows more distractors to fall inside the window (Alvarez & Franconeri, 2007). Consistent with the flexible-resource model, Tombu and Seiffert (2008) found that increased speed increases the attentional demands of tracking, and Alvarez and Franconeri (2007; see also Holcombe & Chen, 2012; Howe et al., 2010) found that as the number of targets increases, the maximum speed at which the targets can move and still be accurately tracked decreases. This trade-off between speed and number of targets tracked has also been predicted by an ideal observer model (Vul, Frank, Alvarez, & Tenenbaum, 2009).

Alternatively, it has been proposed that speed per se actually does not affect tracking. Franconeri and colleagues (Franconeri, Jonathan, & Scimeca, 2010; Franconeri, Lin, Pylyshyn, Fisher, & Enns, 2008) noted that in many real-life and laboratory MOT situations, increases in speed increase the frequency with which targets and distractors pass close to each other. When a target passes within a threshold distance of a distractor (this will be referred to as a *close encounter*), the distractor may be mistaken as the target. Thus, this *close encounters model* proposes that speed itself does not affect MOT but, rather, that the reduction in tracking performance as speed increases is due solely to the increased number of close encounters at higher speeds (Franconeri et al., 2010; Franconeri et al., 2008). Franconeri et al. (2008) provided support for the close encounters model in a study in which observers tracked either on a small display or on a projection of the same display scaled four times larger. Franconeri et al. (2008) posited that the threshold distance for close encounters should scale directly with display size and, thus, the number of close encounters should be the same for the small and large displays. Tracking performance was equal with the small and large displays, even though the speed was four times as fast in the large display, suggesting that there is no effect of speed on tracking if close encounters are not increased. Franconeri et al. (2010) also found evidence for the close encounters model in an experiment using rotational motion MOT displays. The speed of the rotation and the tracking time interval were manipulated to produce several conditions in which the objects traveled the same cumulative distance. For instance, a condition with a high speed but a short time interval and a condition with one-half the speed but twice the time interval would both have an equal cumulative distance traveled by the objects and, thus, an equal number of close encounters. Tracking performance did not differ between the faster and slower speeds, supporting the idea that speed does not affect tracking if close encounters are not increased.

In another study examining the role of proximity in the effect of speed on MOT, Tombu and Seiffert (2011) devised a novel MOT display in which speed was directly and independently manipulated, while controlling for proximity across speeds. In the display, several target–distractor pairs each rotated about the pair's midpoint and about the center of the display. The speed of rotation about the pair's midpoint was manipulated, and the speed of rotation about the center of the display was constant. Tracking performance declined as speed increased, even though the target and distractor of each pair stayed a constant distance apart regardless of the speed. This result suggests that speed influences tracking performance independently of proximity, seemingly in contrast with Franconeri et al.'s (2010; Franconeri et al., 2008) findings that speed has no effect on tracking in the absence of an increase in close encounters.

Given the divergent results of these previous studies, further evaluation of the close encounters model is necessary. The aim of the present study was to provide a direct test of whether speed affects MOT ability outside of its relationship with close encounters, by using a paradigm in which speed can be manipulated exclusively, while keeping the number of close encounters constant across speeds. The present study used displays similar to those of Tombu and Seiffert (2011) but manipulated the speed of rotation about the center of the display, while keeping the speed of rotation about the pairs' midpoints constant. In these displays, increasing the speed of rotation about the center of the display increased the disks' speeds without increasing the number of close encounters between objects on the same target–distractor pair or the number of close encounters between objects on adjacent target–distractor pairs.

The objective of the present study was to examine whether and how speed affects MOT independently of its relationship with close encounters. Experiment 1 found that tracking declines as speed increases, even when the number of close encounters is constant across speeds. Subsequent experiments examined whether the effect of speed on tracking is dependent on the number of targets (Experiment 2), the distance between targets and distractors (Experiment 3), and the number of distractors (Experiment 4), when the effect of speed is isolated from the typical concomitant increase in close encounters.

Experiment 1

The observers here tracked disks moving in two sets of circular "orbits" (see Fig. 1). Each disk rotated on a *little orbit*, and each little orbit rotated on a *big orbit*. The orbits themselves were not visible in the displays. There were two concentric big orbits and six little orbits. Each little orbit had one target disk and one distractor disk on it. The big orbits' rotation speed had four levels that were manipulated across trials. On each trial, the two big orbits moved in the same direction and at the same speed. The little orbits' rotation speed was constant, but each little orbit could rotate in a different direction. Thus, the motion of each disk was a combination of its little orbit motion component and its big orbit motion component. In these displays, increasing the speed of the big orbits increased the disks' speeds but did not increase the number of close encounters. According to the close encounters model, increased speed reduces tracking performance solely by increasing the number of close encounters, so in this experiment, there should be no tracking decrement as speed increases. Alternatively, if the flexible-resource model is correct that more attention is required to track fast-moving targets, tracking performance should decline as speed increases.

Method

Observers

Observers were 19 undergraduate students from San Jose State University. Each participated in one hour-long session and was compensated with course credit. All observers had self-reported normal or corrected-to-normal vision, and none of them was familiar with the purposes of the experiment.

Apparatus

Observers were seated in a darkened room approximately 57 cm from the display. The stimuli were presented on a 20-in. (50-cm) flat-screen CRT monitor with a pixel resolution of 1,600 × 1,200, controlled by a Dell Precision workstation. The experimental procedure was generated in C++, using the OpenGL libraries.

Stimuli

On each trial, 12 light green disks were presented on a light gray background (see Fig. 1b). Each disk had a radius of

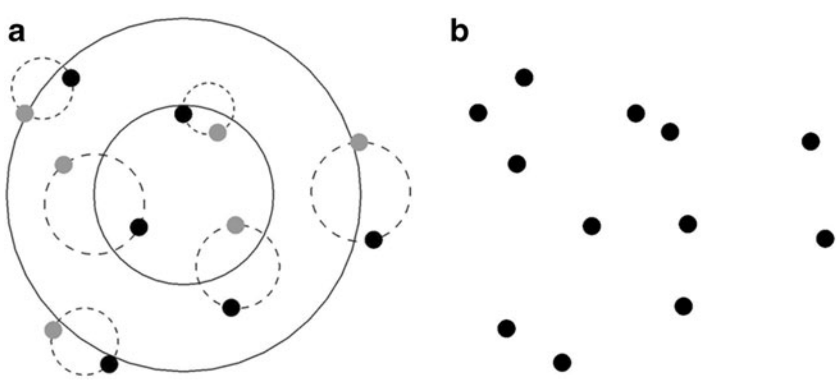

Fig. 1 Illustration of the displays used in Experiment 1. **a** Diagram depicting the motion paths of the disks. Dashed lines represent the little orbits, and solid lines represent the big orbits. The orbits were not visible in the actual displays. Targets are shown here in black and distractors in gray, for illustrative purposes. In the actual displays, all targets and distractors were the same green color. **b** The display as seen by the observers

0.44 deg. (Note that in this article, degrees of visual angle will be denoted as deg, and degrees of angular rotation will be denoted as °.) At the beginning of each trial, six disks flashed on and off 5 times over a period of 2.5 s, to designate them as the targets. The six distractor disks were constantly visible during this time. Next, all the disks moved about the screen for 6 s. After the end of the motion, one disk changed its color to red, and the observer responded as to whether or not it was a target by pressing a mouse button. The disk to be changed to red was randomly selected out of the targets with a probability of .5 and out of the distractors with a probability of .5. Details of the locations and motion paths of the disks are described in the following paragraphs.

The disks moved in two sets of circular "orbits" (see Fig. 1a). Each disk rotated on a *little orbit*, and each little orbit rotated on a *big orbit*. The orbits were not visible in the displays; rather, they defined the motion paths of the disks. There were a total of two big orbits (*inner* and *outer* big orbit) and six little orbits (three on each big orbit). The big orbits were concentric circles, each with its center at the center of the display. At the beginning of each trial, the inner big orbit was randomly assigned a radius between 4.18 and 4.91 deg, the outer big orbit was randomly assigned a radius between 8.60 and 9.83 deg, and each little orbit was randomly assigned a radius between 1.23 and 2.70 deg.

