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BRIEF REPORT

Changing target trajectories influences tracking performance

Justin M. Ericson · Melissa R. Beck

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Abstract People have the ability to attentively select and successfully track several moving objects, a process known as multiple-object tracking (MOT; Pylyshyn & Storm Spatial Vision 3: 179–197, 1988). Various factors have been known to influence MOT performance, such as speed, number of distractors, and proximity, while recent work has suggested that object trajectories may also be a factor (Fencsik, Kleiger, & Horowitz Perception and Psychophysics 69: 567–577, 2007). Meanwhile, unexpected changes in motion information have been demonstrated to be a critical facet for attracting attention Howard & Holcombe Attention, Perception & Psychophysics 72: 2087–2095, (2010). Therefore, we suggest that unexpected changes in target trajectories are an important factor in tracking performance. The research presented here controlled for spatial proximity while manipulating the number of instances in which an object changed trajectory. We found that spatial proximity had no effect on tracking performance but, rather, as the number of trajectory changes increased, tracking performance suffered. Results imply that the ability to track multiple moving objects is limited by unexpected changes in direction.

Keywords Visual perception · Attention

Imagine driving down a busy road tracking the locations of cars while keeping a safe distance to avoid collisions. If one of the cars unexpectedly changes lanes, this unexpected change may attract your attention away from the remaining cars. If another car changes lanes while attention is attracted away from it, an accident can occur. Tracking cars is similar to a laboratory task called *multiple-object tracking* (MOT), where participants must track several independently moving target objects simultaneously (Pylyshyn & Storm, 1988). Several factors are important to MOT performance, such as speed (Alvarez & Franconeri, 2007), number of distractors (Bettencourt & Somers, 2009), and the proximity of objects (Franconeri, Jonathon, & Scimeca, 2010; Pylyshyn, 2004). Recent research suggests that trajectory information is also important for MOT performance: Participants can represent trajectory information (Fencsik, Klieger, & Horowitz, 2007; Horowitz & Cohen, 2010; Iordanescu, Grabowecky, & Suzuki, 2009), they can detect changes in trajectory (Narasimhan, Tripathy, & Barrett, 2009; Pratt, Radulescu, Guo, & Abrams, 2010; Tripathy & Barrett, 2004), and when trajectory information is difficult to discern, MOT performance suffers (Howard & Holcombe, 2010; St. Clair, Huff, & Seiffert, 2010). However, to our knowledge, no studies have directly measured the impact of unexpected changes in trajectory on MOT performance.

The ability to represent trajectory information can be used to predict future trajectories of targets (Fencsik et al., 2007; Horowitz & Cohen, 2010; Horowitz & Kuzmova, 2010; Iordanescu et al., 2009). When trajectory information is difficult to discern or contradictory to the future path of motion, tracking performance can suffer. For example, when the textural surface motion of the tracked objects contradicts the trajectory, performance on the tracking task suffers (St. Clair et al., 2010). In addition, Iordanescu et al. demonstrated that knowing trajectory information is related to the ability to locate targets. Participants indicated the location of a target after all items were removed from the screen. Reported locations close to the actual location were also close to the motion trajectory of the target (Iordanescu et al., 2009). These results suggest that the ability to detect and represent trajectory information could be a primary factor in tracking performance.

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The ability to represent trajectory information is limited by the number of objects that can be represented and by the precision of the trajectory representation (Horowitz & Cohen, 2010; Narasimhan et al., 2009; Tripathy & Barrett, 2004). Tripathy and Barrett examined the ability to detect a change in trajectory for multiple moving objects. When trajectory changes were small, the trajectory of only one item could be monitored. However, if the changes were large, three to four objects could be monitored. Similarly, Horowitz and Cohen measured the deviation of perceived trajectory from the actual trajectory of tracked objects and found that as the tracking load increased, precision declined. This apparent capacity limit for representing trajectory information suggests that if one target required more resources for an accurate representation to be maintained, fewer resources would be available to maintain trajectory representation of the remaining targets.

