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Distractor locations influence multiple object tracking beyond interobject spacing: Evidence from equidistant distractor displacements

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Abstract

Human observers are able to keep track of several independently moving objects among other objects. Within theories of multiple object tracking (MOT), distractors are assumed to influence tracking performance only by their distance toward the next target. In order to test this assumption, we designed a variant of the MOT paradigm that involved spatially arranged target-distractor pairs and sudden displacements of distractors during a brief flash. Critically, these displacements maintained target-distractor spacing. Our results show that displacing distractors hurts tracking performance (Experiment 1). Importantly, target-distractor confusions occur within target-distractor pairs with displaced distractors (Experiment 2). This displacement effect increases with an increasing displacement angle (Experiment 3) but is equal at different distances between target and distractor (Experiment 4). This finding illustrates that distractors influence tracking performance beyond pure interobject spacing. We discuss how inhibitory processes as well as relations between targets and distractors might interfere with target tracking.

148 words

Distractor locations influence multiple object tracking beyond interobject spacing: Evidence from equidistant distractor displacements

Dynamic tasks in everyday life such as driving, watching sport events or supervising children on playgrounds often require human observers to keep track of several moving objects simultaneously. In laboratory experiments this ability is studied with the multiple object tracking paradigm (MOT). This task requires participants to track a set of target objects that move independently among indistinguishable distractors. Participants can typically track up to four or five objects (Pylyshyn & Storm, 1988). Several models have been proposed to explain the observed limitations of performance in MOT with indistinguishable objects. Convergently, these accounts argue that targets receive attentional priority whereas these models remain silent with respect to distractors or suggest that distractors modulate tracking performance only by their spatial proximity to the next target. In general, not much is known about distractor processing in MOT. In the present set of experiments, we provide evidence that distractors influence tracking performance beyond pure interobject spacing.

Pylyshyn and Storm (1988) explained tracking limitations with the FINST model (*FINgers of INSTantiation,* Pylyshyn, 2007). This model suggests that up to four or five pre-attentive indices remain attached to moving objects without requiring attention (but see Tombu & Seiffert, 2008). These indices allow quick attentional access to their corresponding targets during tracking. This is in line with faster change detection on targets than distractors (Sears & Pylyshyn, 2000). Regarding distractors, Pylyshyn (2006) argued that they are inhibited during tracking because detecting probes on distractors is more difficult than on the empty background. This conclusion is in line with experiments from Bettencourt and Somers (2009) who observed reduced tracking performance with more distractors in the display. Importantly, more distractors even hurt tracking performance when the display density was kept constant by enlarging the tracking area.

Cavanagh and Alvarez (2005) explained MOT performance with multifocal attention arguing that multiple locations receive attention simultaneously without attentional enhancement of the space in between (see also Müller, Malinowski, Gruber, & Hillyard, 2003). These multiple spotlights are directed by a control mechanism to stay upon the tracked objects (St. Clair, Huff, & Seiffert, 2010). In line with such a control mechanism directing spotlights, the lag between reported and objective target positions increases with tracking load (Howard & Holcombe, 2008; see also Howard, Masom, & Holcombe, 2011). In this account the role of distractors remains unspecified. It might be argued, however, that reduced target-distractor distances increase the difficulty of correctly directing the multiple spotlights on the target objects only.

Alvarez and Franconeri (2007) suggest that a limited attention resource is flexibly allocated between all actively tracked objects (FLEX). Attention resources are deployed to enhance the local resolution of attention and the required amount increases with individual target features such as increasing speed or decreasing distance to the next distractor. Whenever the sum of required resources exceeds the overall amount of resources, tracking performance declines. Franconeri, Jonathan, and Scimeca (2010) even suggested that interobject spacing is the only limitation for object tracking performance whereas the influence of other factors such as speed can be retraced to increasing the number of spatial interactions between objects (but see Holcombe & Chen, 2012; Tombu & Seiffert, 2011). To test this idea, Franconeri et al. (2010) designed a new variant of the MOT paradigm in which multiple pairs of objects were rotating around their center. They manipulated object speed as well as tracking duration and observed that tracking performance depended rather on the travelled distance than on the object speed itself. To explain these results, Franconeri et al. argued that longer motion paths moderate tracking performance by increasing the number of close interactions with other objects. Indeed, target and distractors are more likely confused when target-distractor distances are small (Bae & Flombaum, 2012) and there is evidence that decreasing target-distractor distance increases the precision of the representation of targets (Iordanescu, Grabowecky, & Suzuki, 2009).

Despite the lack of theoretical accounts addressing distractors during tracking, recent research has started to investigate how distractors interfere with targets during tracking. This research has mostly focused on the similarity of targets and distractors or the number of distractors presented in the tracking display. Typically, interference from distractors declines with an increasing number of distinguishing features such as the presence of motion, color, and shape (Feria, 2012; see also Papenmeier, Meyerhoff, Jahn, & Huff, 2014; Pylyshyn, Haladjian, King, & Reilly, 2008) and a decreasing number of distractors independent of the display density (Bettencourt & Somers, 2009). In contrast, the influence of the spatial information of visually indistinguishable distractors has not yet been systematically investigated although there is evidence that location information of distractors is processed during tracking. For instance, Alvarez and Oliva (2008) asked participants to identify an individual object location or the centroid of the targets or the distractors after brief interruptions at the end of a tracking trial. Although localization performance for individual objects was less precise for distractors than targets, it was still well above chance. Further evidence for the evaluation of distractor locations during tracking arises from a variant of the contextual cueing paradigm (Ogawa, Watanabe, & Yagi, 2009; see also Chun & Jiang, 1998). Ogawa et al. (2009) repeated motion paths of targets and/or distractors across multiple trials. Repeating targets and distractors enhanced performance above a pure repetition of targets suggesting that distractor information can guide attention towards targets.