The center of each little orbit was a location on one of the big orbits (which is described as an angle about the big orbit). These locations were assigned at the beginning of each trial in the following fashion. For the little orbits on the inner big orbit, the first little orbit's center was located at a randomly chosen angle on the big orbit, the second little orbit's center was located at an angle between 110° and 130° away from the first little orbit's center, and the third little orbit's center was located at an angle between 230° and 250° away from the first little orbit's center. For the little orbits on the outer big orbit, their centers were located at angles offset from the locations of the centers of the little orbits on the inner big orbit. The center of the first little orbit on the outer big orbit was located at an angle between 50° and 70° from the angle of the center of the first little orbit on the inner big orbit. This same process was used to assign the locations of the second and third little orbits on the outer big orbit, at angles offset from the angles of the second and third little orbits on the inner big orbit, respectively.

Each little orbit had two disks on it, one of which was a target and the other a distractor. On each trial, the starting location of each disk on its little orbit (which is described as an angle about the little orbit) was chosen randomly, with the constraint that the two disks on a given little orbit could not be closer than 80° to one another. As a result of these parameters, across all trials and all observers, on the first frame of each trial the distance between the two closest disks in the display had a mean of 1.51 deg and standard deviation of 0.38 deg.

The big orbits' angular rotation speed was 9, 18, 36, or 72 °/s on each trial. The rotation direction (clockwise or counterclockwise) of the big orbits was randomly assigned on each trial. On each trial, the two big orbits always moved in the same direction and at the same speed. Little orbits' angular rotation speed was always 27 °/s. The rotation direction (clockwise or counterclockwise) of each little orbit was randomly assigned on each trial; thus, each little orbit could move in a different direction. Each orbit's speed and direction remained constant throughout the trial. Thus, the motion of each disk was a combination of its little orbit motion component and its big orbit motion component.

Procedure

Observers were instructed to track the target disks during the motion and, at the end of the motion, to respond as to whether the red selected disk was a target or not by pressing a mouse button. After responding, observers were given feedback that their response was either correct or incorrect. After viewing the feedback, observers pressed a key to move on to the next trial.

Design

The independent variable was the *speed of the big orbits* (9, 18, 36, 72 °/s), which was run within subjects. The dependent variable was the proportion of correct responses in identifying whether the red selected disk was a target or a distractor. Each observer completed two blocks. The first block consisted of 16 practice trials followed by 72 experimental trials, and the second block consisted of 5 practice trials followed by 72 experimental trials. Each block contained 18 experimental trials in each of the four conditions. Within each block, the trials were presented in a random order for each observer.

Results

The mean proportion of correct responses was calculated for each observer for each of the four speed conditions and was submitted to a repeated measures analysis of variance (ANOVA). Figure 2 depicts the results.

Tracking performance decreased significantly as speed increased, $F(1.9, 33.9) = 30.97$, $p < .001$. (Note that all tests of within-subjects independent variables with more than two levels were adjusted using the Greenhouse–Geisser procedure, to compensate for possible deviations from sphericity.) Fisher's least significant difference (LSD) post hoc tests showed that tracking performance declined significantly from the 9-°/s ($M = .83$, $SD = .13$) to the 18-°/s speed ($M = .79$, $SD = .16$), $p < .05$; from

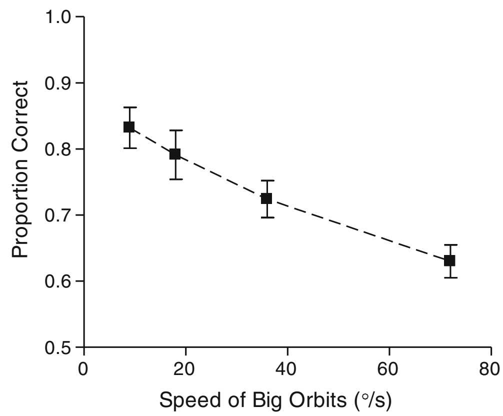

Fig. 2 Proportion correct as a function of the speed of the big orbits in Experiment 1. Error bars represent the standard error

the 18-°/s to the 36-°/s speed (M = .72, SD = .12), p < .01; and from the 36-°/s to the 72-°/s speed (M = .63, SD = .11), p < .001.

Discussion

In Experiment 1, MOT performance declined as the speed of the objects increased, which is in agreement with the results of previous studies (Alvarez & Franconeri, 2007; Bettencourt & Somers, 2009; Fencsik et al., 2006; Huff et al., 2010; Liu et al., 2005; Tombu & Seiffert, 2011). However, unlike the previous studies that found a speed effect, in Experiment 1 the number of close encounters was constant across speeds. Thus, the finding that tracking performance declined here with increased speed indicates that the increased number of close encounters that typically accompanies higher speeds cannot be the *only* reason that higher speeds impair tracking. This result is inconsistent with the close encounters model and, instead, is consistent with the assertion of the flexible-resource model that fast-moving targets require more attention, so that fewer targets can be tracked at higher speeds.

Experiment 2

Experiment 1 demonstrated that MOT is affected by speed even when the number of close encounters is held constant, which suggests that speed affects tracking in ways other than solely through increasing close encounters. However, as was noted by Franconeri et al. (2010), a reduction of MOT performance at a very high speed could be due not to resource-limited processes, but rather to data-limited processes (see Norman & Bobrow, 1975). That is, the reduction of MOT performance might be due to (1) the limited amount of processing resources available setting a constraint on the number of targets that can be tracked (i.e., a limitation on MOT capacity), or (2) lower-level limitations of the visual system, such as visual acuity, direction discrimination, and the speed with which attention can be shifted between locations. In accordance with this idea, Alvarez and Franconeri (2007) posited that there is a speed above which only a single target can be accurately tracked. The fact that one object can be tracked indicates that this speed is not beyond the threshold of what it is possible to track accurately given the lower-level limitations of the visual system. Therefore, the inability to track more than one object at that speed must be due to a lack of processing resources (Alvarez & Franconeri, 2007). Notably, Franconeri et al. (2010) found a reduction in tracking performance in their highest speed condition, even though the total cumulative distance was the same as with the other speeds. However, they also found that a similar reduction in tracking performance occurred in the highest speed condition when there were only two targets, rather than six targets. Franconeri et al. (2010) asserted that if a reduction of MOT performance at a high speed is due to data limitations (as opposed to resource limitations on MOT capacity), the effect of speed should not interact with the number of targets to be tracked. Thus, they interpreted their result as being due to data limitations, and not to an effect of speed on MOT capacity.

Some studies have estimated the maximum speed at which a single object can be tracked, but the estimates vary depending on the display and task (Alvarez & Franconeri, 2007; Horowitz, Holcombe, Wolfe, Arsenio, & DiMase, 2004; Verstraten, Cavanagh, & Labianca, 2000). Since it is unknown what the maximum speed is at which a single object could be tracked in the present displays, it is important to consider the possibility that data limitations could account for the result of Experiment 1. If the effect of speed found in Experiment 1 was due to data limitations and not to resource limitations on MOT capacity, the result would be consistent with the proposition of the close encounters model that speed itself does not actually affect MOT capacity.

On the other hand, according to the flexible-resource model, when objects are moving at fast speeds, more attention must be allocated to each target to be tracked. Yet as the number of targets increases, fewer resources are available per target (Alvarez & Franconeri, 2007). Thus, this model would predict that the effect of speed should be greater when there are a large number of targets, because as the number of targets increases there are fewer resources available for each target, thus making it impossible to meet the increased attentional requirements of fast speeds. Huff, Jahn, and Schwan (2009) found such an interaction between speed and number of targets, however, across several experiments, Liu et al. (2005) found inconsistent results regarding whether or not there is such an interaction. Notably, though, in those studies, the number of close encounters increased as speed increased. Holcombe and Chen (2012) used widely separated objects to reduce the effects of spatial interference and found that the fastest speed at which targets could be accurately tracked was slower with two targets than with one target.

