Distinguishing influences of overt and covert attention in anticipatory attentional target tracking

Andrea F. Frielink-Loing Radboud University Nijmegen, Donders Institute for Brain, Cognition and Behaviour, Nijmegen, The Netherlands

Arno Koning Radboud University Nijmegen, Donders Institute for Brain, Cognition and Behaviour, Nijmegen, The Netherlands

Rob van Lier Radboud University Nijmegen, Donders Institute for Brain, Cognition and Behaviour, Nijmegen, The Netherlands

This study investigated the relative contributions of overt and covert attention on the apparent anticipatory nature of attention in two experiments, using two different object tracking tasks, both combined with a probe detection task. In Experiment 1, we investigated the distribution of attention for overtly and covertly tracked targets separately at low tracking load using a single-object tracking task (one target, one distractor). We found anisotropic distributions of probe detection rates for both overtly tracked and covertly tracked targets, with highest detection rates at locations ahead of the target's movement. In Experiment 2, we investigated the distribution of attention in overt and covert tracking at a relatively higher tracking load using a multiple-object tracking task (two targets, two distractors) in which viewers overtly tracked one target while simultaneously covertly tracking a second target. We found anisotropic distributions of probe detection rates around covertly tracked targets only. We conclude that covert attention always anticipates motion when keeping track of moving objects, while overt attention is more flexible and its anticipatory nature depends on the tracking task.

Introduction

Real life situations require us to spread our attention over complex scenes containing multiple objects, which may or may not be moving. Moving objects in the real world often follow predictable paths (Ramachandran & Anstis, 1983). For example, a car moving along a road can keep following the same road in the same direction, it can go left or right at a junction, or it can stop in front of a red light. This predictability makes it possible to anticipate an object's future location in space. Crucially, our attention is selective: A car moving away requires less attention than, for example, an approaching cyclist. Its selective property can also be seen in the fact that we can only attend to a limited number of items (up to four or five) simultaneously (Cavanagh & Alvarez, 2005; Oksama & Hyönä, 2004; Pylyshyn & Storm, 1988; Scholl, 2001, 2009); although the exact number may depend on several factors (cf. Alvarez & Franconeri, 2007). Finally, there is the intuitive notion that the visuo-attentional system can reference multiple objects in parallel. To test this hypothesis, Pylyshyn and Storm (1988) devised the multiple-object tracking (MOT) task, in which observers are asked to simultaneously track several targets within a set of identical objects. Over the last decades, this task has been used to investigate space- and object-based theories of attention (e.g., Yantis, 1992), underlying mechanisms of object tracking (e.g., Oksama & Hyönä, 2004), hemifield-dependence of tracking capacity (Alvarez & Cavanagh, 2005), and many other aspects of attention (see Scholl, 2009, for a more detailed overview). More recently, Atsma, Koning, and van Lier (2012) used MOT to show that the attentional spread around a moving object is biased towards the object's movement direction. In the present study we investigate this apparent anticipatory allocation of attention in further detail by making a distinction between overt and covert attention (Posner, 1980). More specifically, we are

Citation: Frielink-Loing, A. F., Koning, A., & van Lier, R. (2017). Distinguishing influences of overt and covert attention in anticipatory attentional target tracking. *Journal of Vision*, *17*(4):3, 1–16, doi:10.1167/17.4.3.

doi: 10.1167/17.4.3 Received July 4, 2016; published April 7, 2017 ISSN 1534-7362 Copyright 2017 The Authors

interested in the relative contributions of overt and covert attention with regard to anticipatory attention.

In the original MOT task (Pylyshyn & Storm, 1988), observers viewed a display containing 10 identical white objects on a black background. One to five of these objects blinked for a few seconds to indicate them as targets. The observers were instructed to track these targets without making eye movements while all objects moved around on the screen, following unpredictable paths. During this movement period, a square was briefly presented (flashed) over a target preceded by zero to three similar flashes over distractors. Observers were instructed to press a button whenever they saw a flash occur on a target. Target flash detection (error) rates were used as a measure of tracking performance. Pylyshyn and Storm (1988) found that observers were in fact able to keep track of multiple objects simultaneously without being able to rely on distinguishing visual features other than physical location. Additionally, the theory of a single attentional spotlight was initially ruled out by comparing the observed results with a computational model of serial tracking (Pylyshyn & Storm, 1988), leading to the conclusion that targets must be tracked in parallel. Alternative single-spotlight explanations of MOT, such as perceptual grouping of targets (Yantis, 1992), were suggested. However, a study by Alvarez and Cavanagh (2005) showed that each visual hemifield has its own tracking capacity, again ruling out a single attentional spotlight.