The findings that distractor locations might be represented during multiple object tracking (Alvarez & Oliva, 2008; Ogawa et al., 2009) contrasts with the suggestion that only the spatial distance between targets and distractors modulated tracking performance. In order to explore this question, we designed a variant of the original MOT paradigm (Pylyshyn & Storm, 1988) that involved sudden displacements of distractors once during a trial. Brief flashes covered these displacements in order to prevent attentional capture from the abrupt displacements of the distractors. Importantly, all other factors that are known to influence tracking performance such as travel distance and spatial proximity (Franconeri et al., 2010) remained constant across conditions. To anticipate our results, we show that targets are lost more likely when a distractor is displaced at equal target-distractor spacing during the brief flash (Experiment 1). This displacement effect increases with the number of displaced distractors (Experiment 2) and the angular distance of distractor displacements (although small displacements have no effect, Experiment 3). Finally, interobject spacing has no effect on the displacement manipulation although tracking gets more difficult in general with close distractors (Experiment 4). Taken together, these results show that distractor locations are evaluated during object tracking and that the influence of distractors on tracking performance is not restricted to pure interobject spacing. We will discuss theoretical implications of these results in the general discussion.

Experiment 1

In Experiment 1, we investigated whether sudden displacements of distractors during a brief flash impair tracking performance. We asked participants to perform a tracking task with four out of eight objects. Once during the trial, the objects formed four target-distractor pairs, which occupied defined locations at one time during a trial. In the critical trials, we displaced the distractor of each pair around the associated target during a brief flash (to avoid abrupt onsets) thus changing the position of the distractor while preserving target locations and target-distractor spacing. Thus, if distractors interfered with target tracking only due to their spatial proximity to targets, this manipulation should leave tracking performance unaffected. In contrast, if distractor locations influenced tracking beyond interobject spacing, performance should be worse with displaced distractors.

Method

Participants

Ten students (10 female; 22-28 years) recruited from the participant pool of the Knowledge Media Research Center Tübingen participated in the experiment. All participants reported normal or corrected to normal vision and received monetary compensation for their participation. One additional participant was excluded due to chance level tracking performance.

Apparatus, Stimuli, and Procedure

All stimuli were presented on a 15.4’’ HP EliteBook 8530p with an ATI Mobility Radeon HD3650 video card at an unrestricted viewing distance of approximately 60cm under laboratory conditions. All trials were created offline by a program written in Python using the graphics software Blender.

Stimuli were eight identical white (174.54 cd/m^2, measured with a xrite i1pro) discs moving inside a light grey (27.49 cd/m^2) square wireframe that appeared against a black (0.27 cd/m^2) background. Each disc subtended 0.7 degrees of visual angle. The wireframe measured 15.4 by 15.4 degrees of visual angle. Each trial began with the presentation of the empty wireframe. After 2000ms the discs were positioned inside the wireframe. Four of them were designated as targets by flashing on and off in red (40.33 cd/m^2) four times in 200ms intervals and subsequently remained red for 2000ms before they turned back to white. Thereafter, all objects started to move at a constant speed of four degrees/s for 8000ms. This speed value was derived from previous experiments to ensure that average tracking performance was in the optimal measuring range between chance level and ceiling. Each time an object hit the wireframe, its movement was reflected in a physically correct way, however, objects streamed through each other in case of a collision event. After 2950ms, 3950ms, or 4950ms of object movement a brief flash turned the display white for 100ms. All objects stopped moving during the flash. Thereafter, objects continued moving for the remaining trial time. At the end of the tracking period all objects stopped and the mouse pointer appeared. Participants were instructed to mark all targets they were able to track and guess the remaining.

The trials were prearranged so that each distractor was close to one target (1.5-3.5 object diameter center-to-center distance), but far away from any other object in the display (minimum of 8 object diameters) at the moment of the flash. Because previous research has indicated that target-distractor spacing influences the attentional allocation in multiple object tracking for pairs of objects with a spatial separation of less than three degrees (Iordanescu et al., 2009), this minimum spacing ensures that displaced distractors may interfere only with the proximate target but not with any other object in the display. We used these rather implicit target-distractor associations to maintain the regular target tracking impression of randomly moving objects. To ensure this impression, the trials were generated starting from the moment of the flash by adding a randomly selected motion vector. Then, the remaining frames were calculated (forward and backward in time). In half of the trials, all distractors were displaced randomly around their associated targets. The displacement of a distractor always exceeded one object diameter to avoid overlaps with the previous position. Furthermore, distractor displacements maintained interobject spacing for each target-distractor pair – the distance between target and distractor was identical before and after the flash event. Targets were unaffected by the displacement manipulation (see Figure 1). The displacement manipulation also had no effect on the average interobject spacing which did not differ between trials with and without displacements, $t(10)=1.21$, $p=.253$ (average across all frames computed separately for each participant). Because previous research has demonstrated that tracking performance is immune against brief interruptions especially with temporarily stationary objects (Keane & Pylyshyn, 2006), we introduced the flash to avoid the perception of apparent motion in the condition with displaced distractors. The same spatial arrangement without displacing distractors was used in Meyerhoff, Papenmeier, Jahn, and Huff (2013).

Video demonstrations of our stimuli are available at http://www.iwm-kmrc.de/cybermedia/distractor-displacement/. Participants were debriefed with respect to the target-distractor manipulations before the experiment. Each participant performed 18 practice trials, and 120 experimental trials. The trials were presented in a randomized order.