The purpose of Experiment 2 was to investigate whether speed has a larger effect on MOT when many targets need to be tracked than when few targets need to be tracked. The number of close encounters was held constant across speed conditions, to isolate the effect of increased speed itself from the typical concomitant increase in close encounters. In Experiment 2, the number of targets on each trial could be one, two, four, or six, and only the slowest and fastest speeds from Experiment 1 were used (see Fig. 3). The total number of disks was always 12. If the decline of tracking at higher speeds found in Experiment 1 was due to data limitations, and not to an effect of speed on MOT capacity, then in Experiment 2, tracking should decline equally with increased speed regardless of the number of targets (Franconeri et al., 2010). Thus, if it is found that speed affects tracking equally with one or two targets as with six targets, the results will be compatible with the close encounters model. Alternatively, the flexible-resource model predicts that the larger the number of targets, the greater effect speed should have.

Method

Observers, apparatus, and procedure

The observers, apparatus, and procedure were the same as those in Experiment 1, except that there were 43 observers.

Stimuli

The stimuli were the same as those in Experiment 1, with the following exceptions. The big orbits' angular rotation speed was either 9 or 72 °/s on each trial. On each trial, there were one, two, four, or six targets. The total number of disks (targets and distractors) was 12 on every trial. On trials with six targets, each little orbit had one target and one distractor, as in Experiment 1. On trials with fewer than six targets, some little orbits had one target and one distractor, and other little orbits had two distractors (see Fig. 3).

Design

The design was the same as that in Experiment 1, with the following exceptions. The independent variables were *speed of the big orbits* (9 or 72 °/s) and *number of targets* (one, two, four, six). Both of these variables were run within subjects. The first block consisted of 16 practice trials followed by 80 experimental trials, and the second block consisted of 5 practice trials followed by 80 experimental trials. Each block contained 10 experimental trials in each of the eight conditions.

Results

The mean proportion of correct responses was calculated for each observer for each of the eight conditions and was submitted to a 2 (speed) × 4 (number of targets) repeated measures ANOVA. Figure 4 depicts the results. The main effect of speed was significant, $F(1, 42) = 144.14$, $p < .001$, indicating higher tracking performance at the slower speed.

There was also a significant main effect of number of targets, $F(1.6, 68.4) = 250.41$, $p < .001$, in that tracking performance declined as number of targets increased. LSD post hoc tests found a significant reduction in tracking performance with each increase in number of targets (one vs. two, $p < .05$; two vs. four, $p < .001$; four vs. six, $p < .001$).

Critically, there was a significant interaction between speed and number of targets, $F(1.7, 72.5) = 53.28$, $p < .001$. LSD comparisons indicated that when there were four or six targets, tracking performance was significantly higher with the 9-°/s speed than with the 72-°/s speed (*p*s < .001). However, when there were one or two targets, tracking performance did not differ significantly between the 9- and 72-°/s speeds (*p*s > .05). A separate ANOVA on only the four- and six-target data showed a significant interaction between speed and number of targets, $F(1, 42) = 29.21$, $p < .001$, indicating that the effect of speed was greater with six targets than with four targets. Although the effect of number of targets was smaller with the 9-°/s speed than with the 72-°/s speed, a separate ANOVA on only the 9-°/s data indicated a

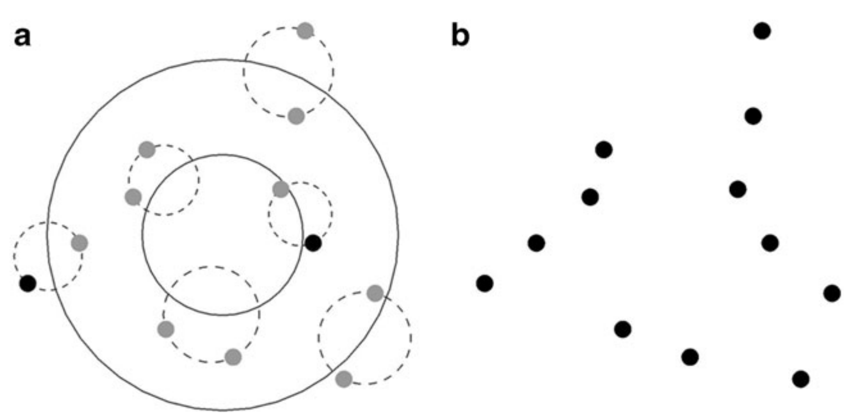

Fig. 3 Illustration of the two target condition in Experiment 2. **a** Diagram depicting the motion paths, targets, and distractors, and **b** the display as seen by the observers

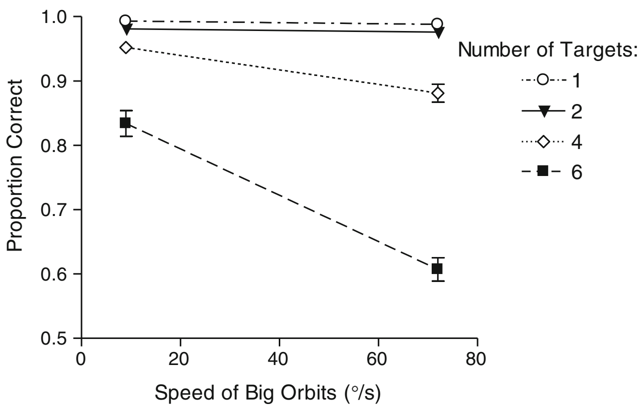

Fig. 4 Proportion correct as a function of the speed of the big orbits and the number of targets in Experiment 2

significant effect of number of targets, $F(1.5, 62.1) = 52.03$, $p < .001$.

The significant interaction between speed and number of targets potentially could have been influenced by ceiling effects. However, single-sample *t*-tests with an alpha level of .05 indicated that tracking performance was significantly below ceiling (i.e., 1.0) in all eight conditions. Since proportion correct data may compress effects toward ceiling, the data were submitted to an arcsine transformation, which generated similar ANOVA results. Most important, the arcsine transformed data indicated a significant interaction between speed and number of targets, $F(2.6, 107.6) = 23.98$, $p < .001$. LSD comparisons found that with four or six targets, tracking performance was significantly higher with the 9-°/s speed than with the 72-°/s speed ($ps < .001$). Yet with one or two targets, there was no significant difference in performance between the 9- and 72-°/s speeds ($ps > .05$). A separate ANOVA on only the four- and six-target data also found a significant interaction between speed and number of targets, $F(1, 42) = 9.38$, $p < .01$. The replication of the results of the analyses in the arcsine transformed data reinforces the presence of the interaction between speed and number of targets.

Discussion

Experiment 2 found that, with close encounters held constant across speeds, tracking declined with increased speed when there were four or six targets to be tracked, but not when there were only one or two targets to be tracked. The effect of speed was also greater when there were six targets than when there were four targets. These results suggest that the decline of tracking at higher speeds is due to an effect of speed on MOT capacity, and not to data limitations. The fact that one object could be tracked with uniformly high accuracy at all of the speeds used shows that all of these speeds are within the threshold of what it is possible to track accurately given the lower-level limitations of the visual system. Thus, the reduction in ability to track with increasing speed when there are six targets must be due to a lack of processing resources (Alvarez & Franconeri, 2007).

The finding that the more targets are being tracked, the greater is the effect of speed is consistent with the flexible-resource model. Both increasing the number of targets and increasing the speed draw from the same limited pool of attentional resources. This result is also consistent with previous findings of a trade-off between the speed of object motion and the number of objects that can be tracked (Alvarez & Franconeri, 2007; Howe et al., 2010) and with the finding of a larger effect of speed with greater numbers of targets in some of the experiments by Liu et al. (2005) and Huff et al. (2009). However, in these previous studies, higher speeds were accompanied by an increased number of close encounters, so the relationship between number of targets and speed could have been due either to speed itself or to the increased number of close encounters. In other words, it might be harder to track increasing numbers of targets when the targets are moving more quickly, or it might be harder to track increasing numbers of targets when the targets are having close encounters more often. The present experiment clarified these findings, indicating that the interaction of speed and number of targets is not due only to increased close encounters at higher speeds. This suggests that the same resource pool that is drawn on by increasing the number of targets is also drawn on by increases in speed, and not solely by the increases in number of close encounters that often accompany increased speed.