Although MOT is now often assumed to employ object-based attention (Pylyshyn, 2004, 2006; Scholl, 2001, 2009; Scholl, Pylyshyn, & Feldman, 2001), recent investigations at the object level show that attention is not uniformly distributed across an object (Alvarez & Scholl, 2005; Atsma, Koning, & van Lier, 2012). Alvarez and Scholl (2005) used an MOT paradigm with moving line objects combined with transient probe detection at the centers and endpoints of the lines. They showed that attention was concentrated at the centers of objects rather than homogeneously distributed within the objects. Moreover, this attentional concentration effect was found to be stronger for longer lines than for short lines, providing evidence against the idea of attentional spotlights. In a similar experiment with circular objects, Atsma et al. (2012) showed that the focus of attention around tracked objects leans towards the direction of movement. In their experiment, Atsma et al. (2012) used probe detection rate as a measure to determine the relative allocation of attentional resources around tracked targets. They found that the attentional field is anisotropically distributed around the object; probes that were presented ahead of a target (i.e., at a future location) were detected more often than probes that were presented behind a target (i.e., at a previous location). Their findings show that object-based attention as employed in an MOT task is not restricted to the object, but its extent is modulated by the movement direction of the objects. More specifically, the attentional system appeared to anticipate movement. The idea of taking movement direction into account was proposed earlier by Pylyshyn and Storm (1988), but it was soon abandoned because their original paradigm did not include predictable motion. Similar attentional anticipation was found by Iordanescu, Grabowecky, and Suzuki (2009), where viewers systematically overestimated the final location of a moving target after it had disappeared.

The alleged sensitivity to an object's motion path is still under discussion, and also seems to depend on the applied paradigm. Several studies using variations on the original MOT task have found that viewers do not take motion paths into account. For example, Franconeri, Pylyshyn, and Scholl (2012) examined which information is used when tracking multiple objects that pass behind an occluder and came to the conclusion that the proximity between the pre-occlusion location and the reappearance location influences tracking performance, independent of whether the object's motion was the same before and after occlusion. In addition, Keane and Pylyshyn (2006) showed that viewers are very good at tracking several targets when all objects suddenly disappear for a short interval and reappear at the same location, but not when the objects reappear at the location where they would have been if they had continued their movement during the interval. A subsequent study by Fencsik, Klieger, and Horowitz (2007) showed that this is indeed the case for a high tracking load (e.g., four targets), while for a low tracking load (e.g., two targets) motion information does seem to be taken into account. Finally, Howe and Holcombe (2012) showed that tracking performance was equal for predictable (straight line) and unpredictable (random direction) motion when viewers tracked four objects. However, the same study showed that viewers performed better with predictable motion when only two objects needed to be tracked. Luu and Howe (2015) suggested that eye movements could have influenced the results found by Howe and Holcombe (2012) as they could have aided extrapolation. They performed the same experiment, this time controlling for eye movements by introducing a central fixation point, and also found that tracking performance was better for predictable motion than for unpredictable motion for low tracking load.

The eye movement restriction introduced by Luu and Howe (2015) allowed viewers to only use covert attention to track targets. Another recent study by Szinte, Carrasco, Cavanagh, and Rolfs (2015) using a paradigm with apparent motion also showed that covert attention is shifted ahead of an attended target object. In other studies using apparent motion, Shiori, Cavanagh, Miyamoto, and Yaguchi (2000) and Shiori, Yamamoto, Kageyama, and Yaguchi (2002) showed that covert attention shifts along smoothly with an attended object, in a way predicting its future apparent location. For overt tracking, one study showed that top-down attentional processes allocate resources broadly ahead of an object during smooth pursuit (Khan, Lefèvre, Heinen, & Blohm, 2010), while other studies showed that overt attention was centered on tracked objects (Lovejoy, Fowler, & Krauzlis, 2009; Watamaniuk & Heinen, 2015). These examples are investigations of overt or covert attention in isolation. However, in many object tracking tasks, as well as in real-life situations, a mix of overt and covert attention may play a role (cf. Fehd & Seiffert, 2008). In the study presented here, we therefore investigate the relative contributions of overt and covert attention (Posner, 1980) with regard to anticipatory attention in object tracking tasks, first at the lowest possible tracking load in the form of single-object tracking (SOT), and later at a higher tracking load (but still low enough to expect anticipatory attention) in the form of a two-target MOT task. We use a similar probe detection paradigm as in Atsma et al. (2012), because it allows us to map the relative allocation of attentional resources around tracked targets by presenting probes at specific locations relative to the target's movement direction. By definition, overt attention corresponds to target fixation, whereas covert attention corresponds to attending a target without fixation (Posner, 1980). Using this assumption, we combine the abovementioned paradigm with specific fixation instructions (and corresponding control), such that viewers have to fixate either the moving target or a fixation cross at the center of the display (Experiment 1), or fixate one target while covertly tracking a second target (Experiment 2). As a measure for anisotropy we compare probe detection rates at different angles relative to the target's movement direction. If eye fixation on a target is necessary for anticipation, we expect to see an anisotropic distribution of probe detection rates around overtly tracked targets rather than covertly tracked targets, with better detection ahead rather than behind the target (i.e., anticipatory). However, if attention anticipates movement regardless of where you look, we expect to see anisotropic distribution of probe detection rates around covertly tracked targets as well.