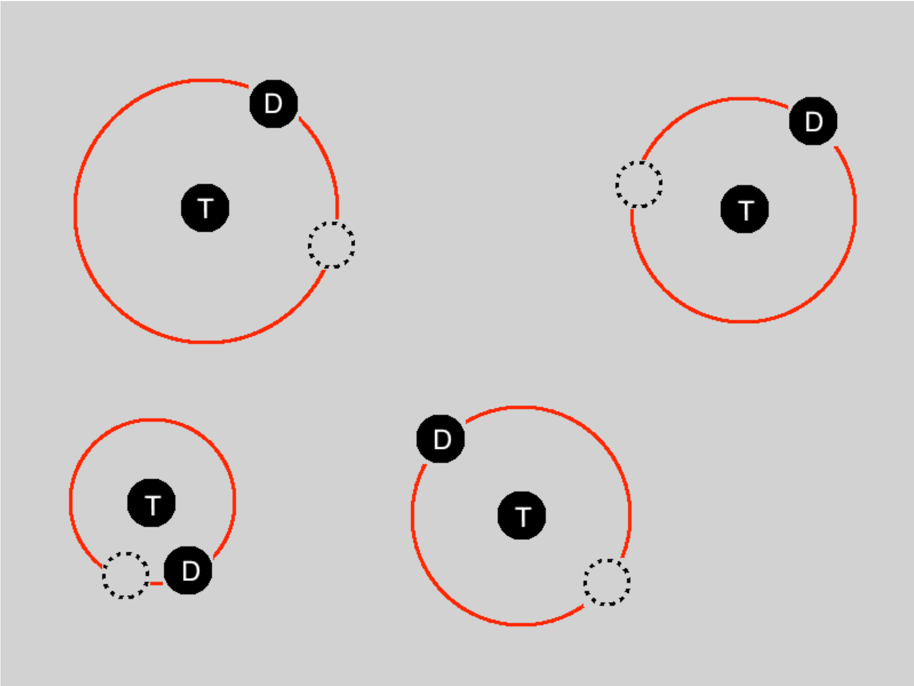

Figure 1. Illustration of the displacement manipulation of Experiment 1. Targets (T) were unaffected by this manipulation. Distractors (D) were displaced at equal target-distractor distances. Dotted object positions refer to previous distractor positions. Note that neither letters nor circular lines were visible during the experiment and that all objects were presented in white against a black background.

Results and Discussion

Participants performed worse when distractors were displaced during the trial. Mean proportion correct scores are plotted in Figure 2. A repeated-measures ANOVA with distractor displacement and duration of the tracking interval before the flash as independent variables confirmed impaired tracking performance following distractor displacements, *F*(1,

9) = 73.89, p < .001, η^2_p = 0.89. There was neither a main effect of the duration of the tracking interval before the flash, $F(1, 9) = 1.81$, p = .192, η^2_p = 0.17, nor did the duration of the tracking interval before the flash interact with the distractor displacement manipulation, $F(1, 9) = 2.31$, p = .128, η^2_p = 0.20. Because the displacement manipulation maintained spatial proximity between targets and distractors, this finding indicates that distractor locations influence tracking performance beyond pure target-distractor spacing.

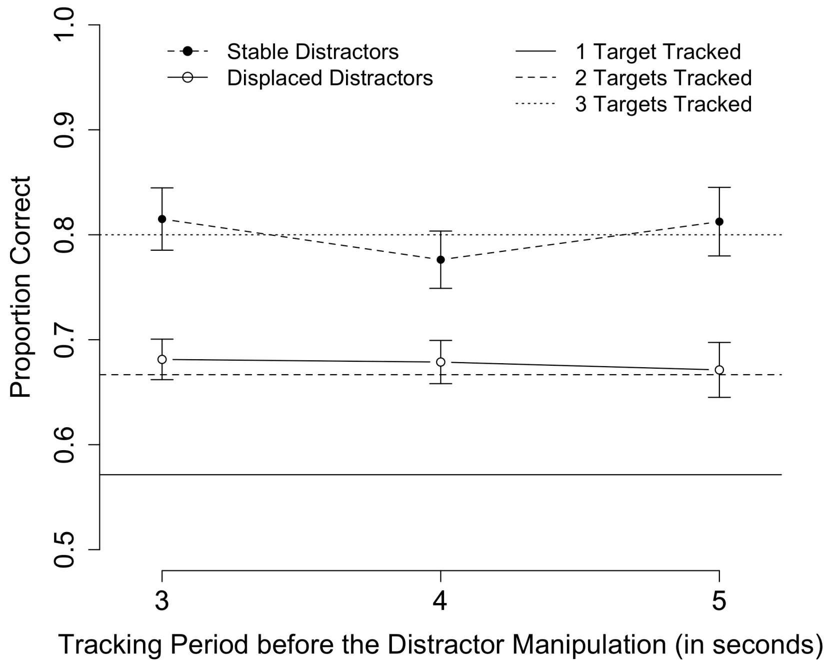

Figure 2. Mean proportion correct scores in Experiment 1. The solid, dashed, and dotted lines indicate expected performance for different tracking capacities (i.e., the number of actually tracked targets when corrected for guessing; see Hulleman, 2005). Error bars indicate the SEM.

Experiment 2

We argue that the distractor displacement effect of Experiment 1 indicates that distractors influence tracking beyond pure interobject spacing. In this experiment, we further explore the effect of distractor displacements at equal target-distractor distances. If distractor displacements affect tracking performance of the associated target, tracking errors should arise more frequently at target-distractor pairs with distractor displacements than at target-distractor pairs without distractor displacements. Thus, tracking errors should cumulate at pairs with distractor displacements. Alternatively, tracking errors might be equally distributed among target-distractor pairs with and without distractor displacements. Such a result pattern would suggest that participants failed to recognize the global object configuration (e.g., Jiang, Olson, & Chun, 2000; Papenmeier, Huff, & Schwan, 2011) after the flash thus leaving errors unrelated to individual distractor displacements.