Given that tracking performance relies on trajectory information and that there are limited resources available for representing trajectory information, unexpected changes in a target's trajectory may disrupt tracking performance by attracting attention away from other targets (Howard & Holcombe, 2010; Pratt et al., 2010). As evidence that changes in trajectory attract attention, Howard and Holcombe reported that participants were worse at reporting the orientation of a rotating grating on the surface of the target item if a nonqueried target had recently changed trajectory. Furthermore, adding a display boundary, such as a box, indicating where an object would change direction, eliminated the effect. This suggests that *unexpected* changes are more likely to attract attention and potentially have a negative effect on tracking ability.

Given the evidence that trajectory information is an important factor in tracking performance, unexpected changes in trajectory may be a confounding factor when it is not measured or controlled in tracking studies. Using a planets and moons tracking (PMT) design (Howe, Cohen, Pinto, & Horowitz, 2010; Tombu & Seiffert, 2011), in which target–distractor proximity is held constant, Franconeri et al. (2010) found that distance traveled was the greatest predictor for performance accuracy and concluded that this was the result of greater target–target proximity when a greater distance was traveled. However, the target–distractor pairs randomly changed trajectory every 0.1 to 2 revolutions, making it likely that pairs that traveled further also had more changes in trajectory. Therefore, it is possible that the unexpected changes in trajectory also contributed to the effect of distance traveled found in Franconeri et al.'s study.

In the present study, we hypothesized that unexpected changes in target trajectory would influence PMT performance. It has been suggested that in order to successfully perform MOT, a flexibly allocated resource is distributed across the target items (Alvarez & Franconeri, 2007). Furthermore, as was demonstrated by Howard and Holcombe (2010), although attention may initially be distributed to all the targets, attention may be attracted toward a target item that has recently changed direction and moved away from the remaining target items. Attentional resources would need to be directed to the changed target to update its trajectory representation. Meanwhile, the decrease in attentional resources toward the remaining targets may result in increases in tracking errors. Although targets are enhanced while distractors are suppressed (Doran & Hoffman, 2010; Pylyshyn, 2006), the fluctuating distribution of attention may affect the precision for target representations throughout the course of a MOT sequence, leading to potential confusions between targets and distractors.

In the present study, we used a PMT design similar to that in Franconeri et al. (2010) and manipulated the number of changes in trajectory. To test our hypothesis, we measured tracking performance while controlling for the cumulative distance the dots traveled (four or eight revolutions) and for the number of trajectory changes that occurred (one, four, or eight) for each target–distractor pair. This design affords the ability to determine whether the number and/or the frequency of trajectory changes affect performance. In addition to controlling for target–distractor proximity in the PMT design, we also account for target–target proximity.

Method

Participants

Twenty-four (3 male, 21 female) undergraduates, mean age of 19.75 years, with reported normal or corrected-to-normal vision, participated in the experiment for course credit.

Apparatus and stimuli

Stimuli were presented on three Apple iMac computers, with 20-in. LCD displays, with a 1,680 × 1,050 pixel resolution. The experiment was managed using MATLAB R2008b (The Mathworks Inc., Natick, MA) and the Psychophysics Toolbox (Brainerd, 1997; Pelli, 1997). Participants were seated 57 cm from the monitor, but viewing distance was not constrained. For each trial, eight black dots, each 0.5° of visual angle in diameter, were presented on a white background. Four dots were targets, and each target was paired with a corresponding distractor dot. The four target–distractor pairs were located around a cross in the center of the display; each pair rotated around a circle 2.8° in diameter, while the midpoint for each pair was placed on an imaginary square 7.8° per side (see Fig. 1).