Franconeri et al. (2010) found reductions in tracking performance at their highest speed, even when there were only two targets to be tracked, but this did not occur in the present experiment. It is difficult to compare the speeds in the present study with those used by Franconeri et al. (2010), because the displays differed substantially, but it may be that the highest speed used by Franconeri et al. (2010) was faster than the highest speed condition in Experiment 2. At very high speeds, beyond the threshold of what it is possible to track accurately given the lower-level data limitations of the visual system, reductions in tracking performance would be expected, even if only one or two targets need to be tracked.

Experiment 3

Experiments 1 and 2 have demonstrated that speed affects MOT and that the effect of speed on MOT is not due only to the increased number of close encounters that typically accompanies higher speeds; nor can it be attributed solely to data limitations. Another factor that is known to affect MOT performance is object proximity (Alvarez & Franconeri, 2007; Bae & Flombaum, 2012; Intriligator & Cavanagh, 2001; Shim et al., 2008; Tombu & Seiffert, 2011). According to the flexible-resource model, when object spacing is closer, a more narrow target selection window is necessary, requiring more attention per target. Consistent with this idea, Tombu and Seiffert (2008) found evidence that increased object proximity increases the attentional demands of tracking. In the flexible-resource model, because both speed and proximity draw from a limited pool of attentional resources, as speed increases it should become increasingly difficult to meet the attentional requirements to maintain the very narrow selection window that would be necessary to exclude more proximate distractors. Consequently, the flexible-resource model predicts that the cost for decreasing spacing between targets and distractors should be greater with fast speeds than with slow speeds (Alvarez & Franconeri, 2007). Some studies have supported the presence of such an interaction between speed and proximity (Alvarez & Franconeri, 2007; Tombu & Seiffert, 2011), although others have found no interaction (Shim et al., 2008). Yet in previous studies, higher speeds were accompanied by an increased number of close encounters, so the finding in some previous studies of an interaction between proximity and speed could have been due either to speed itself or to the increase in close encounters at higher speeds. Thus, it will be informative to assess the presence of an interaction between speed and proximity in the present paradigm, isolating the effect of increased speed itself from the typical concomitant increase in close encounters.

In Experiment 3, the targets and distractors could be either near one another or far apart, which was accomplished by placing the target and distractor on each little orbit at a smaller or larger distance apart on their little orbit (see Fig. 5). The big orbits' rotation speed was varied across trials.

Method

Observers, apparatus, and procedure

The observers, apparatus, and procedure were the same as those in Experiment 1, except that there were 16 observers.

Stimuli

The stimuli were the same as those in Experiment 1, with the following exceptions. On each trial, each little orbit was randomly assigned a radius between 1.72 and 2.21 deg. The assignment of the starting locations of the disks depended on whether the trial was a *near* trial or a *far* trial (see Fig. 5). On near trials, the location of each disk on its little orbit (which is described as an angle about the little orbit) was randomly assigned such that the two disks on a given little orbit were 60° to 90° apart from one another. On far trials, the location of each disk on its little orbit was randomly assigned such that the two disks on a given little orbit were 150° to 180° apart from one another.

As a result of these parameters, across all trials and all observers, the distance between a target and distractor on the same little orbit ranged from 0.84 to 2.18 deg in the near condition. In the far condition, the distance between a target and distractor on the same little orbit ranged from 2.44 to 3.49 deg. Disk speeds on a given frame (resulting from the combination of the big and little orbit rotation components of the disk), across all trials and all observers, in the 9-°/s big orbit rotation condition ranged from 0 to 2.91 deg/s, with an average of 1.35 deg/s. Disk speeds in the 18-°/s big orbit rotation condition ranged from 0 to 4.78 deg/s, with an average of 2.34 deg/s. In the 36-°/s big orbit rotation condition, disk speeds ranged from 0.22 to 8.52 deg/s, with an average of 4.48 deg/s. Finally, disk speeds in the 72-°/s big orbit rotation condition ranged from 1.47 to 16.03 deg/s, with an average of 8.91 deg/s.

Design

The design was the same as that in Experiment 1, with the following exceptions. The independent variables were *speed of the big orbits* (9, 18, 36, 72 °/s) and *proximity of targets to distractors* (near, far). Both of these variables were run within subjects. The first block consisted of 16 practice trials followed by 80 experimental trials, and the second block consisted of 5 practice trials followed by 80 experimental trials. Each block contained 10 experimental trials in each of the eight conditions.

Results

Figure 6 depicts the results. An ANOVA showed a significant main effect of speed, $F(2.3, 34.2) = 14.32$, $p < .001$, in that tracking performance decreased as speed increased. The main effect of proximity was also significant, $F(1, 15) = 23.83$, $p < .001$, indicating higher tracking performance in the far condition than in the near condition.

Crucially, there was no significant interaction between speed and proximity, $F(2.1, 31.6) = 0.40$, $p > .05$. A single-sample t-test indicated that tracking performance in the 72-°/s, near condition was significantly higher than chance (i.e., .5), $t(15) = 2.79$, $p < .05$, suggesting that a floor effect was not likely to have occurred. The data were also submitted to an arcsine transformation, which generated similar ANOVA results, including the finding of no significant interaction between speed and proximity, $F(2.3, 35.0) = 0.82$, $p > .05$.

Discussion

In Experiment 3, tracking performance was impaired when targets and distractors were closer together, consistent with

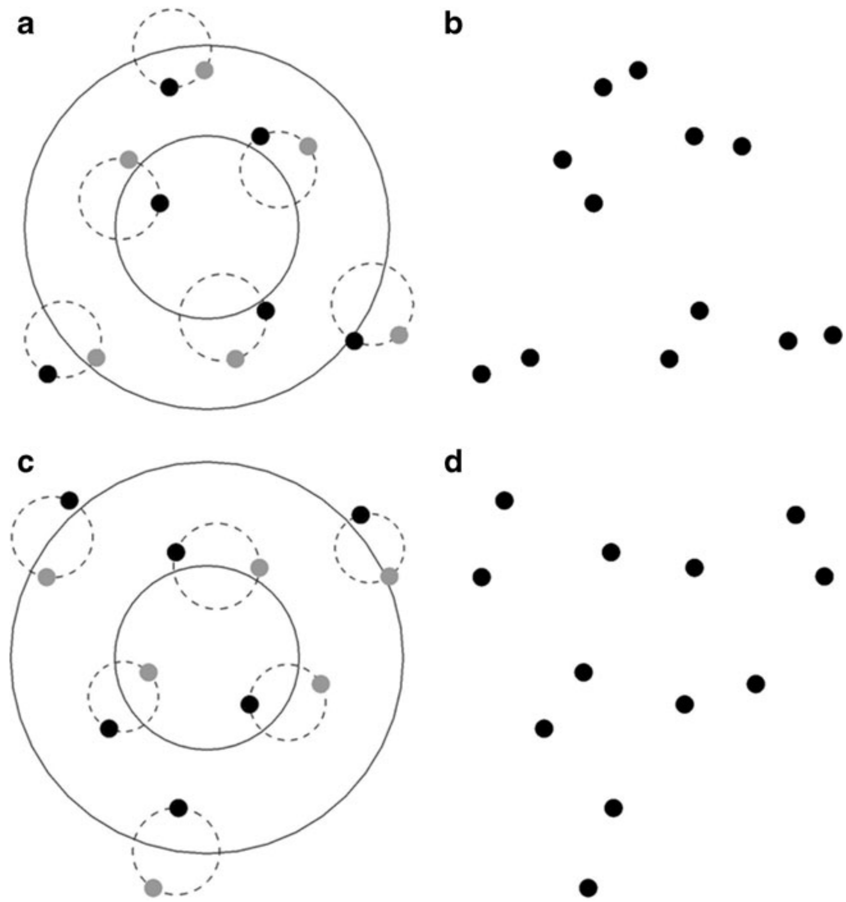

Fig. 5 Illustration of the displays used in Experiment 3. **a** Diagram depicting the motion paths, targets, and distractors in the *near* condition, and **b** the display as seen by the observers. **c** Diagram depicting the motion paths, targets, and distractors in the *far* condition, and **d** the display as seen by the observers

previous findings (Alvarez & Franconeri, 2007; Intriligator & Cavanagh, 2001; Shim et al., 2008; Tombu & Seiffert, 2011), and tracking performance declined as speed increased. Critically, however, the effect of target–distractor proximity did not depend on the motion speed. Previous studies had inconsistent results on this relationship, with some finding a greater cost for decreasing spacing at faster speeds (Alvarez & Franconeri, 2007; Tombu & Seiffert, 2011) and others not (Shim et al., 2008). Experiment 3 adds to the previous findings by showing that when the effect of increased speed is isolated from the typical concomitant increase in the number of close encounters, there is no interaction between speed and proximity. This result does not fit the prediction of the flexible-resource model and brings into question whether both motion speed and target–distractor proximity draw from the same limited pool of attentional resources.