In Experiment 2, we varied the number of displaced distractors to address this issue. If distractor locations influence tracking performance beyond pure spacing, targets with displaced distractors should get lost more likely than targets without displaced distractors. This predicts a linear decline in tracking performance with an increasing number of displaced distractors. Importantly, performance for targets without displaced distractors should exceed performance for targets with displaced distractors. Thus, participants should more likely identify targets without displaced distractors at the end of trials that include both targets with and targets without distractor displacements. Furthermore, participants should more likely incorrectly identify displaced distractors as targets in the same trials. Whereas a general linear decline in tracking performance also might be in line with the global configuration hypothesis, selective impairments at target-distractor pairs with displaced distractors would rule out this alternative account.

Method

Participants

Twelve new students (9 female; 19-31 years) were recruited from the same participant pool as those of Experiment 1.

Apparatus, Stimuli, and Procedure

Apparatus, stimuli, and procedure were identical to Experiment 1 with the following exceptions. All distractor displacements occurred after four seconds of tracking because Experiment 1 provided no evidence for possible effects of displacement anticipations. During the brief flash 0, 1, 2, 3, or 4 distractors were displaced around their spatially associated targets maintaining interobject spacing. The remaining distractors were not displaced.

Results and Discussion

Tracking performance declined with an increasing number of displaced distractors (see Figure 3). In order to evaluate the shape of this decline, we analyzed the proportion correct data with a linear mixed effects-model (lme; Baayen, 2008; Pinheiro, Bates, DebRoy, Sarkar, & R Development Core Team, 2011). This approach aims to model data with as few parameters as possible. Obviously, a saturated model with as many parameters as conditions always fits the data best but is rather uninformative. Thus, the most suitable model does not explain the data worse than the saturated model but has less parameters that can be interpreted such as intercept (i.e., the performance with 0 displaced distractors) and slope (i.e., the decline in performance for each additional distractor in the display). In all models, the participants were included as random effect. In order to analyze whether tracking performance decreases linearly with the number of displaced distractors, we tested a model with an intercept only (i.e., null-effect) against a model with an intercept and a slope (i.e., linear decline) and the model with intercept and slope against the saturated model. As visible in Table 1, this analysis confirmed that a model including intercept and slope explained the data significantly better than the model with the intercept only. Importantly, the model including intercept and slope does not explain the data significantly worse than the saturated model and thus is the most suitable model for our analysis. Thus, the lme-analysis confirmed that tracking performance decreases linearly with the number of displaced distractors.

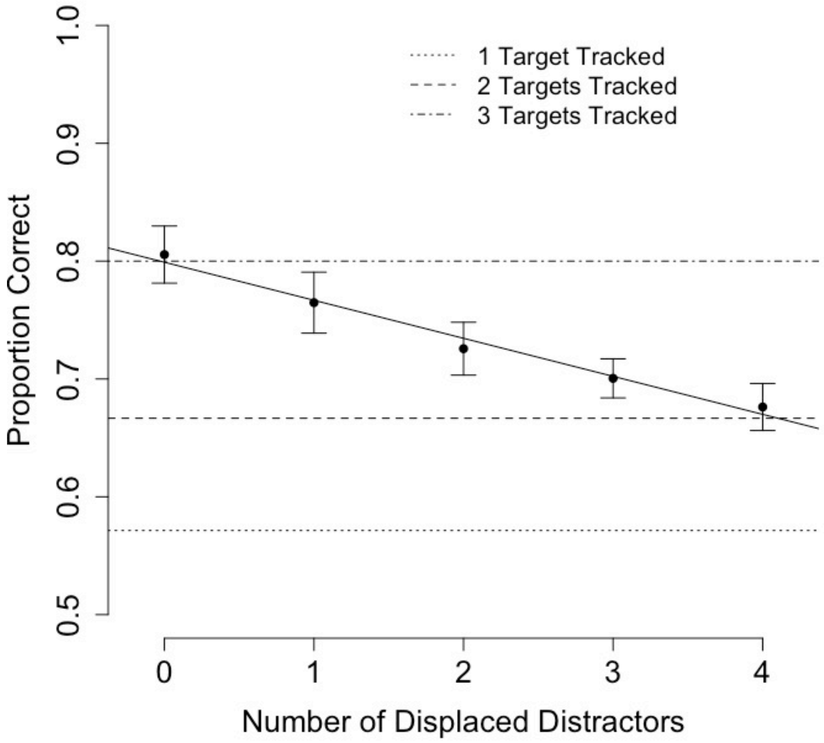

Figure 3. Mean proportion correct scores in Experiment 2. The solid line is the regression line. The dashed and dotted lines refer to tracking capacities (Hulleman, 2005). Error bars indicate the SEM.

Table 1. Results of the LME analysis of Experiment 2: Linear decline of tracking performance with an increasing number of displaced distractors

Model	df	AIC	Test	χ^2	*p*
1. Intercept	3	-134.26			
2. Intercept + Slope	4	-181.42	1 vs. 2	49.17	< .001
3. Saturated	7	-176.81	2 vs. 3	1.38	.709

To decide whether tracking errors arise selectively at targets with displaced distractors, we calculated the proportion of selected targets and distractors for target-distractor pairs with and without displaced distractors for the conditions with one, two, or three displaced distractors (see Figure 4). Note that the number of target-distractor pairs with and without distractor displacements was equal only in the condition with two displaced distractors. Then, we analyzed the proportion of selected objects with a repeated-measures ANOVA with identity (target vs. distractor), distractor displacement (displaced vs. stable distractor), and the total number of displaced distractors in a trial (1 vs. 2 vs. 3) as independent variables. Most importantly, we observed a strong interaction between the identity of the selected object and distractor displacement, $F(1, 11) = 18.54$, $p < .001$, $\eta^2_p = 0.63$. As visible in Figure 4, this interaction demonstrates that participants identified targets more likely at the end of the trial when their associated distractors remained stable during the flash whereas they falsely identified distractors more likely as targets when these distractors were displaced during the flash. Thus, our participants showed selective impairments at target-distractor pairs with displaced distractors. Of course, we also observed a main effect of the identity, $F(1, 11) = 107.46$, $p < .001$, $\eta^2_p = 0.91$, indicating that participants selected targets more likely than distractors at the end of the trials. No other main effect or interaction reached significance (all $p > .1$).