The experiment employed a 3 × 2 factorial design with number of trajectory changes (one, four, or eight) and

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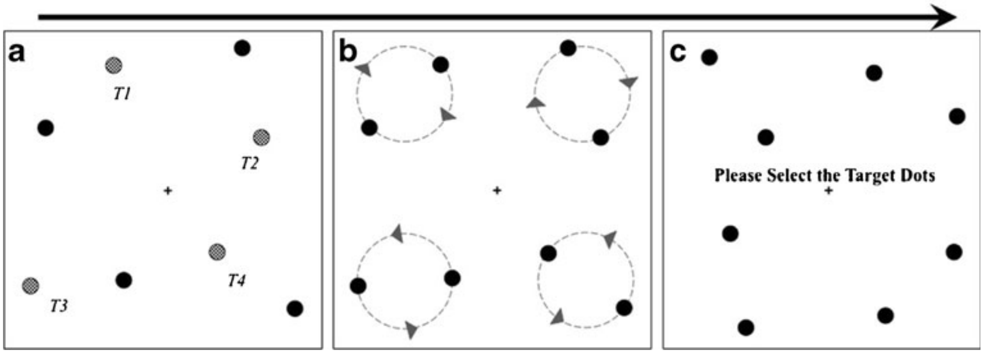

Fig. 1 Sample trial sequence **a** Targets cued in red, 2 s (labels included for identifying target pairs in spatial proximity analysis). **b** Cues removed 1 s; tone sounds and dot pairs begin rotational movement for either short (four revolutions) or long (eight revolutions) distances. **c** Dots stop moving, and participants use mouse and space bar to select the targets; feedback given for "correct" and "incorrect" responses

distance traveled (short, long) as within-subjects factors. Within a trial, each target–distractor pair changed trajectory independently of the other pairs 1, 4, or 8 times. Therefore, across all target–distractor pairs, there were a total of 4 trajectory changes in the 1-change condition, 16 in the 4-changes condition, and 32 in the 8-changes condition. Timing for trajectory changes was randomly predetermined for each pair. Trajectory changes were constrained so that each target–distractor pair traveled a minimum of 0.10 revolutions between each change and before the start and end of the trial. For example, in an 8-changes/4-revolutions trial, for each object pair, after a minimum of 0.10 revolutions, 8 subsequent changes in direction would occur with a minimum of 0.10 revolutions between each change and the final change occurring at least 0.10 revolutions from the end of the trial. Target–distractor pairs traveled at approximately 1.15 revolutions per second, for either 4 (short, 3.5 s) or 8 (long, 7 s) revolutions. Average times between trajectory changes by condition were 1,086 ms for 4-changes/4-revolutions, 543 ms for 8-changes/4-revolutions, 2,249 ms for 4-changes/8-revolutions, and 1,142 ms for 8-changes/8-revolutions.

Procedure

Instructions were presented both verbally and on the monitor. Participants were instructed to track four target dots, which were cued in red for 2 s. Once the cues were removed, a tone sounded indicating that the motion was about to begin. At the end of the motion sequence, participants selected one dot from each target–distractor pair by pointing at a dot with the mouse and pressing the space bar. Cue circles appeared around each selected dot, and feedback was provided with "Correct" or "Incorrect" presented above the cross at the center of the display. Trial conditions (number of trajectory changes × distance traveled) were randomly intermixed within four blocks, with each block containing 24 trials, resulting in 96 trials.

Results

The dependent variable was the proportion of targets accurately identified (see Fig. 2). Arcsine transformations were performed prior to each analysis; reported means are the nontransformed accuracies. A 3 × 2 repeated measures ANOVA for the number of trajectory changes (one, four, or eight) and the distance the objects traveled (short, long) revealed no significant interaction, $F(2, 46) = 0.12$, $p = .89$; significant main effects were found for both trajectory changes, $F(2, 46) = 7.00$, $p = .002$, $\eta_p^2 = .23$, and distance (short, $M = .89$, $SD = .09$; long, $M = .83$, $SD = .095$), $F(1, 15) = 55.98$, $p < .001$, $\eta_p^2 = .71$. Post hoc Bonferroni pairwise comparisons revealed a significant difference between the one ($M = .88$, $SD = .09$) and eight ($M = .85$, $SD = .10$) ($p = .014$), but not between the one and four ($M = .86$, $SD = .10$) or the four and eight trajectory change conditions. Planned comparisons revealed significant differences between the one and eight trajectory change conditions for both distances [short, $t(23) = 2.45$, $p = .022$; long, $t(23) = 2.43$, $p < .023$]. A main effect for trajectory changes

