Multiple object tracking: Anticipatory attention doesn't "bounce"

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We investigated motion extrapolation in object tracking in two experiments. In Experiment 1, we used a multiple-object-tracking task (MOT; three targets, three distractors) combined with a probe detection task to investigate the distribution of attention around a target object. We found anisotropic probe detection rates with increased probe detection at locations where a target is heading. In Experiment 2, we introduced a black line (wall) in the center of the screen and block-wise manipulated the object's motion: either objects bounced realistically against the wall or objects went through the wall. Just before a target coincided with the wall, a probe could appear either along the bounce path or along the straight path. In addition to MOT, we included a single-object-tracking task (SOT; one target, five distractors) to control for attentional load. We found that linear extrapolation is dominant (better probe detection along the straight path than bounce path) regardless of attentional load and the motion condition. Anticipation of bouncing behavior did occur but only when attentional load was low. We conclude that attention is not tightly bound to moving target objects but encompasses the object's current position and the area in front of it. Furthermore, under the present experimental conditions, the visuo-attentional system does not seem to anticipate object bounces in the MOT task.

Keywords: multiple object tracking (MOT), visual attention, prediction, anticipation, motion, spatiotemporal information, attentional allocation

Citation: Atsma, J., Koning, A., & van Lier, R. (2012). Multiple object tracking: Anticipatory attention doesn't "bounce". *Journal of Vision*, *12*(13):1, 1–11, http://www.journalofvision.org/content/12/13/1, doi:10.1167/12.13.1.

Introduction

Our ability to visually track multiple objects is crucial in daily life. For example, when driving a car, you usually have to track several objects in order to avoid a collision. In such a context it is useful to encode not only an object's current position but also to predict where the object will be located in the near future. This prediction based on motion information is called motion extrapolation. Intuitively, motion extrapolation becomes more difficult when an object collides with another object, for example, when catching a ball that is about to bounce back from a wall. After all, in this case the angle of deflection also needs to be taken into account. Nevertheless, we appear to be able to do this very well as apparent from games like squash. In the abovementioned situations of motion extrapolation, attention plays an important role. When distracted from driving, you are less able to avoid collision (e.g., Brookhuis, de Vries, & de Waard, 1991). Similarly, when you are distracted while playing squash, you are less likely to correctly anticipate the location of a bouncing ball. In this study we will first investigate how attention is distributed around objects that are successfully being tracked. If motion extrapolation is used in a context of divided attention like tracking multiple objects, it is plausible that not only the object itself but also the area ahead of the object is attended. In addition, we will investigate the distribution of attention around objects that are about to bounce.

Previous studies have shown that we are readily able to extrapolate an object's motion path. For example, Ramachandran and Anstis (1983) used apparent motion displays in which the perceived direction of motion of dots was initially ambiguous. By adding

doi: 10.1167/12.13.1 Received March 19, 2012; published December 3, 2012 ISSN 1534-7362 © 2012 ARVO

neighboring dots, the authors manipulated the perceived direction of apparent motion and found that motion extrapolation can indeed bias the perceived direction of motion. The authors postulated that "if an object has once been seen moving in one direction, there is a strong tendency to continue seeing motion in that direction" (Ramachandran & Anstis, 1983, p.84). This suggests that an object's trajectory is extrapolated using the Gestalt law of good continuation (Ramachandran & Anstis, 1983; cf. Wertheimer, 1950): An object that is moving along a straight line is expected to continue to move in a similar direction. This can also be seen in a more recent study by Lyon and Waag (1995) who found that participants can accurately extrapolate a target's position in case of constant velocity circular motion paths. More related to the current study, with an emphasis on the role of attention, when a moving object suddenly disappears and an observer is asked to localize its final position, the observer's estimation is typically shifted in the direction of motion (e.g., Gray & Thornton, 2001; Hubbard, 1995; Iordanescu, Grabowecky, & Suzuki, 2009; Kerzel, 2003a, 2003b). However, when attention is diverted between the moment of object disappearance and response, the forward shift disappears (Kerzel, 2003a). This suggests that directed attention is a prerequisite for motion extrapolation. Verghese and McKee (2002) showed that motion extrapolation may occur also in a more automatic manner. They found that when, within a time window of 70–100 ms, unidirectional movement of a single dot is detected (among randomly moving dots), attention is automatically allocated to the subsequent segments of its trajectory leading to enhanced detectability of the dot. Recently Howard, Masom, and Holcombe (2011) reported that, in a multiple object tracking task (MOT, see below), after the disappearance of a target the remembered target location lagged behind the actual target location. These findings seem to be at odds with the findings that observers anticipate in the direction of motion. Howard et al. (2011) suggested that a combination of factors may have caused the lag without providing a definite conclusion. For example, they argued that encoding in short term memory might have caused the lag they found in their particular task as opposed to anticipatory processes as found in other tasks (as in, e.g., Iordanescu et al., 2009). In the current study, instead of focusing on remembered object locations, we focus on the attentional spread around targets during the actual movement.