Overall, the results of Experiment 2 indicate that displacing distractors at equal interobject spacing hurts tracking performance because participants confuse targets with the displaced distractors (and unnoticedly track distractors). Most importantly, the selectivity of the tracking errors demonstrates that the displacement effect cannot be attributed to changes in the global configuration. In line with Experiment 1, this result indicates that distractor locations are evaluated beyond pure target-distractor spacing. Displacing a distractor induces uncertainty about the target identity even when the target remains at its previous location.

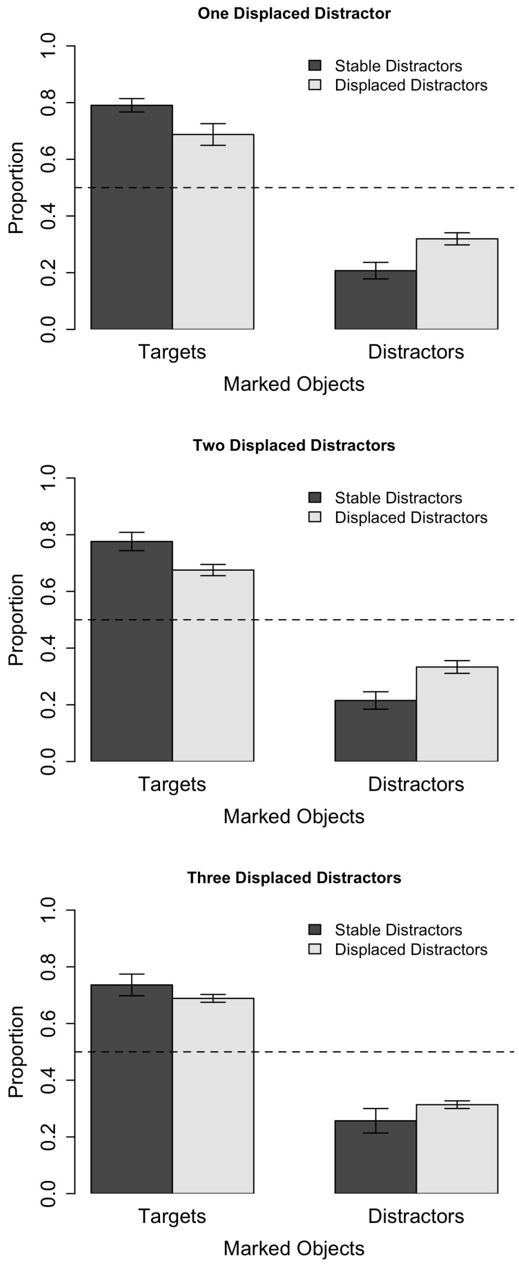

Figure 4. Results of the conditions with both displaced and stable distractors. The left bars indicate the proportion of correctly identified targets whereas the right bars indicate the proportion of distractors that were incorrectly identified as targets at the end of the trial. Note that the individual panels refer to the conditions with one (upper), two (middle), or three (lower) displaced distractors. Dark gray bars indicate pairs of targets and distractors without displacements whereas light grey bars indicate a pair of target and distractor with distractor displacement. The dashed line indicates chance level. Error bars indicate the SEM.

Experiment 3

Experiment 1 and 2 showed that displacing distractors impairs tracking performance. However, the amount of angular displacement varied randomly in the first two experiments. Therefore, we manipulated the angular displacement systematically within this experiment. We created trials in which three of the four distractors were displaced by different angles. In each trial one distractor remained at its previous location whereas the others were displaced by 50°, 100°, and 150°. If distractor locations influence tracking beyond pure spacing, more tracking errors should arise following larger displacements. In addition, if displaced distractors interfere with their associated target (see Experiment 2), distractors with larger displacements should be falsely identified as targets more likely at the end of a trial.

Method

Participants

Eleven new participants (8 female; 18-28 years) were recruited from the same participant pool as those of Experiment 1.

Apparatus, Stimuli, and Procedure

Apparatus, stimuli, and procedure were identical to Experiment 1 with the following exceptions. In all trials, three out of four distractors were displaced. We manipulated the amount of distractor displacement during the brief flash. In all trials one distractor remained at its previous location (0 degree displacement) whereas the others were displaced by 50, 100, and 150 degrees, respectively. Therefore, all trials included the same overall amount of distractor displacements.

Results and Discussion

As visible in Figure 5, multiple object tracking performance declined non-linearly with increasing displacement angles. Performance remained at the level of no displacements with displacements of 50 degrees. However, performance declined with displacements of 100 and 150 degrees. We analyzed the proportion of correctly identified targets and the proportion of falsely marked distractors for each value of distractor displacements. Note that each proportion arises from a single target-distractor pair of each trial. We conducted two repeated-measures ANOVAs with displacement angle as independent variable and either the proportion of correctly identified targets or the proportion of falsely marked distractors as dependent variable. Increasing displacement angles of distractors reduced the probability of correctly identifying the associated target, $F(3, 30) = 27.77$, $p < .001$, $\eta^2_p = 0.74$, but increased the probability of falsely marking the displaced distractor as target at the end of the trial, $F(3, 30) = 41.65$, $p < .001$, $\eta^2_p = 0.81$. Holm-corrected pairwise *t*-tests confirmed that the proportion of correctly identified targets did not differ significantly between the conditions with no displacements and a displacement angle of 50 degrees, whereas the conditions with displacement angles of 100 as well as 150 degrees differed significantly from all other conditions (all ps < .05). Results for the proportion of falsely marked distractors were comparable. Displacement angles of 100 as well as 150 degrees differed significantly from all other displacement angles (all ps < .05), whereas there was no significant difference between the 0 and 50 degrees conditions.