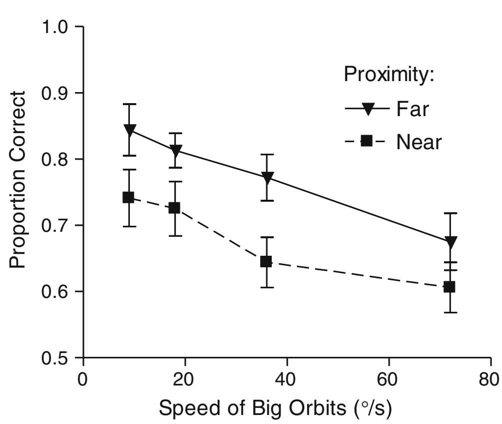

Fig. 6 Proportion correct as a function of the speed of the big orbits and the proximity of targets to distractors in Experiment 3

It could be contended that an interaction between proximity and speed might have occurred if the range of speeds had been larger or if the difference between the near and far distance conditions had been greater. However, the fact that both proximity and speed individually affected tracking suggests that the sizes of these two manipulations were sufficiently large to influence tracking and that the speeds and distances used required varying amounts of attentional resources. Thus, we believe it unlikely that the lack of an interaction was due to the range of speeds or distances used. In this experiment, tracking might have been affected not only by spatial proximity, but also by temporal proximity (Verstraten et al., 2000) and similarity of motion (Suganuma & Yokosawa, 2006) of the targets and distractors, which may have been increased in the near distance condition.

Experiment 4

Previous studies have shown that MOT performance declines as the number of distractors increases (Bettencourt & Somers, 2009; Feria, 2012; Sears & Pylyshyn, 2000; Tombu & Seiffert, 2011). One way in which distractors may impair tracking is by being confused with nearby targets (Alvarez & Franconeri, 2007; Intriligator & Cavanagh, 2001; Iordanescu et al., 2009; Oksama & Hyönä, 2004; Sears & Pylyshyn, 2000). Evidence for this mechanism comes from findings that as distractors get closer to targets, target–distractor identity swaps are more likely to occur (Pylyshyn, 2004) and findings that tracking is improved when distractors have distinct features making them less confusable with targets (Bae & Flombaum, 2012; Feria, 2012; Horowitz et al., 2007; Makovski & Jiang, 2009). However, other studies suggest that the effect of distractors on tracking cannot be due only to the confusion of targets with proximate distractors. Tracking worsens with greater numbers of distractors even when crowding is held constant (Bettencourt & Somers, 2009; Tombu & Seiffert, 2011) and when distractors are unlikely to be confused with targets due to having distinct features (Feria, 2012) or to being located in the opposite visual hemifield (Störmer et al., 2011). These results have been interpreted as suggesting that a second way that distractors may impair tracking is by exogenously diverting attention away from tracking targets due to their physical salience (Bettencourt & Somers, 2009; Feria, 2012; Störmer et al., 2011).

In the flexible-resource model (Alvarez & Franconeri, 2007), distractors interfere with tracking by being confused with a target when they fall inside a target selection window. The presence of a greater number of distractors entails that distractors will be passing close to targets more often and, thus, a more narrow selection window will be necessary, which will require more attention per target. Additionally, Bettencourt and Somers (2009) posited that since distractors can involuntarily attract attention based on their salience, they must be attentionally suppressed, and that this suppression occurs regardless of whether they are located within a target selection window or not. Bettencourt and Somers proposed that this suppression draws on the flexible-resource pool. According to this hypothesis, the greater the number of distractors, the more resources will be used for suppression, leaving fewer resources available for tracking targets. Whether distractors draw on the resource pool by necessitating a narrower selection window, by requiring suppression, or by both of these mechanisms, increasing the number of distractors will increase the resources required. And when objects are moving at higher speeds, more attention must be allocated for tracking the targets, so it will be more difficult to meet the attentional demands of the larger number of distractors. Thus, the flexible-resource model would predict that the cost for increasing the number of distractors should be greater with fast speeds than with slow speeds.

The purpose of Experiment 4 was to examine whether the effect of distractors on tracking depends on the motion speed. On each trial, there could be either 5 or 11 distractors, and there were always five targets (see Fig. 7). The big orbits' rotation speed was varied across trials.

Method

Observers, apparatus, and procedure

The observers, apparatus, and procedure were the same as those in Experiment 1, except that there were 35 observers.

Stimuli

The stimuli were the same as those in Experiment 1, with the following exceptions. There was a total of two big orbits and eight little orbits (four on each big orbit; see Fig. 7). On each trial, each little orbit was randomly assigned a radius between 1.23 and 2.21 deg. The center of each little orbit was a location on one of the big orbits (which is described as an angle about the big orbit). These locations were assigned at the beginning of each trial in the following fashion. For the little orbits on the inner big orbit, the first little orbit's center was located at a randomly chosen angle on the big orbit, the second little orbit's center was located at an angle between 82° and 98° away from the first little orbit's center, the third little orbit's center was located at an angle between 172° and 188° away from the first little orbit's center, and the fourth little orbit's center was located at an angle between 262° and 278° away from the first little orbit's center. For the little orbits on the outer big orbit, their centers were located at angles offset from the locations of the centers of the little orbits on the inner big orbit. The center of the first little orbit on the outer big orbit was located at an angle between 37° and 53° from the angle of the center of the first little orbit on the inner big orbit. This same process was used to assign the locations of the second, third, and fourth little orbits on the outer big orbit, at angles offset from the angles of the second, third, and fourth little orbits on the inner big orbit, respectively.

On each trial, there were either 5 or 11 distractors. There were five targets on every trial. Thus, the total number of disks on each trial could be either 10 or 16. On each trial, five of the little orbits were randomly chosen to have a target on them. On trials with 11 distractors, five of the little orbits had one target and 1 distractor, and the other three little orbits had 2 distractors. On trials with 5 distractors, each little orbit could have one target alone, 1 distractor alone, one target and 1 distractor, or 2 distractors. For little orbits

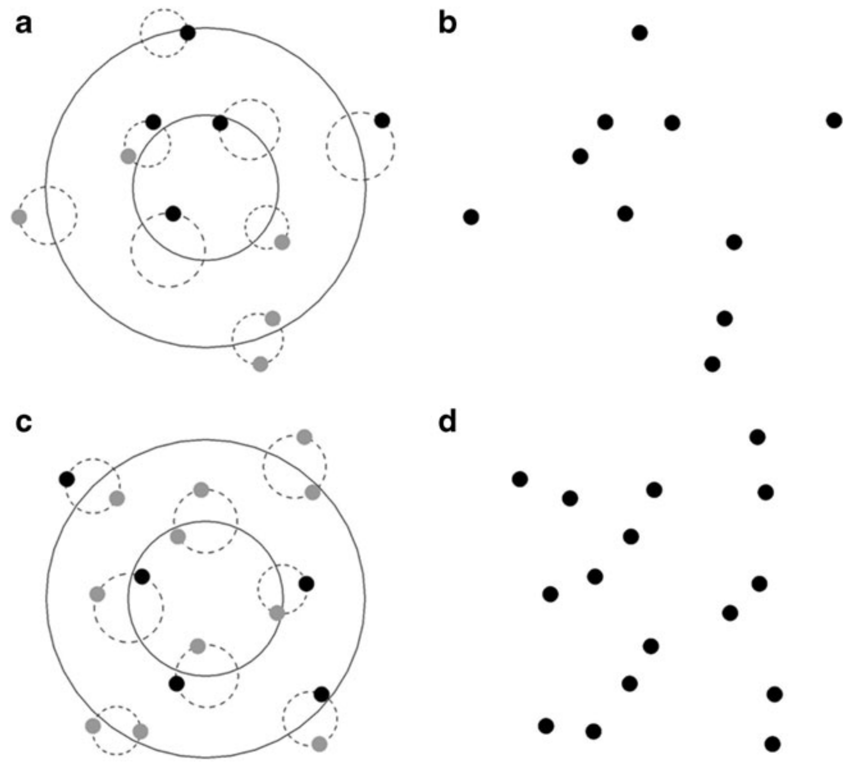

Fig. 7 Illustration of the displays used in Experiment 4. **a** Diagram depicting the motion paths, targets, and distractors in the *5 distractor* condition, and **b** the display as seen by the observers. **c** Diagram depicting the motion paths, targets, and distractors in the *11 distractor* condition, and **d** the display as seen by the observers