In the last couple of decades, the functioning of the visuo-attentional system has been studied extensively using an MOT setting (Pylyshyn & Storm, 1988; see Scholl, 2007 for a review). In a typical MOT task, a group of target objects is tracked among a same-sized group of identical distractors. Due to the physical similarity of the objects, only spatiotemporal information can be used to identify the targets. It has been found that participants can track up to five targets (among five distractors). Beyond this number, performance declines rapidly (e.g., Oksama & Hyönä, 2004). During an MOT task, the distribution of attention can be measured using an additional task where appearances of brief dots (probes) have to be detected. Since attention increases visual resolution and therefore visual sensitivity (Handy, Kingstone, & Mangun, 1996; Yeshurun & Carrasco, 1998), detection of probes at specific locations can be used as a measure of the amount of attentional resources allocated to these locations. Using this double task it has been shown that attention is focused on the targets while the distractors appear to be actively inhibited (e.g., Flombaum, Scholl, & Pylyshyn, 2008; Pylyshyn, 2006). MOT combined with a probe detection task thus enables one to map the distribution of attention, while spatiotemporal information of the moving objects can be manipulated experimentally (e.g., Alvarez & Scholl, 2005; Flombaum et al., 2008).

How is attention distributed around a tracked object? Based on the studies mentioned above, we could expect that not only the object itself but also the area ahead of the object is attended. We will test this hypothesis in Experiment 1 by systematically probing locations around randomly moving target objects in an MOT task. Next, in Experiment 2, we will introduce an extra element (a horizontally oriented line) on the screen against which the objects can bounce. When a tracked object is about to bounce, motion extrapolation might take into account the object's (future) bounce-path. This should then be reflected by the spread of attention as measured with the probe detection task.

Experiment 1

The purpose of Experiment 1 is to map the spread of attention with respect to a target's movement direction. In MOT some locations may receive more attentional resources than others based on the objects' identity (target vs. distractor) and their spatiotemporal information (e.g., Alvarez & Scholl, 2005; Matsubara, Shioiri, & Yaguchi, 2007). Here, we use a probe detection task to measure attention at eight different angles relative to the target's movement direction. We hypothesized that probe detection is anisotropic. Particularly, we hypothesized that probes ahead of a target will be detected best, reflecting motion extrapolation. In addition, four distances from the target's center were probed to determine at what distance the target's motion has the most influence on the spread of attention.

Methods

Participants

Twenty-three undergraduate students of the Radboud University Nijmegen took part in the experiment and received course credits for participation. One participant was excluded from analysis because of incomplete data. The participants were aged between 17 and 23 years ($M = 19.2$, $SD = 1.8$). All reported normal or corrected-to-normal vision and were naive about the purpose of the experiment. Two were left-handed. All procedures were conformed to the Declaration of Helsinki.

Stimuli and design

Each trial involved three target and three distractor objects. The objects were all black circular outlines (0.4 cd/m^2) presented on a white background (99.9 cd/m^2) and each circle subtended 2.2° of the visual field (96 pixels). A trial started with a four-second target-designation phase where the targets blinked four times. After this phase, all objects started to move in random directions (using random 2D vectors). Object trajectories and probe locations were generated beforehand using custom made software written in C#. The objects were continuously visible and did not occlude each other. When an object approached the edge of the screen or another object, a new (pseudo) random direction would be assigned just prior to contact. This gave rise to unpredictable bouncing behavior of the objects with the screen's edges and with each other. Object speed was kept constant at 7.0°/s (300 pixels/s).

Probes were grey squares (47.1 cd/m^2) with a width of 0.09° (4 pixels) and could appear on/near an object only when it was more than 7.0° away from other objects. Probes moved along with the associated object which kept the angle and distance to the object's center constant. Each probe was presented for 100 ms (six frames). A total of 33 different probe locations were used. One of these locations was within a target and served as filler. These filler probes were introduced to make sure that attention is concentrated on the targets instead of the space around the targets to avoid ceiling effects, since the area covered by attention increases for large probe ranges (Matsubara, Shioiri, & Yaguchi, 2007). The remaining thirty-two locations were situated around a target and were calculated with respect to the target's movement direction. Eight angles and four distances were used (see Figure 1). The angles were separated by 45° intervals and 0° was always aligned with the target's movement direction. The distances from the target's center were 1.4°, 2.2°, 3.0°, and 3.8° (58, 94, 130, and 166 pixels, respectively). The first distance was very close to the target (0.23°). The fourth distance was more than one object length away but close enough so a probe would always be nearer to the corresponding target than to any other object. Each

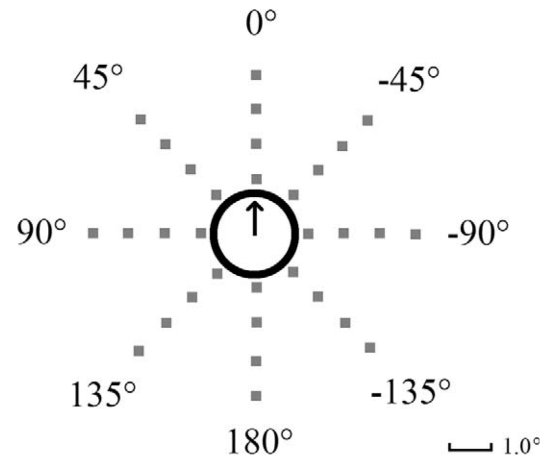

Figure 1. Probed locations in Experiment 1. A target object (black circle, 2.2° diameter) is shown with its movement direction depicted as a black arrow (the arrow was not visible during the experiment). Probe locations are depicted as grey squares (0.09°) and are positioned at eight angles and at four distances from the target's center: 1.4°, 2.2°, 3.0°, and 3.8°.

location around the target was probed six times per participant leading to $32 \times 6 = 192$ experimental probes. An equal amount (192) of filler probes was used. The 384 probes total were divided over 77 trials where all trials contained five probes except for one (which contained four probes). Each trial had a total duration of 20 s and probes within a trial were separated by randomized 1.3–7 s intervals.