In general, the observation that increased displacements hurt tracking performance agrees with the suggestion that distractor locations influence tracking performance beyond pure target-distractor spacing. However, the finding that displacements of 50° have no effect (although the old and new distractor locations were not overlapping) is slightly unexpected. This indicates that displacements need to exceed a certain amount before they impair tracking performance. We will further elaborate on this finding in the general discussion.

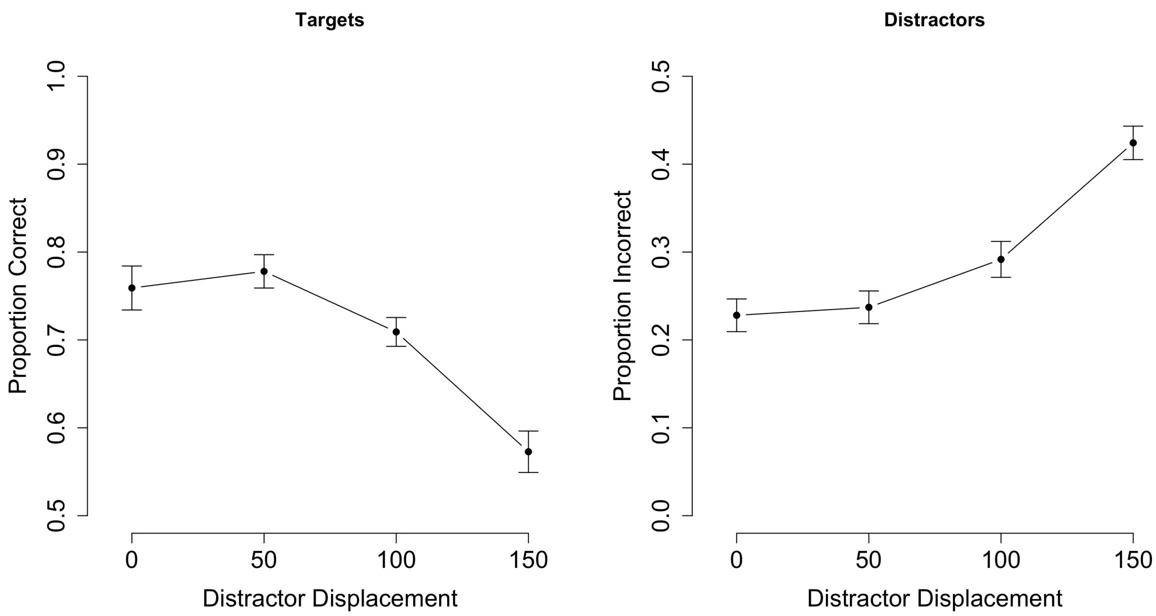

Figure 5. Mean proportion of correctly identified targets (left) and mean proportion of falsely marked distractors (right) in Experiment 3. Chance level is .5; error bars indicate the SEM.

Experiment 4

Experiment 3 demonstrated that increasing the angular displacements also increases the number of tracking errors with respect to the spatially associated target. In the final Experiment 4, we explore how target-distractor spacing interacts with the displacement manipulation. Therefore, we systematically manipulated the spacing between targets and their associated distractors. Specifically, this experiment explores whether the displacement effect occurs only for targets that are very close to the displaced distractor or whether tracking deficits after distractor displacements are a more general effect.

Method

Participants

Twelve new participants (all female; 20-27 years) were recruited from the same participant pool as those of Experiment 1.

Apparatus, Stimuli, and Procedure

Apparatus, stimuli, and procedure were identical to Experiment 1 with the following exceptions. We systematically varied the distance between targets and distractors. In each trial, the distances between the four target-distractor pairs during the flash were fixed to 1.1, 1.6, 2.1, and 2.6 degrees of visual angle. Thus, the overall distances in each trial were identical. Note that the reported distances are center-to-center distances. After the flash, distractors reappeared either at their previous positions or were displaced around their associated targets. All movement vectors remained constant across the flash interval. Each participant performed 24 practice trials, and 120 experimental trials presented in randomized order.

Results and Discussion

The effect of distractor displacements (i.e., the difference between targets with distractor displacements and targets without distractor displacements) was equal at different target-distractor spacings. In general, tracking performance declined when target-distractor distance was reduced. However, distractor displacements had an equal effect at all investigated target-distractor distances. Mean proportion correct scores are plotted in Figure 6. A repeated-measures ANOVA with distractor displacement and target-distractor distance as independent variables confirmed impaired tracking performance following distractor displacements, $F(1, 11) = 156.07$, $p < .001$, $\eta^2_p = 0.93$ and impaired tracking performance with reduced target-distractor distances, $F(3, 33) = 6.17$, $p = .002$, $\eta^2_p = 0.36$. The latter finding is in line with previous research showing that target tracking is less accurate in crowded situations (e.g., Franconeri et al., 2010). Most importantly, there was no interaction between the displacement manipulation and target-distractor distance, $F(3, 33) < 1$, $\eta^2_p = 0.08$, suggesting that the distractor displacement manipulation impaired tracking performance equally at all investigated target-distractor distances. Thus, performance in the conditions including distractor displacement decline only as expected by the general decline in tracking performance at reduced target-distractor distances.

Please note that even the farthest target-distractor distance in this experiment was only 2.6°. In our current paradigm, this reflects the upper limit because we need to avoid interactions between targets and distractors of different target-distractor pairings. Thus, it is possible that displacements at larger spacing might pass without costs in tracking accuracy. In line with Experiments 1-3, this experiment shows that not only the spatial distance between target and distractor influences tracking performance, but that the locations of distractors are also relevant for target tracking.