with 2 disks, the starting location of each disk on the little orbit was chosen as in Experiment 1. For little orbits with 1 disk, the starting location of the disk on the little orbit was chosen randomly. As a result of these parameters, across all trials and all observers, on the first frame of each trial the distance between the 2 closest disks in the display had a mean of 1.50 deg and a standard deviation of 0.41 deg. The big orbits' angular rotation speed was 18, 36, 72, or 144 °/s on each trial. Little orbits' angular rotation speed was always 54 °/s.

Design

The design was the same as that in Experiment 1, with the following exceptions. The independent variables were *speed of the big orbits* (18, 36, 72, 144 °/s) and *number of distractors* (5, 11). Both of these variables were run within subjects. Each block contained nine experimental trials in each of the eight conditions.

Results

Figure 8 depicts the results. An ANOVA indicated a significant main effect of speed, $F(2.3, 77.9) = 43.95$, $p < .001$, in that tracking performance declined as speed increased. There was also a significant main effect of number of distractors, $F(1, 34) = 102.35$, $p < .001$, indicating that tracking performance was higher with 5 distractors than with 11 distractors.

Importantly, there was not a significant interaction between speed and number of distractors, $F(2.3, 77.8) = 0.91$, $p > .05$. A single-sample *t*-test showed that tracking performance in the 144-°/s, 11-distractor condition was significantly greater than chance (i.e., .5), $t(34) = 6.07$, $p < .001$, suggesting that a floor effect was not likely to have occurred. The data were also submitted to an arcsine transformation, which produced similar ANOVA results, including the finding of no significant interaction between speed and number of distractors, $F(2.6, 88.9) = 0.06$, $p > .05$.

Discussion

Tracking performance was worse when there was a larger number of distractors, in agreement with previous findings

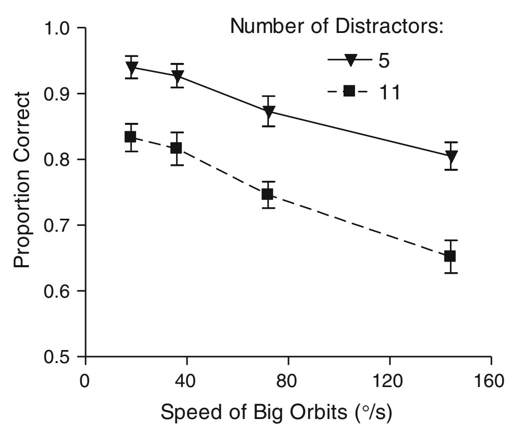

Fig. 8 Proportion correct as a function of the speed of the big orbits and the number of distractors in Experiment 4

(Bettencourt & Somers, 2009; Feria, 2012; Sears & Pylyshyn, 2000; Tombu & Seiffert, 2011), and tracking deteriorated as speed increased. Crucially, the effect of the number of distractors was not dependent on the motion speed. This finding is not consistent with the prediction of the flexible-resource model and casts doubt on the idea that both increases in speed and increases in the need for ignoring distractors draw from the same limited resource pool. If distractors draw on the fixed resource pool either by necessitating a narrower selection window (Alvarez & Franconeri, 2007) or by requiring suppression (Bettencourt & Somers, 2009), it should have been more difficult to meet the attentional requirements of large numbers of distractors when under the increased attentional demands of tracking fast-moving targets.

In Experiment 4, increased proximity of distractors to targets may have contributed to the reduced tracking performance that occurred with a larger number of distractors, since display density increased with the number of distractors (see Bettencourt & Somers, 2009; Tombu & Seiffert, 2011). The primary goal, however, of Experiment 4 was to examine the interaction between number of distractors and speed. Because Experiment 3 already has shown that proximity does not interact with speed, Experiment 4 adds to it by showing that number of distractors also does not interact with speed. Yet the null interaction results of Experiments 3 and 4 should be interpreted cautiously, because as in any study, null effects can occur due to any number of different reasons.

General discussion

Much previous research has demonstrated that MOT performance deteriorates as the speed of the objects increases (e.g., Bettencourt & Somers, 2009; Fencsik et al., 2006; Huff et al., 2010; Liu et al., 2005; Tombu & Seiffert, 2011). However, it has been proposed that speed per se has no effect on tracking and that increased speed reduces tracking performance solely because it increases the number of close encounters between objects (Franconeri et al., 2010; Franconeri et al., 2008). In order to examine this proposition, the present study used displays in which speed was increased with no concomitant increase in the number of close encounters. The goals of the present study were to test whether speed affects MOT outside its relationship with close encounters and to examine whether this effect of speed is dependent on the number of targets, target–distractor proximity, and the number of distractors.

Experiment 1 established the principal finding, that tracking ability declines as speed increases, even when the number of close encounters is held constant across speeds. This result indicates that the increased number of close encounters that accompanies higher speeds in many real-life and laboratory MOT situations cannot be the only reason that speed affects MOT and is, thus, inconsistent with the close encounters model.

This result should *not* be construed as implying that close encounters do not play *any* role in the effect of speed on MOT. In many MOT tasks, the faster the objects are moving, the more frequently close encounters will occur. And it is well-established that when distractors come close to targets, target–distractor confusions are more likely to occur (Pylyshyn, 2004), resulting in worse tracking (Alvarez & Franconeri, 2007; Intriligator & Cavanagh, 2001; Shim et al., 2008; Tombu & Seiffert, 2011). So it is likely that, in most tracking situations, the increased difficulty of tracking at higher speeds is due in part to the increased number of close encounters. What the present study shows, however, is that the effect of speed on MOT cannot be attributed *only* to the increased number of close encounters; object speed must influence MOT ability in other ways, as well.

Experiment 2 demonstrated that, even when speed is isolated from the typical concomitant increase in close encounters, speed has a larger effect on tracking when many targets need to be tracked than when few targets need to be tracked. This finding implies that the decline of tracking at higher speeds is not due to lower-level data limitations, such as visual acuity, direction discrimination, and the speed with which attention can be shifted between locations. Rather, this result indicates that the effect of speed is due to attentional resource limitations, consistent with the assertion of the flexible-resource model that tracking at higher speeds requires more attention per target (Alvarez & Franconeri, 2007). The results of Experiment 2 extend and clarify previous findings of an interaction, or trade-off, between number of targets and speed (Alvarez & Franconeri, 2007; Howe et al., 2010; Huff et al., 2009; Liu et al., 2005) by showing that the interaction is due to speed itself and not just to the increases in close encounters that often accompany increased speed.

Experiment 3 showed that the effect of target–distractor proximity on tracking is not greater at faster speeds, when speed is isolated from the typical concomitant increase in close encounters. Furthermore, Experiment 4 demonstrated that the effect of the number of distractors on tracking is not greater at faster speeds. The finding that speed does not have an interaction with number of distractors or proximity does not follow from the flexible-resource model. If speed, target–distractor proximity, and the need for ignoring distractors all draw from the same limited pool of attentional resources, these factors should interact.