Procedure

Participants were seated in front of a CRT monitor (resolution of 1280 × 1024 pixels, refresh rate 60 Hz) and operated a standard QWERTY keyboard and computer mouse to perform the task. Participants were positioned roughly 60 cm from the monitor so the display subtended approximately 30° × 24° of visual angle. Displays were smoothly rendered using a custom made Delphi application. Participants were instructed to keep track of the targets and to respond to brief grey dots (probes) which could appear at any time and at any location. The required response for the detection of a probe was a spacebar press. Participants were instructed to click on the target objects once all objects stopped moving (no feedback was given). Before the actual experiment started, participants received five practice trials. For each participant a new set of object trajectories was calculated. The whole experiment lasted approximately 35 min.

Results

Tracking accuracy was high among the twenty-two analyzed participants ($M = 94.3\%$, $SD = 3.0$). Only spacebar presses that occurred within 1000 milliseconds after probe appearance were counted as a hit (cf. Flombaum et al., 2008). Individual probe detection rates ranged from 10.7% to 75.6% ($M = 41.7\%$, $SD = 18.7$). Figure 2a shows the (interpolated) mean detection rates for all probe locations (in color codes). The plot suggests that probe detection is anisotropic.

To more closely examine the detection rates at each distance, we performed four repeated measures ANOVAs (one for each distance) with angle (eight levels: 180°, 135°, 90°, 45°, 0°, −45°, −90°, −135°) as the independent variable and probe detection rate as the dependent variable. To correct for multiple comparisons, Bonferroni correction was applied leading to alpha being set at (0.05/4) = 0.0125. For the two distances closest to the object no effect of angle was found (respectively: $p = 0.92$ and $p = 0.08$). Likewise, for the largest distance also no effect of angle was found ($p = 0.65$). For the third distance a highly significant main effect of angle was found, $F(7, 15) = 3.68$, $p < 0.005$. Next, for this third distance (see Figure 2b) we tested the hypothesis that probes ahead of the target are detected best. We defined ahead as 45°, 0°, and −45°. We contrasted ahead with the remaining angles (135°, 90°, 180°, −90°, −135°) and found a significant difference, $F(1, 21) = 11.56$, $p < 0.005$. To further investigate this effect, we subdivided these remaining angles into two groups, behind (135°, 180°, −135°) and middle (90°, −90°). We found that probe detection was higher ahead compared to behind the target, $F(1, 21) = 13.84$, $p < 0.005$. Ahead versus middle and middle versus behind did not differ significantly ($p = 0.07$ and $p = 0.05$, respectively). Note that along the movement direction, the left and right side do not differ significantly. More precisely, when focusing on the third distance and leaving out the 0° and 180° levels, a repeated measures ANOVA with the independent variables side (2 levels: +, −) and angle (3 levels: 45, 90, 180) showed a main effect of angle, $F(2, 20) = 5.74$, $p < 0.01$, but not of side ($p = 0.84$) nor was the interaction significant ($p = 0.14$). Pair-wise comparing individual angles (e.g., −45 and 45) did not show significant differences either.

We additionally tested for learning effects using linear regression analyses (by splitting the data into three equal quantiles) and found no learning effects. In fact probe-detection performance dropped slightly over the course of the experiment, $\beta = -.276$, $F(1, 64) = 5.26$, $p < 0.05$, $R^2 = .08$. Tracking performance also seemed to drop although not significantly, $\beta = -.214$, $F(1, 64) = 3.07$, $p = 0.08$, $R^2 = .05$. This decrease in performance possibly represents fatigue of the participants. To test whether there might exist a tradeoff between probe detection and tracking performance, for each participant we compared the mean probe detection rate in the nonperfect-tracking with the mean probe detection rate in the perfect-tracking trials, but found no significant difference, $t(20) = 1.73$, $p = 0.10$.