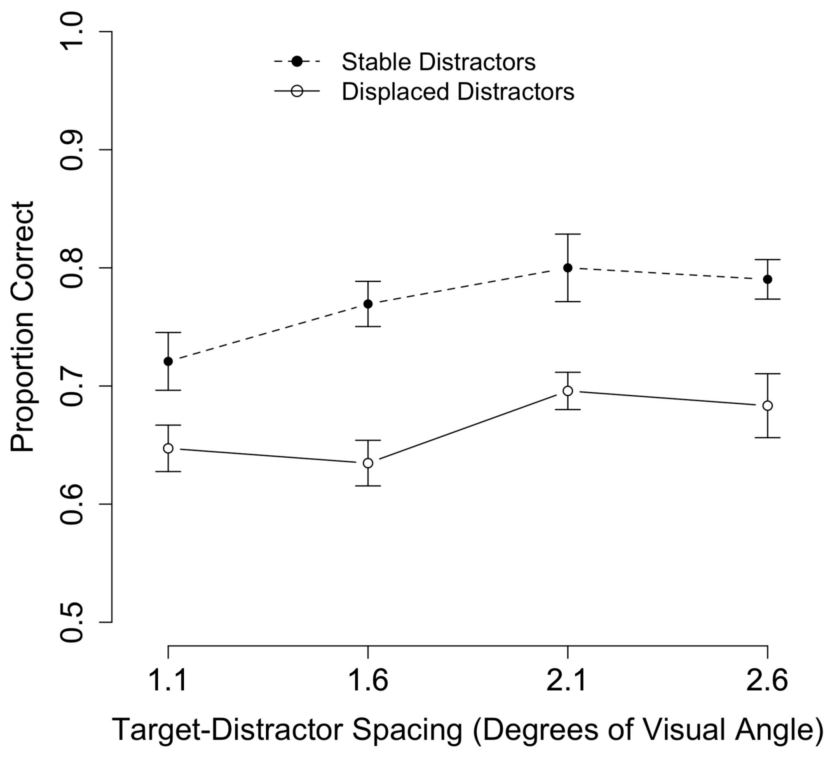

Figure 6. Mean proportion correct scores in Experiment 4. The reported distances are center-to-center distances. Chance level is .5; error bars indicate the SEM.

General Discussion

How do distractors influence tracking performance? One theoretical approach to this question can be derived from the FLEX model of Alvarez and Franconeri (2007). This account suggests that a flexible resource of attention is allocated between the tracked objects depending on momentary demands. In this terminology reduced interobject spacing might increase the actual tracking demand for a specific target. Franconeri et al. (2010) even suggested that target-distractor spacing provides the only limitation for object tracking performance and that all object factors influencing tracking performance such as speed can be retraced to a higher number of target-distractor interactions. For instance, effects of increasing the number of objects (e.g., Bettencourt & Somers, 2009), or object speed (e.g., Franconeri et al., 2010) might affect tracking only due to the increased numbers of close encounters. This suggestion is in line with findings that the target representations get more precise with decreasing target-distractor distances (Iordanescu et al., 2009) and also agrees with the observation that targets with close distractors are lost more frequently (Bae & Flombaum, 2012).

Here, we aimed to explore directly how distractors influence object tracking. More specific, our experiments were designed in order to investigate whether distractors influence object tracking despite equal interobject spacing. We do not claim that our results falsify the importance of target-distractor spacing for object tracking. Indeed, Experiment 4 even shows that a single event with reduced target-distractor spacing is sufficient to impair tracking performance for the whole trial. However, our results show that interobject spacing is not the only factor related to distractors that influences tracking performance.

Note that two aspects of our experimental paradigm differ from traditional tracking displays. First, we displaced distractors during the trial to disentangle interobject spacing from the exact locations of the distractors. Here, an alternative explanation would be that changing distractor locations just added noise to the display causing reduced tracking performance.

However, our results show selective tracking impairments at targets with displaced distractors. This impairment also depends on fine-grained factors such as displacement angle. Therefore, we consider it likely that our results are due to the changed distractor location rather than to additional noise. It also seems unlikely that the displacement manipulation induced a strategy emphasizing memory for distractor locations (for an inverse identification of targets) because these displacements occurred at unpredictable moments in time (Experiment 1) and were intermixed with trials without distractor displacements (all experiments). Further, tracking four moving objects at 8°/s probably is too demanding to voluntarily include distractor locations to the set of tracked objects (see Alvarez & Franconeri, 2007). Second, we introduced a brief flash in order to cover the displacement manipulation. This was necessary to avoid attentional capture at the new distractor location. Previous research has demonstrated that invisibility intervals of up to 900 ms leave tracking performance unaffected (Keane & Pylyshyn, 2006; Meyerhoff et al., 2011). Thus, it seems unlikely that the 100 ms flash enabled the effect of distractor displacements. The suggestion that interobject spacing might not be the only limiting factor during tracking is also supported by recent work demonstrating that object speed influences tracking performance directly rather than just by modulating interobject spacing (Holcombe & Chen, 2012; Tombu & Seiffert, 2011).

In our experiments, displacing a distractor around a spatially associated target increased the probability to confuse target and distractor and to switch to tracking the distractor although this displacement maintained the distance between target and distractor. Thus, our results demonstrate that distractors influence tracking performance beyond their pure spacing toward the next target. This finding can be resolved within the theories of MOT either by arguing that inhibited distractors are released from inhibition after the equidistant displacements or by arguing that spatial relations between target and distractors are maintained during object tracking. In the following section, we will elaborate on these two possibilities.