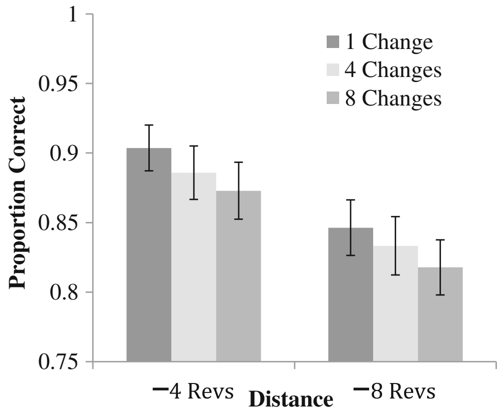

Fig. 2 Proportion correct for the number of trajectory changes by the number of total revolutions the target dot traveled (distance). *Error bars* represent standard errors of the means

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without an interaction with distance traveled suggests that it is the total number of changes, not the rate at which changes occur, that affects performance.

Using Franconeri et al.'s (2010; see supplemental material) method, we examined target–target proximity on the horizontal and vertical, not across the diagonal, resulting in four target–target pairs. We calculated the Euclidian distance between each target–target pair and recorded the number of frames that target–target pairs were closer than 7.8° to each other. On average, targets were approximately 7.9° apart; the distribution of target–target distances varied slightly across conditions (range = 0.06°). Specifically, short-distance conditions had larger standard deviations of distances than did the long-distance conditions, and the conditions with more changes had larger standard deviations than did conditions with fewer changes in trajectory. For example, in the long-distance one-change condition (SD = 0.03°), target–target pairs were more likely to remain approximately 7.9° apart for the entire trial, while in the short-distance eight-changes condition (SD = 0.09°), pairs spent slightly more time closer and further than 7.9° apart from each other. The proportion of correct responses for each target–target pair was examined in bins of 10 % increments according to the percentage of frames in which the targets were closer than 7.8°. Only four bins (25 %–35 %, M = .86, SD = .16; 35 %–45 %, M = .85, SD = .11; 45 %–55 %, M = .86, SD = .09; and 55 %–65 %, M = .89, SD = .10) had a sufficient number of data points and were used for the analysis (see Fig. 3).

We conducted a 4 × 4 (target–target pairs × proximity bins) repeated measures ANOVA. We found no significant interaction $F(9, 207) = 0.19$, $p = .99$, and no main effect for the target–target pairs $F(3, 69) = 0.86$, $p = .467$. We found a main effect for proximity $F(3, 69) = 10.27$, $p < .001$, $\eta_p^2 = .31$, indicating that target–target spatial proximity effects tracking performance. We found the closest target–target proximity (55 %–65 % bin) to be improving performance, thus causing this effect.

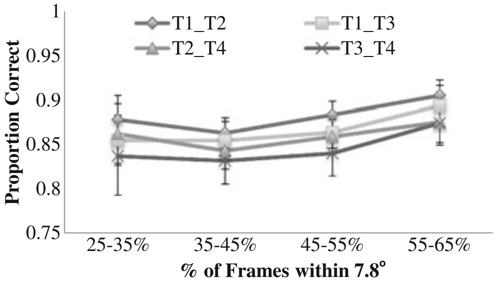

Fig. 3 Proportion correct for each target–target pair (T1 = top left target, T2 = top right target, T3 = bottom left target, and T4 = bottom right target) in each bin of spatial proximity. Bins are in 10 % increments for the percentage of trials on which the two targets were within 7.8° of visual angle with respect to each other