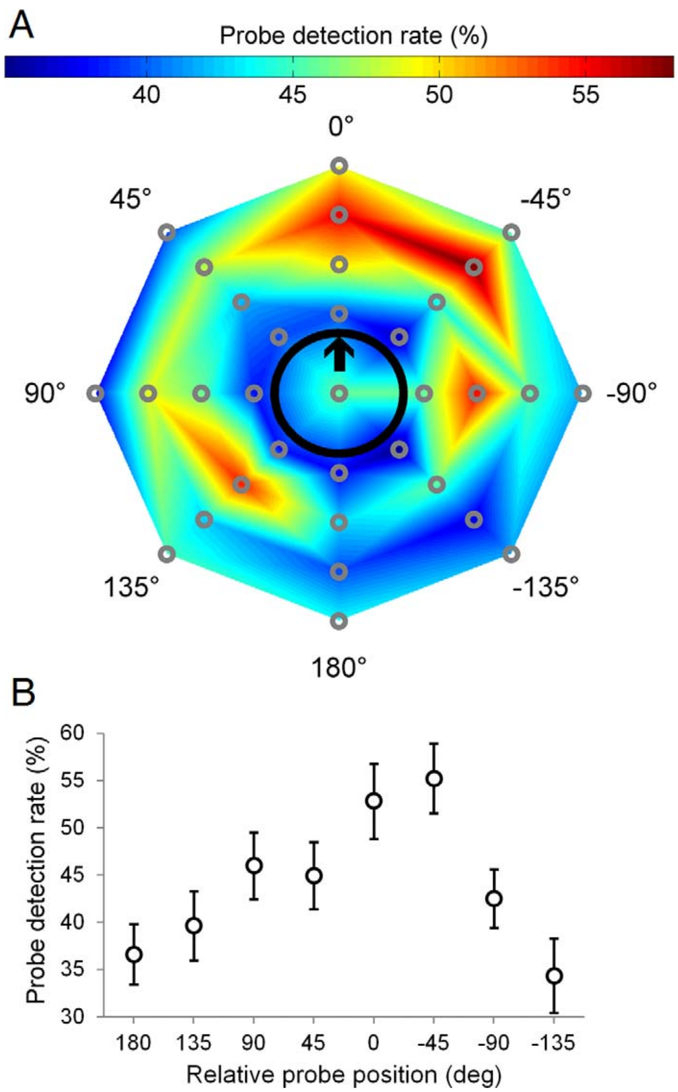

Figure 2. Mean probe detection rates in Experiment 1. (A) Shows all thirty-three probed locations. A target object (black circle) is shown with its movement direction depicted as a black arrow (the arrow was not visible during the experiment). The probe locations are depicted as grey circles. Detection rates are represented using (linear) interpolation and color coding, with a distribution as shown in the legend at the top of the figure. (B) Probe detection at the third distance. Angle 0 represents the target's movement direction. Error bars show *SEM*.

Discussion

In the present experiment, we mapped the spread of attention around an MOT target with respect to its movement direction. We hypothesized that the spread of attention around a target would be anisotropic. Particularly, we hypothesized that the area ahead of a moving target would receive more attentional resources compared the area behind the moving target. This hypothesis was confirmed. Visual inspection of Figure 2 reveals higher detection rates for probes presented in front of the moving target as compared to locations behind the moving target. Note that the probe detection task may have biased attention towards the area surrounding the targets. However, since the probes were distributed isotropically, an anisotropic bias cannot be attributed to the layout of the probe locations.

Analyses revealed that for the third distance from the target's center (3.0°) a significant difference between probe detection rates was found, and a subsequent analysis showed that probes in front of the target (45°, 0°, −45°) were detected significantly more often than probes behind the target (135°, 180°, −135°). The variability in detection rate within the second distance appears rather salient in Figure 2a but does not appear to be significant. The very low detection rate for the smallest distance is quite remarkable; probes that appeared 1.4° from a target's center were detected less often than probes at other distances. This finding might be due to the very near presence (0.23°) of the target's edge. Possibly, this created less probe-background contrast (by means of crowding) which made probes harder to spot.

This experiment showed increased attention in the direction a target is heading. Given that the objects moved at a rate of 7.0° per second, a target moved 3.0° in 433 milliseconds. Now, assuming that the visual system uses the center of an object (cf. Alvarez & Scholl, 2005) as a reference for calculating motion extrapolation, here it seems that the targets' motion paths were extrapolated around 400 milliseconds ahead. This finding is in line with previous research investigating an observer's estimation of future object locations based on motion extrapolation (e.g., Gray & Thornton, 2001; Hubbard, 1995; Iordanescu, Grabowecky, & Suzuki, 2009; Kerzel, 2003a, 2003b).

The results point in a direction that differs from the earlier discussed findings of Howard et al. (2011). However, recalling a target's location (as in Howard et al., 2011) and the sensitivity of detecting probes around an actual moving target (as in our Experiment 1) may very well appeal to different updating mechanisms. Although the memory of a target's location may lag behind its exact location, the attentional spread around a moving target may still be biased in a forward direction.

Our results indicate that attentional allocation need not be bound to moving objects themselves, but rather to a larger area around the attended objects with a preference towards their motion direction. This can be taken to mean that in an MOT task, the attentional system always tends to anticipate the future location of a target object. Such future locations may be just ahead of the current position (in the direction of the motion) or may follow a different but plausible trajectory, for example after a bounce. In Experiment 2 we will explicitly test this.

Experiment 2

When you have to catch a ball that is thrown against a wall, it seems necessary to anticipate the bounce off the wall. Relying only on linear motion extrapolation, as found in Experiment 1, is likely to result in being too late to catch a ball. Rather, attentional allocation using top-down information, such as knowledge about kinetics, seems necessary in order to correctly predict a ball's post-bounce location. Previous studies have shown that in ball sports, such as for example cricket, perceiving the prebounce ball flight is used to predict the ball's trajectory, especially by skilled players (Müller & Abernethy, 2006). This prediction may then be reflected by a heightening of attention at regions along the object's bounce path. In Experiment 2 we will investigate this hypothesis using the MOT paradigm combined with a probe detection task, which to our knowledge has not been done before.

In order to test anticipatory behavior in case of object bounces, a black horizontal line is introduced in the center of the screen. This line could act either as a solid wall off which the objects could bounce in a physically plausible way or not (objects keep on moving in the same direction). So in one condition the objects would realistically bounce off the wall (bounce-motion condition), whereas in the other condition the objects will move straight through the wall (straight-motion condition). Similar to Experiment 1, we will use probe detection rates as a measure of attention at specific locations. More specifically, when a target is about to hit the wall, we will probe along the straight path (linear motion extrapolation) and along the bounce path (anticipatory motion extrapolation).