Experiment 1

We first employed an SOT task combined with a probe detection task. Participants were instructed to keep track of the target, and either fixate the target (target disk fixation) or a fixation cross presented at the center of the display (center screen fixation), while ignoring a second object (the distractor). Additionally, participants were instructed to try to detect probes that could appear at various positions on the screen. Similar to Atsma et al. (2012), we showed probes at eight different angles relative to the target's movement direction and used probe detection rate as a measure of the amount of attentional resources allocated to those specific points in space. We expected to see an anisotropic distribution of attention, specifically relatively high probe detection rates were expected ahead of the target and low detection rates behind the target, replicating the results found by Atsma et al. (2012). In addition we showed probes around distractors and at positions in open space further away from the objects.

If the distribution of probe detection rates around fixated targets (i.e., in the target disk fixation condition) is more anisotropic compared to nonfixated targets (i.e., in the center screen fixation condition), we might assume that gaze is necessary for anticipation of the object's future location. Conversely, if detection rates are also distributed anisotropically around nonfixated targets, then it might be the case that attention, independent of gaze, takes motion information into account.

Method

Participants

Twenty-four participants aged between 19 and 29 ($M = 23.4$, $SD = 3.2$) were recruited through the Research Participation System of the Radboud University. All reported normal or corrected-to-normal vision. Twenty were right-handed, three were left-handed, and one participant reported to be ambidextrous without preference for left or right. All participants received payment after completing the experiment. All procedures conform to the Declaration of Helsinki.

Stimuli and design

Each trial involved one target object and one distractor object. The objects were identical circular black outlines subtending 2.2° of the visual field presented on a light gray background. Object movement was restricted by a bounding box subtending 25° × 20° presented as a black outline centered on the screen. Stimuli were created with Matlab for Windows and the Psychophysics Toolbox (Brainard, 1997; Kleiner, Brainard, & Pelli, 2007; Pelli, 1997) running on a Dell Precision T3610 PC. Before each trial, a random number generator was used to determine whether it would be a target disk fixation or a center screen fixation trial. At the beginning of a trial, the two objects appeared at randomly generated, nonoverlapping locations within the bounding box (Figure 1). One

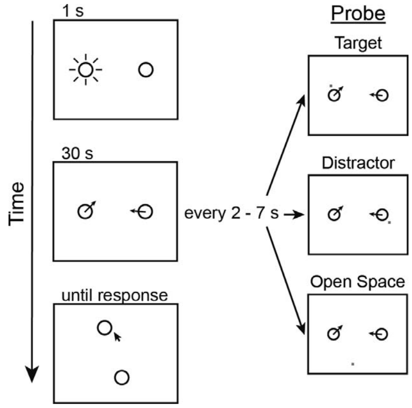

Figure 1. Timeline. Each trial started with the indication of the target. Subsequently, both objects started moving for 30 s, during which time probes appeared every 2–7 s. Probes could appear near the target, near the distractor, or in the empty space. When the objects stopped moving, participants had unlimited time to click on the object they remembered to be the target.