Due to the range of variability between experimental conditions, it is possible that as the number of changes in trajectory increased, the number of frames with close proximity (<7.8°) also increased. However, collapsed across target pairs and distance traveled, average proximity was the same (M = 7.9°), and although the standard deviations differed between conditions, the differences were very small (one change, SD = 0.01°; four changes, SD = 0.02°; eight changes, SD = 0.03°), suggesting no bias in proximity frames as the number of trajectory changes increased. To investigate the potential confound between target–target proximity and number of trajectory changes, we collapsed the proportion correct for the target–target pairs together, then examined whether the number of changes in trajectory affected performance differently, on the basis of the percentage of frames on which targets were close to each other (see Fig. 4).

We conducted a 3 × 4 (number of changes × proximity bin) repeated measures ANOVA. Analysis revealed no significant interaction, $F(6, 138) = 1.39$, $p = .22$. There was a main effect for proximity, $F(3, 69) = 12.14$, $p < .001$, $\eta_p^2 = .35$, but it is driven by higher accuracy when the targets are closer to each other (55 %–65 % bin). Finally, a significant main effect for the number of trajectory changes was found, $F(2, 46) = 11.81$, $p < .001$, $\eta_p^2 = .34$.

Discussion

Previous research suggests that object trajectory is an influential factor in the ability to track multiple moving objects (Fencsik et al., 2007; Horowitz & Cohen, 2010; Iordanescu et al., 2009; Narasimhan et al., 2009; St. Clair et al., 2010; Tripathy & Barrett, 2004) and that unexpected changes in the trajectory of an object can attract attention (Howard & Holcombe, 2010; Pratt et al., 2010). However, no studies have directly examined the effects of unexpected changes in trajectory on MOT performance while also controlling and/or measuring other factors that could impact MOT performance. Using a PMT task, we manipulated the number of trajectory

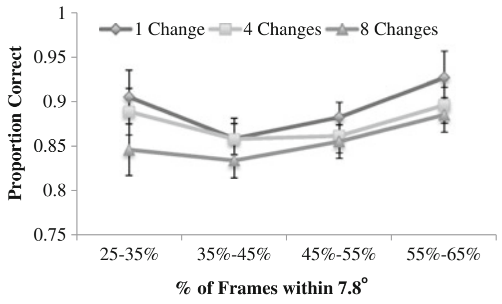

Fig. 4 Proportion correct for the number of trajectory changes in each bin of spatial proximity. Bins are the averaged 10 % increments for the percentage of trials on which the cumulative average of target–target pairs were within 7.8° of visual angle to each other

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changes while holding target–distractor distance and speed constant. We measured target–target proximity and manipulated distance traveled to determine whether these factors would interact with changes in trajectory. We found that as the number of trajectory changes increased, MOT accuracy decreased. Replicating Franconeri et al. (2010), we also found that participants had poorer performance when the objects traveled a longer distance, but no negative effect of target–target proximity on performance. Furthermore, changes in trajectory did not interact with distance traveled, demonstrating that it is the total number of changes, not the rate at which the changes occur, that increases the probability of errors in the tracking task. Because tracking performance relies on attention (Alvarez & Franconeri, 2007; Howe et al., 2010) and changes in trajectory attract attention (Howard & Holcombe, 2010; Pratt et al., 2010), it is likely that changes in trajectory increase tracking errors because they momentarily attract attention away from the nonchanging targets.

The advantage of using PMT instead of the traditional MOT task is the control of target–distractor proximity, which is imperative to being able to reliably test the effects of distance traveled and number of trajectory changes. There are also some potential disadvantages to using the PMT task. First, trajectory changes are unidirectional (Howe et al., 2010), meaning that even though you cannot anticipate when a change in trajectory will occur, the direction of the change is predictable. This “disadvantage” should decrease the effect of trajectory changes because unpredictable changes should result in a greater capture of attention (Howard & Holcombe, 2010; Pratt et al., 2010), whereas, in a standard MOT task, object movements are more variable and, therefore, trajectory changes are less predictable. A second disadvantage of using the PMT task is that the number of possible trajectory changes was limited, potentially limiting the effect size of the trajectory change variable. More than eight changes would have resulted in the appearance of the objects alternating back and forth across a very short distance on the display, rather than revolving. Therefore, if a traditional MOT task were used in which target–distractor distance was closely controlled and more than eight changes occurred, the effect of trajectory changes may be larger than that found here. Finally, the PMT design limited the target–target proximity. It is possible that if the targets were closer to each other, performance would have suffered.