Previous MOT studies suggest that the location of disocclusion is not anticipated (e.g., Franconeri, Pylyshyn, & Scholl, 2005; Keane & Pylyshyn, 2006). It's possible that in order to extrapolate an object's motion path the object's motion information must continuously be present at the proximal level. In addition, including the results of our Experiment 1 and the study by Verghese and McKee (2002), it might thus be expected that probes along the straight path will be detected more often compared to probes along the bounce path, regardless of whether or not the objects bounce. If this would be the case, it could mean that the attentional load in MOT is too high for taking into account object bounces and thus to anticipate object movement. To control for this, a less attentional demanding tracking situation was administered: single object tracking (SOT). Similar to the block-wise administration of the bounce versus straight motion, SOT and MOT conditions are administered block-wise.

We hypothesize that when a target object is about to bounce, the distribution of attention around the target differs from the straight-motion situation in a way that reflects bounce anticipation. This could mean enhanced probe detection at the bounce path, a decreased probe detection at the straight path, or both. Furthermore, we expect bounce anticipation to be more pronounced in the SOT task compared to the MOT task.

Methods

Participants

Nineteen undergraduate students of the Radboud University Nijmegen took part in the experiment and received course credits for participation. All participants reported normal or corrected-to-normal vision and were naive about the purpose of the experiment. All participants were right-handed. All procedures were conformed to the Declaration of Helsinki.

Stimuli and design

Stimuli were the same as in Experiment 1, with the following exceptions: When an object hit another object or the edge of the screen, it now deflected in a physically plausible way (instead of randomly). This was realized by taking into account the angle of incidence when the object trajectories were calculated. In addition, a horizontal black line (to be referred to as the wall) was positioned in the center of the screen (dimensions: 16.4° × 0.2°/700 × 10 pixels). In the bounce-motion condition, the objects bounced realistically off the wall while in the straight-motion condition objects ignored it and could be perceived as going straight through the wall; see Figure 3a. When the objects hit each other or the edges of the screen they also deflected in a plausible manner in the straight-motion condition. Thus, only the object's behavior with respect to the wall was different.

Regarding the probes, when a target object approached the wall, one of six locations around the target could be probed. Probe presentation ended when the target had reached the wall. Probes appeared at three different distances along either the target's direction of movement (straight-path probes) or along the direction of a possible bounce (bounce-path probes); see Figure 3b. The probed distances were the same as in Experiment 1 with the omission of the smallest distance because probes at 1.4° would coincide with the wall. A target could approach the wall from any angle provided that the probes did not coincide with the wall. All precalculated trajectories were presented twice, once with a probe appearing along the straight path and once along the bounce path.

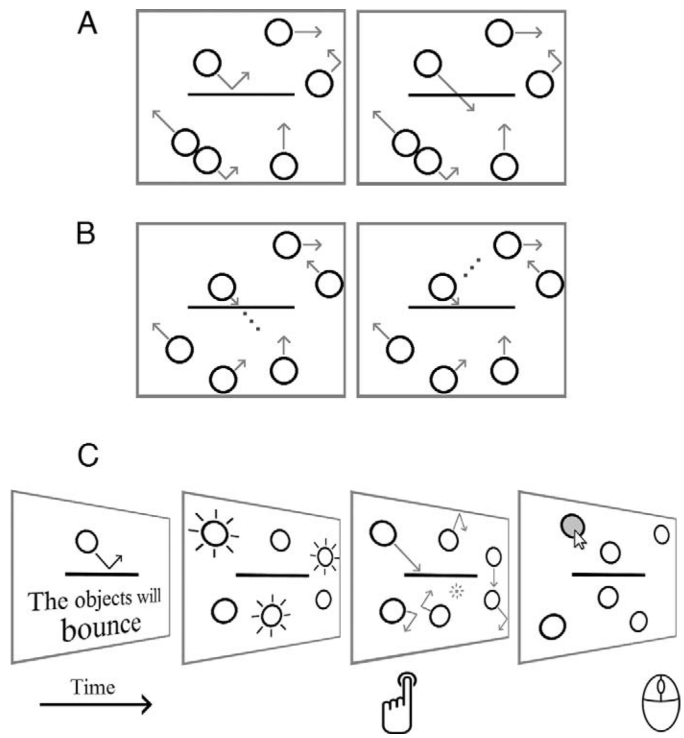

Figure 3. Illustration of the conditions and task of Experiment 2. (A) When an object collided with the edge of the screen or another object, it bounced in a physically plausible way. A horizontal black line was positioned in the center of the screen (wall). In the bounce-motion condition (left), objects bounced against this wall. In the straight-motion condition (right), objects moved straight through the wall. (B) Left image: Straight-path probes were presented at three distances along the target's movement direction. Right image: Bounce-path probes were presented at three distances along the direction of a possible bounce. (C) Timeline of the procedure. Each block (ten trials) started with a text and 6 s animation showing the motion condition. Next, depending on the task of that specific block (i.e., multiple object tracking or single object tracking), one or three of the objects (black circles) was/were highlighted for 4 seconds, signaling which object(s) to track. After this, all objects started to move for sixteen seconds and brief probes appeared which required a button press. Once all objects were static again the participant selected the target(s) with the mouse, after which the next trial was initiated.