However, the flexible-resource model can account for the present findings, if a key modification is made to the model. In the original flexible-resource model, attention is directed only toward the targets being tracked, and distractors are not processed unless they fall within a target selection window

(Alvarez & Franconeri, 2007). Bettencourt and Somers (2009) suggested that due to the ability of distractors to involuntarily attract attention based on their salience, distractors must be attentionally suppressed, and that this suppression occurs regardless of whether they are located within a target selection window or not. Thus, Bettencourt and Somers proposed that the resource pool is affected by two processes, attentional enhancement of target representations and suppression of distractor representations. Evidence of distractor suppression has been found in several MOT studies (Flombaum, Scholl, & Pylyshyn, 2008; Pylyshyn, 2006; Pylyshyn, Haladjian, King, & Reilly, 2008; but see Drew, McCollough, Horowitz, & Vogel, 2009) and in other attentional tasks (e.g., Awh, Matsukura, & Serences, 2003; Braithwaite, Humphreys, & Hulleman, 2005; Koshino, 2001; Ogawa, Takeda, & Yagi, 2002). Additionally, several studies using neurophysiological measures have found evidence of both target attentional enhancement and distractor suppression (e.g., Couperus & Mangun, 2010; Hillyard, Vogel, & Luck, 1998; Luck, 1995; Pinsk, Doniger, & Kastner, 2004; Somers, Dale, Seiffert, & Tootell, 1999). Although Bettencourt and Somers conceived the target attentional enhancement and distractor suppression processes as both drawing on a single resource pool, if these processes are characterized as two independent resource pools, then the flexible-resource model would account for the results of the present study. Speed and number of targets both affect the target attentional enhancement process. With faster motion, more attention is necessary per target; and with greater numbers of targets, attention gets divided up more, leaving less attention per target, just as postulated in the original flexible-resource model (Alvarez & Franconeri, 2007). On the other hand, number of distractors and proximity of distractors both affect the distractor suppression process. When distractors are closer to targets, more attentional suppression is necessary per distractor; and with greater numbers of distractors, attentional suppression resources get divided up more, leaving less ability to effectively suppress each distractor. In this model, because the number and proximity of distractors draw on a separate pool of resources than does speed, it follows that number of distractors and proximity would not interact with speed.

Further research is needed to test the idea that attentional enhancement of targets and suppression of distractors comprise two separate resource pools. This model produces predictions that can be tested using a probe-dot methodology to measure distractor suppression during MOT (see Flombaum et al., 2008; Pylyshyn, 2006; Pylyshyn et al., 2008). According to the model, the magnitude of suppression of a given distractor should decrease with farther spacing of the distractor from targets and should also decrease with increased number of distractors (if spacing is held constant), but should not be affected by the number of targets or motion speed.

Although this model is very preliminary, it is worth exploring how the target attentional enhancement resource might function and how it might limit MOT ability. Greater allocation of the attentional enhancement resource to a target might result in greater precision of target localization (Alvarez & Franconeri, 2007) and greater precision of motion direction representation, which would facilitate tracking the target. Both precision of target localization (Howard & Holcombe, 2008) and motion direction representation (Horowitz & Cohen, 2010; Shooner, Tripathy, Bedell, & Öğmen, 2010) in MOT have been found to decrease with increased number of targets, and precision of target localization has been found to decrease with increased speed (Howard, Masom, & Holcombe, 2011). These findings suggest that the precision of these representations is dependent on a limited resource. Also, the target attentional enhancement resource might be linked with working memory limitations, since MOT and working memory have been shown to share some processing resources (e.g., Allen, McGeorge, Pearson, & Milne, 2006; Bettencourt, Michalka, & Somers, 2011; Fougnie & Marois, 2006). Future studies are required to assess the role of each of these factors.

The present study and previous studies have shown that as the number (Bettencourt & Somers, 2009; Feria, 2012; Sears & Pylyshyn, 2000; Tombu & Seiffert, 2011) and proximity (Alvarez & Franconeri, 2007; Intriligator & Cavanagh, 2001; Shim et al., 2008) of distractors increase, MOT ability declines. In this modified flexible-resource model, this is explained by the greater distractor suppression resources that would be required under these circumstances exceeding the size of the suppression resource pool. This results in less ability to effectively suppress each distractor, which increases the likelihood of distractors becoming confused with targets and the likelihood of distractors exogenously diverting attention away from tracking targets by their salience, consequently resulting in worse tracking performance.

In the present experiments, the range of disk speeds was larger in the faster disk speed conditions, which leads to the possibility that increased variability of disk speed may have contributed to the reduction in tracking performance at faster speeds. Even if variability of speed played a role, the present results would still be inconsistent with the close encounters model, which asserts that close encounters are the root cause of all limitations on MOT performance (Franconeri et al., 2010), since performance declined even while the number of close encounters was held constant, and, instead, would suggest that variability of speed affects attentional resource requirements. Although we cannot exclude the possibility that variability of speed may have affected tracking, we consider it most likely that disk speed primarily produced the observed reduction in tracking, since there is much evidence that increased speed reduces MOT ability (e.g., Alvarez & Franconeri, 2007; Bettencourt & Somers, 2009; Fencsik et al., 2006; Huff et al., 2010; Liu et al., 2005; Tombu & Seiffert, 2011).

In summary, the present study demonstrates that even when the number of close encounters is held constant across speeds, speed affects MOT performance and that this effect is greater when the number of targets is large. This result indicates that speed itself affects MOT capacity and that the effect of speed is not due solely to the number of close encounters. It supports the idea that speed affects the attentional allocation required per target from the attentional resource pool (Alvarez & Franconeri, 2007). The present study also shows, however, that when speed is isolated from the typical concomitant increase in close encounters, neither the number of distractors nor the target–distractor proximity interacts with speed. This result suggests that suppression of distractors in MOT may involve a separate pool of resources than those involved with attentional enhancement of targets.

Author Note Cary S. Feria, Department of Psychology, San Jose State University.

This research was supported by a California State University Research Funds grant and a grant from the San Jose State University College of Social Sciences. Part of this research was presented at the annual meeting of the Vision Sciences Society, Naples, FL, May 2011. I thank Jeffrey Cibotti, Leonna Davis-Ross, Veronica Gunawan, Jia Liang, Dianne Lim, Zlata Malicevic, Samantha Pesenti, Justin Shaw, Trevor Southard, Blanca Tapia, and The Anh Truong for assistance with data collection and helpful conversations. For computer programming help, I thank Clare Lanam. I thank Gilbert Remillard for his invaluable input regarding the design of the display.

Correspondence concerning this article should be addressed to Cary S. Feria, Department of Psychology, One Washington Square, San Jose State University, San Jose, CA 95192–0120, USA. E-mail: cary.feria@sjsu.edu

References

Allen, R., McGeorge, P., Pearson, D. G., & Milne, A. (2006). Multiple-target tracking: A role for working memory? *Quarterly Journal of Experimental Psychology, 59,* 1101–1116.

Alvarez, G. A., & Franconeri, S. L. (2007). How many objects can you track?: Evidence for a resource-limited attentive tracking mechanism. *Journal of Vision, 7*(13), 1–10.

Awh, E., Matsukura, M., & Serences, J. T. (2003). Top-down control over biased competition during covert spatial orienting. *Journal of Experimental Psychology. Human Perception and Performance, 29,* 52–63.

Bae, G. Y., & Flombaum, J. I. (2012). Close encounters of the distracting kind: Identifying the cause of visual tracking errors. *Attention, Perception, & Psychophysics, 74,* 703–715.

Bettencourt, K. C., Michalka, S. W., & Somers, D. C. (2011). Shared filtering processes link attentional and visual short-term memory capacity limits. *Journal of Vision, 11*(10), 1–9.

Bettencourt, K., & Somers, D. (2009). Effects of target enhancement and distractor suppression on multiple object tracking capacity. *Journal of Vision, 9*(7), 1–11.

Braithwaite, J. J., Humphreys, G. W., & Hulleman, J. (2005). Color-based grouping and inhibition in visual search: Evidence from a probe detection analysis of preview search. *Perception & Psychophysics, 67,* 81–101.

Cavanagh, P., & Alvarez, G. A. (2005). Tracking multiple targets with multifocal attention. *Trends in Cognitive Sciences, 9,* 349–354.

Couperus, J. W., & Mangun, G. R. (2010). Signal enhancement and suppression during visual-spatial selective attention. *Brain Research, 1359,* 155–177.

Drew, T., McCollough, A. W., Horowitz, T. S., & Vogel, E. K. (2009). Attentional enhancement during multiple-object tracking. *Psychonomic Bulletin & Review, 16,* 411–417.