The first possibility to explain our results is to assume modulations in inhibitory processes on distractors after distractor displacements. When attention is focused on an object in space, sensory activation from the surround of the attended object is inhibited compared to locations that are further away from the focus of attention (Hopf, et al., 2006; Müller, Mollenhauer, Rösler, Kleinschmidt, 2005). As mentioned previously, Franconeri et al. (2010) suggested that inhibitory processes around tracked objects provide the only limitation for tracking performance. They argued that tracking performance declines only when a distractor breaks through the inhibitory surround of a close target or when the inhibitory surround of one target interferes with another target. This happens when the space between multiple targets (Shim, Alvarez & Jiang, 2008) or between targets and distractors (e.g., Bae & Flombaum, 2012; Bettencourt & Somers, 2009; Franconeri et al., 2010) decreases. Indeed, there is evidence for distractor inhibitions during tracking from both behavioral and ERP studies (e.g., Bettencourt & Somers, 2009; Doran & Hoffman, 2010a; Pylyshyn et al., 2008). In line with the studies exploring a single focus of attention, there is even evidence that distractors close to targets are more inhibited than distractors further away from targets during object tracking (Doran & Hoffman, 2010b). Within this framework, our results can be resolved by arguing that displaced distractors lose their inhibition and thus compete with tracked targets. This would suggest that inhibitory processes during object tracking are object-based. A potential concern regarding this explanation is that the effect of distractor displacements is equal for different target-distractor spacings although one might expect more inhibition for closer targets. Consequently, displacing close distractors should result in higher costs than displacing distractors farther away. However, because we had to avoid interactions between targets and distractors of different pairs of objects, even the farthest distance evaluated in our experiments might still be within the inhibition zone.

The second possibility to resolve the effect of distractor displacements is to assume that not only targets are tracked during object tracking but also relations between targets and distractors or the distractors themselves. With respect to the latter alternative, it seems unlikely that observers indeed temporarily track close distractors maintaining their identity in order to distinguish them from targets. Although it is possible to switch tracked objects voluntarily during tracking (i.e., multiple object juggling; Wolfe, Place, and Horowitz, 2007; see also Drew, Horowitz, Wolfe, & Vogel, 2012), tracking hidden identities reflects an extremely difficult task (Pylyshyn, 2004). Furthermore, because our target-distractor pairs are grouped up at the same time, this would require participants to track up to eight objects simultaneously. As demonstrated by earlier studies such a tracking load would clearly exceed the available capacities (e.g., Alvarez & Franconeri, 2007).

Instead of tracking distractors directly, we consider it more likely that the relations between targets and close distractors are evaluated during tracking. For instance, when a distractor is shifted to the right side of the same target, the probability of tracking errors increases. In this sense, targets and close distractors build a configuration that supports tracking. This suggestion is in line with previous experiments that highlighted the importance of target-target configurations for tracking performance (e.g., Fehd & Seiffert, 2008; Huff, Papenmeier, Jahn, & Hesse, 2010; Yantis, 1992). These experiments have demonstrated that tracking performance increases when participants track the polygon that is formed by the targets rather than individual target objects. Applying this logic to target-distractor relations would suggest that it might be easier to maintain a relation between a target and a distractor than one individual object.

An alternative to the latter account is that target locations might be generally encoded relative to distractor locations. Previous research has demonstrated that targets are encoded within a reference frame (Liu et al., 2005; Huff, Meyerhoff, Papenmeier, & Jahn, 2010; Meyerhoff, Huff, Papenmeier, Jahn, & Schwan, 2011). Thus it seems to be plausible that tracked objects can also be encoded with respect to other dynamic objects in the display. However, research from our own lab (Jahn, Papenmeier, Meyerhoff, & Huff, 2012) has shown that tracked objects are encoded with respect to reference objects in a display only when participants track very few objects (i.e., clearly less than four such as in the experiments reported here).

With respect to multiple object tracking in general, our results indicate that the role of distractors might have been underestimated. Independent of the exact explanation for the effect of distractor displacements, our results show that distractors influence tracking performance beyond pure target-distractor distances. The suggestion of a more active processing of distractor locations is also in line with the data of Alvarez and Oliva (2008) who have demonstrated that distractors in general are represented more precisely than expected by chance but less precisely than targets. This enables the possibility that distractors close to targets might be represented in the tracked configuration (e.g. Yantis, 1992) whereas distractors far from targets might be represented less precisely or not at all. When averaging across all distractors this results in a less precise overall representation of distractors than targets.

An interesting venue for future research would be to distinguish between the two proposed explanations for the effect of distractor displacements. To do so, one possibility would be to investigate by means of ERP experiments whether the tracking load changes dynamically before and/or during the displacement manipulation. Drew and Vogel (2008) reported two ERP components that vary with tracking load. Whereas the N2pc component reflects the number of selected objects, the contralateral delay activity (CDA) reflects the number of attentionally tracked objects. Further work showed that the CDA is sensitive to changes of tracking load within a trial (Drew et al., 2012). This sensitivity for tracking load results in different predictions for the explanation based on released inhibition and the explanation based on tracking relations between targets and distractors. If a loss of inhibition explains the distractor displacement effect, tracking load remains unaffected and therefore, CDA should not be sensitive to the displacement manipulation. In contrast, if participants track the relations between close targets and distractors (or even the distractors themselves), this should increase tracking load prior to the displacement manipulation and thus should be reflected in the CDA.

Conclusion

Most theories of MOT remain silent with respect to distractor processing. Typically, they suggest that distractors modulate tracking performance only by their spacing toward the next target. In four experiments, we manipulated distractor locations while preserving target-distractor spacing. Our experiments demonstrate that displacing distractors at equal target-distractor distances hurts tracking performance. This finding can be resolved within theories of multiple object tracking either by suggesting that displaced distractors are released from inhibitory processes or by suggesting that spatial relations between close targets and distractors are evaluated during tracking but lost after distractor displacements.

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