In both the SOT and the MOT tasks, the bounce- and straight-motion conditions were presented, making up a total of four different blocks. Each of the six probe locations (three straight-path and three bounce-path probes) was probed eight times per block, leading to a total of 48 experimental probes. In contrast to Experiment 1 all probes were stationary because otherwise bounce-path probes would move into a different direction (the bounce direction) than the target object, which would possibly create a response bias as this is likely to draw participant's attention. Finally, open-space probes were added to decrease the probability of probes occurring around the wall. Open space probes appeared at random locations and were pseudorandomly alternated with experimental probes. A one to one ratio of experimental and open space probes was used, leading to 48 + 48 = 96 probes per block. These 96 probes were divided over 20 trials. Each trial contained zero to seven probes at 1.5–7 s (pseudorandomized) intervals. In sum, the number of probes that were presented to each participant was 4 Blocks × 96 Probes per Block = 384. Each block was split into two groups of 10 trials, which brings a total of 80 trials. The blocks were presented in randomized order.

Procedure

The procedure was the same as Experiment 1, with the following exceptions: Participants were told that the experiment comprised eight blocks of ten trials (with each type of block being presented twice) and that each block started with a short (6 s) animation in which the condition (bounce-motion or straight-motion) was illustrated (see Figure 3c). Furthermore, participants were told that half of the blocks contained one target and five distractors whereas the other half contained three targets and three distractors. The experiment lasted approximately 40 min.

Results

Tracking accuracy was high among all participants ($M = 87.4\%$, $SD = 9.0$). First, to investigate tracking performance across the four blocks, a repeated measures ANOVA with the independent variables task (two: SOT, MOT) and motion (two: bounce, straight) was performed. This revealed a significant main effect of Task, $F(1, 18) = 42.5$, $p < 0.001$, with better tracking for SOT as compared to MOT (see Figure 4). There was no effect of motion on tracking performance ($F < 1$). Regarding probe detection performance, because SOT and MOT are essentially different task-sets (as evidenced by the main effect of tracking performance), we will analyze the probe detection rates for each task separately. First, we will analyze the SOT task using a repeated measures ANOVA with motion (two), probed path (two), and distance (three) as independent variables and probe detection rate as the dependent variable. Second, we will analyze the MOT task in the same way as the SOT. For both analyses, only spacebar presses that occurred within 1000 milliseconds after probe appearance were counted as a hit (cf. Flombaum et al., 2008).

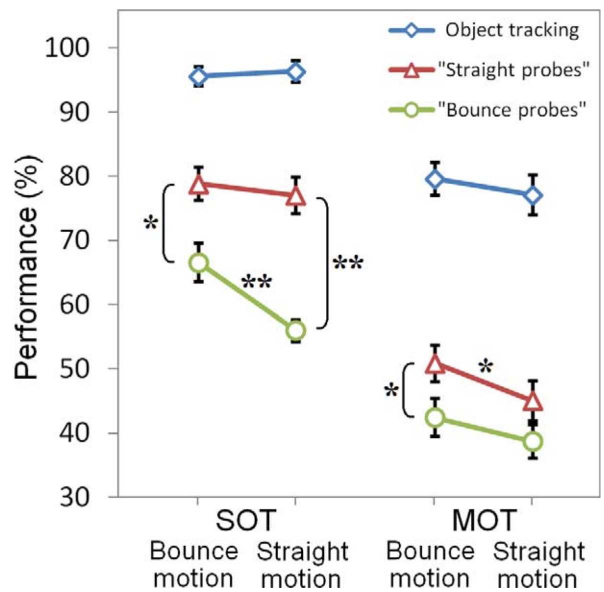

Figure 4. Probe detection rates as a function of object Motion (bounce, straight) and Probed Path (bounce-path probes, straight-path probes) for the single object tracking task (SOT, on the left) and the multiple object tracking task (MOT, on the right). Also for each block type the mean tracking performance is shown. Note that in the SOT task, bounce-path probes were better detected in the bounce-motion condition than in the straight-motion condition. In the MOT task, straight-path probes were better detected in the bounce-motion condition than in the straight-motion condition. Asterisks indicate which pairs differ significantly from each other (* $p < 0.05$, ** $p < 0.01$). Error bars indicate *SEM*.

Single object tracking

Mean probe detection rates ranged from 32.3% to 99.0% ($M = 68.8\%$, $SD = 22.2\%$). A repeated measures ANOVA was performed with motion (two: bounce, straight), probed path (two: bounce, straight), and distance (three: 2.2°, 3.0°, 3.8°) as independent variables and probe detection rate as the dependent variable. All three variables had a significant main effect on probe detection. Probe detection was higher when the objects bounced compared to when they moved straight, $F(1, 18) = 7.83$, $p < 0.05$. Straight-path probes were detected better than bounce-path probes, $F(1, 18) = 45.83$, $p < 0.001$. Finally, distance had a significant main effect, $F(1, 18) = 4.44$, $p < 0.05$, with the best performance at 3.0° and the worst at 3.8° (similar to Experiment 1). Furthermore, the interaction of motion and Probed Path was significant, $F(1, 18) = 4.54$, $p < 0.05$. Figure 4 (left side) shows this interaction effect, that is probe detection rate as a function of motion (bounce,