Fencsik, D. E., Urrea, J., Place, S. S., Wolfe, J. M., & Horowitz, T. S. (2006). Velocity cues improve visual search and multiple object tracking. *Visual Cognition, 14,* 92–95.

Feria, C. S. (2012). The effects of distractors in multiple object tracking are modulated by the similarity of distractor and target features. *Perception, 41,* 287–304.

Flombaum, J. I., Scholl, B. J., & Pylyshyn, Z. W. (2008). Attentional resources in visual tracking through occlusion: The high-beams effect. *Cognition, 107,* 904–931.

Fougnie, D., & Marois, R. (2006). Distinct capacity limits for attention and working memory: Evidence from attentive tracking and visual working memory paradigms. *Psychological Science, 17,* 526–534.

Franconeri, S. L., Jonathan, S. V., & Scimeca, J. M. (2010). Tracking multiple objects is limited only by object spacing, not by speed, time, or capacity. *Psychological Science, 21,* 920–925.

Franconeri, S. L., Lin, J. Y., Pylyshyn, Z. W., Fisher, B., & Enns, J. T. (2008). Evidence against a speed limit in multiple-object tracking. *Psychonomic Bulletin & Review, 15,* 802–808.

Hillyard, S. A., Vogel, E. K., & Luck, S. J. (1998). Sensory gain control (amplification) as a mechanism of selective attention: Electrophysiological and neuroimaging evidence. *Philosophical Transactions of the Royal Society: Biological Sciences, 353,* 1257–1270.

Holcombe, A. O., & Chen, W.-Y. (2012). Exhausting attentional tracking resources with a single fast-moving object. *Cognition, 123,* 218–228.

Horowitz, T. S., & Cohen, M. A. (2010). Direction information in multiple object tracking is limited by a graded resource. *Attention, Perception, & Psychophysics, 72,* 1765–1775.

Horowitz, T. S., Holcombe, A. O., Wolfe, J. M., Arsenio, H. C., & DiMase, J. S. (2004). Attentional pursuit is faster than attentional saccade. *Journal of Vision, 4,* 585–603.

Horowitz, T. S., Klieger, S. B., Fencsik, D. E., Yang, K. K., Alvarez, G. A., & Wolfe, J. M. (2007). Tracking unique objects. *Perception & Psychophysics, 69,* 172–184.

Howard, C. J., & Holcombe, A. O. (2008). Tracking the changing features of multiple objects: Progressively poorer perceptual precision and progressively greater perceptual lag. *Vision Research, 48,* 1164–1180.

Howard, C. J., Masom, D., & Holcombe, A. O. (2011). Position representations lag behind targets in multiple object tracking. *Vision Research, 51,* 1907–1919.

Howe, P. D. L., Cohen, M. A., Pinto, Y., & Horowitz, T. S. (2010). Distinguishing between parallel and serial accounts of multiple object tracking. *Journal of Vision, 10*(8), 1–13.

Huff, M., Jahn, G., & Schwan, S. (2009). Tracking multiple objects across abrupt viewpoint changes. *Visual Cognition, 17,* 297–306.

Huff, M., Papenmeier, F., Jahn, G., & Hesse, F. W. (2010). Eye movements across viewpoint changes in multiple object tracking. *Visual Cognition, 18,* 1368–1391.

Intriligator, J., & Cavanagh, P. (2001). The spatial resolution of visual attention. *Cognitive Psychology, 43,* 171–216.

Iordanescu, L., Grabowecky, M., & Suzuki, S. (2009). Demand-based dynamic distribution of attention and monitoring of velocities during multiple-object tracking. *Journal of Vision, 9*(4), 1–12.

Koshino, H. (2001). Activation and inhibition of stimulus features in conjunction search. *Psychonomic Bulletin & Review, 8,* 294–300.

Liu, G., Austen, E. L., Booth, K. S., Fisher, B. D., Argue, R., Rempel, M. I., & Enns, J. T. (2005). Multiple-object tracking is based on scene, not retinal, coordinates. *Journal of Experimental Psychology. Human Perception and Performance, 31,* 235–247.

Luck, S. J. (1995). Multiple mechanisms of visual-spatial attention: Recent evidence from human electrophysiology. *Behavioural Brain Research, 71,* 113–123.

Makovski, T., & Jiang, Y. (2009). The role of visual working memory in attentive tracking of unique objects. *Journal of Experimental Psychology. Human Perception and Performance, 35,* 1687–1697.

Norman, D. A., & Bobrow, D. G. (1975). On data-limited and resource-limited processes. *Cognitive Psychology, 7,* 44–64.

Ogawa, H., Takeda, Y., & Yagi, A. (2002). Inhibitory tagging on randomly moving objects. *Psychological Science, 13,* 125–129.

Oksama, L., & Hyönä, J. (2004). Is multiple object tracking carried out automatically by an early vision mechanism independent of higher-order cognition? An individual difference approach. *Visual Cognition, 11,* 631–671.

Pinsk, M. A., Doniger, G. M., & Kastner, S. (2004). Push-pull mechanism of selective attention in human extrastriate cortex. *Journal of Neurophysiology, 92,* 622–629.

Pylyshyn, Z. W. (2004). Some puzzling findings in multiple object tracking (MOT): I. Tracking without keeping track of object identities. *Visual Cognition, 11,* 801–822.

Pylyshyn, Z. W. (2006). Some puzzling findings in multiple object tracking (MOT): II. Inhibition of moving nontargets. *Visual Cognition, 14,* 175–198.

Pylyshyn, Z., Haladjian, H., King, C., & Reilly, J. (2008). Selective nontarget inhibition in multiple object tracking (MOT). *Visual Cognition, 16,* 1011–1021.

Pylyshyn, Z. W., & Storm, R. W. (1988). Tracking multiple independent targets: Evidence for a parallel tracking mechanism. *Spatial Vision, 3,* 179–197.

Sears, C. R., & Pylyshyn, Z. W. (2000). Multiple object tracking and attentional processing. *Canadian Journal of Experimental Psychology, 54,* 1–14.

Shim, W. M., Alvarez, G. A., & Jiang, Y. V. (2008). Spatial separation between targets constrains maintenance of attention on multiple objects. *Psychonomic Bulletin & Review, 15,* 390–397.

Shooner, C., Tripathy, S. P., Bedell, H. E., & Öğmen, H. (2010). High-capacity, transient retention of direction-of-motion information for multiple moving objects. *Journal of Vision, 10*(6), 1–20.

Somers, D. C., Dale, A. M., Seiffert, A. E., & Tootell, R. B. H. (1999). Functional MRI reveals spatially specific attentional modulation in human primary visual cortex. *Proceedings of the National Academy of Sciences of the United States of America, 96,* 1663–1668.

Störmer, V. S., Li, S.-C., Heekeren, H. R., & Lindenberger, U. (2011). Feature-based interference from unattended visual field during attentional tracking in younger and older adults. *Journal of Vision, 11*(2), 1–12.

Suganuma, M., & Yokosawa, K. (2006). Grouping and trajectory storage in multiple object tracking: Impairments due to common item motions. *Perception, 35,* 483–495.

Tombu, M., & Seiffert, A. E. (2008). Attentional costs in multiple-object tracking. *Cognition, 108,* 1–25.

Tombu, M., & Seiffert, A. E. (2011). Tracking planets and moons: Mechanisms of object tracking revealed with a new paradigm. *Attention, Perception, & Psychophysics, 73,* 738–750.

Verstraten, F. A. J., Cavanagh, P., & Labianca, A. T. (2000). Limits of attentive tracking reveal temporal properties of attention. *Vision Research, 40,* 3651–3664.

Vul, E., Frank, M. C., Alvarez, G., & Tenenbaum, J. B. (2009). Explaining human multiple object tracking as resource-constrained approximate inference in a dynamic probabilistic model. In Y. Bengio, D. Schuurmans, J. Lafferty, C. K. I. Williams, & A. Culotta (Eds.), Advances in Neural Information Processing Systems 22 (pp. 1955–1963). Retrieved from http://books.nips.cc/papers/files/nips22/NIPS2009_0980.pdf

Yantis, S. (1992). Multielement visual tracking: Attention and perceptual organization. *Cognitive Psychology, 24,* 295–340.