In the present study, we did not find a negative effect of target–target proximity on MOT performance (Franconeri et al., 2010), suggesting that target–target proximity may be a factor in some situations but not others. For example, target–target proximity may be more likely to influence performance in displays where there are more opportunities for targets to come into close proximity of each other. In Franconeri et al., two additional central target–distractor pairs were presented; these central pairs may have increased the likelihood of an additional competition for attentional resources between objects. Specifically, when the central pairs are present, the likelihood of a distractor coming in close proximity of a target is higher. Target–target proximity may also be more of a factor in MOT performance when observers must maintain fixation at the center of the screen. In Franconeri et al.’s study, observers were required to maintain fixation, but this requirement was not present in the current study. Although participants are likely to look at a point between the targets (Fehd & Seiffert, 2008), they may bias attention toward targets that are in close proximity to each other. This direction of attention may occur more readily when participants are free to move their eyes, and this direction of attention and fixation may diminish the proximity effect. Therefore, the target–target proximity effect may be most prevalent during frequent close target–target contact, while attention is less easily directed toward these targets.

A distinguishing characteristic of our design, as opposed to other designs (Horowitz & Cohen, 2010; Iordanescu et al., 2009) used to examine motion or trajectory information of tracked objects, is that we directly manipulated trajectory information for the objects during the motion sequence, rather than relying on participant responses from a static set of items at the end of a trial. Performing a static selection at the end of a trial requires the observer to maintain a representation in working memory not just for the spatial location of the target objects, but also for the contextual motion information of the targets. The maintenance of this contextual information could come from an inner-scribe mechanism, a memory component that continually rehearses the motion information of the target items (Logie, 2011), utilizing other vital working memory resources. In the present study, all trajectory manipulations were conducted within the motion sequence of the trial, with only the spatial location for target items being maintained during the response process. Thus, the present design removes any other potential maintenance processes at test that could interfere with response selection.

In addition to the effect of trajectory changes, MOT performance also decreased as total distance traveled increased. MOT can be thought of as a sustained attention or vigilance task; as distance increases, the ability to maintain attention may decrease. In addition, attention during MOT is used as a flexible resource; attention can be allocated to several items or fewer items, depending on the difficulty of the tracking task (Alvarez & Franconeri, 2007). Therefore, as the distance increases, vigilance decreases, and the number of items that attention is allocated to could decrease. In the present study, we did not find an interaction between number of trajectory changes and distance traveled. This may be because, as distance increases and the number of objects tracked decreases, there are fewer trajectory changes to potentially capture attention and fewer tracked targets for

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the changed target to attract attention away from. In sum, just as a change in trajectory could pull attention away from other targets, attention may be more likely to wander away from items as the distance traveled increases.

In summary, the results here demonstrate that changes in target trajectory are an important factor for tracking performance. Changes in trajectory capture attention (Howard & Holcombe, 2010; Pratt et al., 2010), which would pull attention away from other targets and potentially increase tracking errors. Therefore, studies that do not control for or measure changes in target trajectory may be confounded, and the conclusions may need to be reconsidered. We suggest that limits associated with PMT performance are most likely related to abrupt changes in target trajectories, as well as the cumulative distance that targets travel and are less related to target–target proximity. These findings agree with previous work on target trajectories (Horowitz & Kuzmova, 2010; Howard & Holcombe, 2010; Pratt et al., 2010; Tripathy & Barrett, 2004) and support a tracking process that utilizes trajectory information, as proposed by St. Clair et al. (2010).

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