	Bounce-motion		Straight-motion	
Distance	Bounce-path	Straight-path	Bounce-path	Straight-path
Single object tracking				
2.2°	72.8 (25.5)	77.0 (21.0)	56.6 (29.7)	74.4 (25.8)
3.0°	65.3 (33.6)	81.0 (14.8)	59.3 (28.7)	79.7 (27.5)
3.8°	59.4 (31.3)	72.5 (24.5)	50.7 (28.4)	75.7 (25.2)
Multiple object tracking				
2.2°	42.8 (22.6)	50.1 (20.8)	42.0 (22.6)	40.1 (27.3)
3.0°	46.1 (25.5)	52.1 (23.4)	40.8 (21.2)	55.4 (25.2)
3.8°	36.7 (27.2)	50.1 (31.0)	38.2 (28.5)	40.7 (26.4)

Table 1. Probe detection results of Experiment 2. *Notes*: For both the SOT and the MOT task, for each Motion versus Probed Path condition the probe detection rate (%) and standard deviation (in between brackets) are shown per probe distance.

straight) and probed path (bounce, straight) for the single-object-tracking task. To investigate this interaction effect, pair-wise comparisons showed that straight-path probes were detected better than bounce-path probes in both the bounce-motion condition, $F(1, 18) = 8.44$, $p < 0.01$, and the straight-motion condition, $F(1, 18) = 55.45$, $p < 0.001$. An important finding was that bounce-path probes were detected significantly more often in the bounce-motion condition than in the straight-motion condition, $F(1, 18) = 11.51$, $p < 0.01$. No such difference was found for the straight-path probes ($F < 1$).

Multiple object tracking

Mean probe detection rates ranged from 14.3% to 80.3% ($M = 44.6\%$, $SD = 20.3\%$). A repeated measures ANOVA was performed with motion (two: bounce, straight), probed path (two: bounce, straight), and distance (three: 2.2°, 3.0°, 3.8°) as independent variables and probe detection rate as the dependent variable. Probed path showed a main effect, $F(1, 18) = 10.11$, $p < 0.01$: straight-path probes were detected more often than bounce-path probes. Distance was also significant, $F(1, 18) = 3.40$, $p < 0.05$, showing a pattern similar to Experiment 1. Motion did not have a significant main effect on probe detection rate, $F(1, 18) = 2.51$, $p = 0.13$. The interaction Motion × Path was not significant, $F(1, 18) = .85$, $p = 0.37$. Other interaction effects were also not significant. The right side of Figure 4 shows probe detection rate as a function of motion (bounce, straight) and probed path (bounce, straight) for the MOT task.

Although the interaction Motion × Probed Path was not significant, to more closely investigate the results, pair-wise comparisons were performed. These comparisons showed that straight-path probes were detected more often than bounce-path probes in the bounce-motion condition, $F(1, 18) = 7.41$, $p < 0.05$, but not significantly different in the straight-motion condition, $F(1, 18) = 3.51$, $p = 0.074$. Additionally, straight-path probes were detected more often in the bounce-motion condition than in the straight-motion condition, $F(1, 18) = 5.28$, $p < 0.05$. In Table 1 the probe detection rates for each of the distances are shown for both the SOT and MOT tasks.

We additionally tested for learning effects with regard to probe detection within each of the four block types (SOT-bounce-motion; SOT-straight-motion; MOT-bounce-motion; MOT-straight-motion). We therefore split the data into three equal quantiles (tertiles). We performed four repeated measures ANOVAs with probed path (two levels: bounce, straight) and time (three levels: first, second, third tertile) as independent variables. Each of the four block types did not show a main effect of time ($p = 0.09$; $p = 0.68$; $p = 0.60$; $p = 0.90$, respectively) or an interaction effect of Probed Path × Time ($p = 0.23$; $p = 0.27$; $p = 0.75$; $p = 0.74$, respectively). To test whether there might exist a tradeoff between probe detection and tracking performance, for each participant we compared the mean probe detection rate in the nonperfect-tracking trials with the mean probe detection rate in the nonperfect-tracking trials. We did this for SOT and MOT separately (see Figure 5). We found that in MOT, probe detection in perfect tracking trials did not differ significantly from nonperfect-tracking trials, $t(18) = .93$, $p = 0.37$. In contrast, in SOT, losing track of the target object was often accompanied by a drop in probe detection performance, $t(10) = 3.23$, $p < 0.01$. In Figure 5, the probe detection rate when tracking was successful is plotted as a function of probe detection rate when tracking failed, for each participant and for both tasks separately.

Discussion

The aim of Experiment 2 was to investigate anticipatory attention in case of physically plausible object bounces. Three main results stand out in this experiment. First, performance in the SOT task was

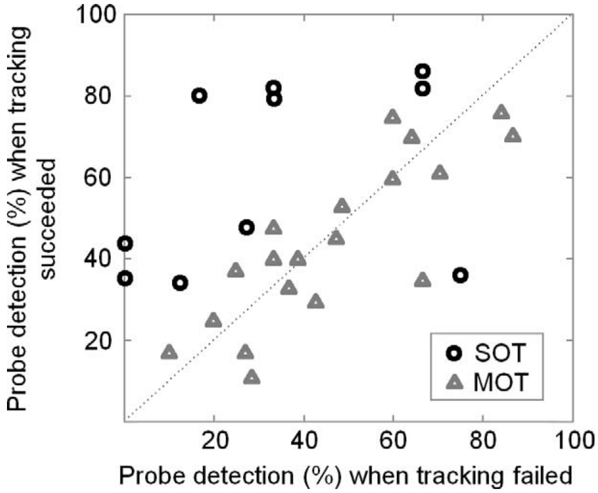

Figure 5. Probe detection rate when tracking succeeded versus probe detection when tracking failed for both the SOT task and the MOT task. Data points represent individual subjects. There appears to be no probe-detection–target-tracking-performance trade-off.

better than in the MOT task, indicating that the attentional load was lower in the SOT task. Though this effect was as expected, the lower attentional load during SOT may serve as a baseline for the further investigation of anticipatory behavior while tracking objects. Second, in both tracking tasks, probes that were presented along the movement direction of a target object were detected better than probes that were presented along the bounce-path, regardless of whether the wall caused the objects to bounce. This effect resembles the findings of Experiment 1 and points to an attentional reliance on proximal stimulation. That is, in both experiments anticipatory behavior appeared to rely heavily on the good continuation of the objects' movements. Third, in the SOT but not in the MOT task an interaction effect was found between object behavior (bounce/no bounce) and the probed path. The interaction effect in the SOT task can be explained as an enhanced probe detection at the bounce path when the target is about to bounce compared to when it is not, while probe detection at the straight path is unaffected. For both the SOT and the MOT tasks there were no learning effects with respect to probe detection. In addition, for each of the conditions there was no probe-detection-tracking trade-off: For the MOT task probe detection was independent of tracking performance, whereas for the SOT task, the probe detection was even worse when tracking performance decreased.

These results are in line with our Experiment 1 and also support the results by Verghese and McKee (2002), that an important part of anticipatory behavior is likely to be an automatic, bottom-up process. It is remarkable that even in a context of low attentional load (i.e., tracking only a single object), probe detection is much better along the object's direction of movement compared to probes along the upcoming bounce path. When looking at the effect of the motion manipulation for both tasks (SOT and MOT), an additional interesting pattern was observed: In SOT, bounce motion resulted in an increase of attention along the bounce path compared to when objects did not bounce. In MOT, even though an interaction effect was not found, pair-wise comparisons revealed that bounce motion resulted in an increase of attention along the straight path. It seems that when a bounce is expected (compared to when it is not), extra attentional resources are allocated. Where these resources are allocated, however, depends on the attentional load. Here, when attentional load was low (SOT), extra attentional resources were allocated to the bounce path, indicating anticipatory behavior. When attentional load was high (MOT), extra attentional resources were allocated to the straight path, indicating increased reliance on proximal stimulation.

General discussion and conclusion

In this study we investigated the distribution of attention around a moving object that is being tracked. In Experiment 1 (MOT) probes ahead of a tracked target were detected significantly more often compared to probes that appeared at other angles around that same target. Given these results we conclude that the attentional field around the moving targets is anisotropic, with more attention ahead of a target. In Experiment 2 we replicated this finding both when the participant's attentional load was high (MOT: tracking three objects simultaneously) and when the attentional load was low (SOT: tracking only a single object). This effect was found regardless of whether the objects bounced against a centered wall or not. Finally, anticipation of bouncing behavior did occur, but only when attentional load was low (SOT).

What do these current results mean for established theories on visual attention and on object tracking? First, in the well-known debate on space- versus object-based attention, where in its extreme form attention is metaphorically described as a mental spotlight (Eriksen & St. James, 1986; Posner, 1980) or attention is considered to be specifically bound to objects (Duncan, 1984; Lappin, 1967; Treisman, Kahneman, & Burkell, 1983), the current results are in line with the notion that the visuo-attentional system is likely to employ both depending on the stimuli, but also the specific task (e.g., Davis, Driver, Pavani, & Shepherd, 2000; Soto & Blanco, 2004; Vecera & Farah, 1994; Weber, Kramer, & Miller, 1997). Second, in previous studies on trajectory detection (Verghese & McKee, 2002) and representational momentum (Hubbard, 1995; Iordanescu et al., 2009; Kerzel, 2003a, 2003b) it has been suggested that linear extrapolation, based on proximal stimulation, is used when future locations of objects have to be judged. The experiments reported here are in line with these studies and complement them by adding a more dynamic context. That is, we showed that linear extrapolation is also dominant when one or more objects are being tracked in a continuous manner. Moreover, in the case of more complex object behavior (i.e., bouncing objects), we found anticipation only when the attentional load was lowered (i.e., tracking only a single object compared to multiple objects). This apparent dominance of proximal stimulation, here in the case of probe detection around objects, bears resemblance to studies using eye movements wherein saccades have to be made to objects. For example, Vishwanath, Kowler, and Feldman (2000) showed that when participants have to make a saccade to a partly occluded object, the landing position is based primarily on the visible part of the object to which the saccade is made, rather than to its representation. In other words, in directing a saccade towards an object, the eyes do not take into account the representation of an object. Rather, the so-called center of gravity of the visible part of the object is to where the eyes tend to saccade. Thus, in various studies, which used different methodologies, it has been found that bottom-up aspects play an important role in the behavior of the visuo-attentional system. This reliance on proximal based stimulation by the visuo-attentional system that is reported here and found elsewhere must not be taken to mean that the system only relies on this type of information. Naturally, this is task dependent. After all, if this would be the case, catching bouncing balls would be impossible to do.

All in all, we showed that in object tracking, anticipatory behavior is present along the direction to where an object is heading; regardless of any obstacles along the way. It seems that more complex object behavior, such as object bounces, are not necessarily taken into account or anticipated by the visuo-attentional system. Only when attentional load is lowered does the system seem to take such behavior into account.

Acknowledgments

Commercial relationships: none.
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