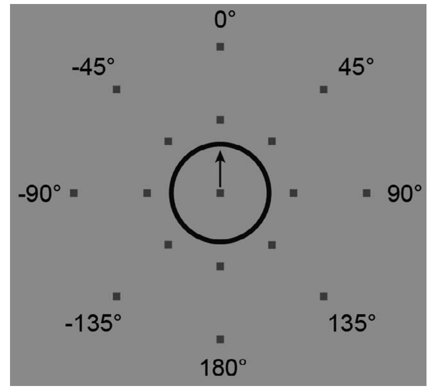

Figure 2. The 17 probe locations used in both experiments. An object (black circle, 2.2° diameter) is shown with an arrow (not visible during the experiment) depicting its movement direction. Probe locations are shown as gray squares (0.13°) and are positioned at eight angles and two distances from the object's center (1.65° and 3.3°), and at the center of the object.

object blinked three times, indicating it as the object to be tracked (i.e., the target). On target disk fixation trials, a fixation cross subtending $0.6° \times 0.6°$ was additionally presented inside the target, which disappeared after the blinking had stopped. On center screen fixation trials, a fixation cross was presented at the center of the display and remained there throughout the trial.

After the target had been indicated, the two objects began to move in randomly generated directions for 30 s at a constant speed of 7°/s. When an object encountered a wall or the other object, bounces would occur near-naturally,[1] with the exception that there would be no loss of energy—that is, keeping their speed of 7°/s. During the 30 s of movement (i.e., a single trial), probes were presented every 2–7 s and could appear near the target or near the distractor (object probes), or in empty space further away from the two objects (open space probes), but always within the bounding box. Probe types (object probes, open space probes) were randomly distributed over the trials. Probes were dark gray squares with a width of 0.13° and could appear on or near an object only if the objects were at least 7° away from each other. Each object probe was presented at one of 17 different locations, one of which was at the center of the object (see Figure 2). The remaining 16 locations were divided over eight angles relative to the object's movement direction (from −135° to 180°, separated by 45° steps) and two distances from the object's center (1.65° and 3.3°). Each probe was presented for 100 ms. For the object probes, in order to keep the probe's distance and angle with respect to the object constant, the probe moved along with the object. Consequently, each object probe remained stationary with respect to the probed object during its presentation. Open space probes moved at a speed of 7°/s in a random direction.

For every participant, in each tracking condition, each of the 17 object probe locations around the target and around the distractor was probed five times, leading to a total of 2 (object: target, distractor) $\times$ 2 (condition: target disk fixation, center screen fixation) $\times$ 17 (location) $\times$ 5 (presentation) = 340 object probes. Additionally, a total of 100 open space (filler) probes were presented to each participant, 50 in each condition. Probes could not appear in the first or last 3 s of a 30-s trial and were separated by 2–7-s intervals. Due to the fact that object probes could only appear when the target and the distractor were at least 7° apart, some intervals between probe presentations were automatically increased by the system when the two objects were too close to each other at a chosen probe time. The total of 440 probes were divided over 84 trials on average.

Procedure

Participants were seated in front of an LCD monitor (resolution of 1920 $\times$ 1080 pixels, refresh rate 120 Hz) at a distance of approximately 60 cm. Participants received instructions to follow the target by either continuously fixating the target with their eyes (i.e., the target disk fixation condition) or by fixating on the small cross in the center of the screen and keeping track of the target "with their mind's eye" (i.e., the center screen fixation condition; see Figure 3). Participants were given a button box and were instructed to respond to probes by pressing a button as quickly as possible. After the objects stopped moving, participants were asked to click on the target using a computer mouse. No feedback was given. This target identification phase

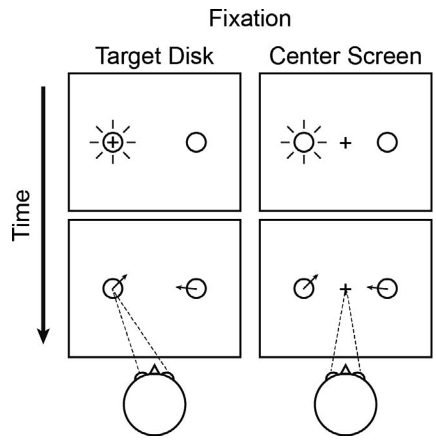

Figure 3. Viewing conditions. In the target disk fixation condition (left), a fixation cross appeared inside the target for 1 s during target indication to indicate that the target had to be fixated throughout the trial. In the center screen fixation condition (right), a fixation cross was presented at the center of the display throughout the whole trial to indicate fixation on the center of the screen was required.

lasted until the participant had clicked on an object, enabling them to go through the experiment at their own pace. Before the start of the experiment, participants performed five practice trials. On average, the whole experiment lasted about 75 min.

During the experiment, eye movements were monitored using a remote eye tracking system (SensoMotoric Instruments RED500, SensoMotoric Instruments, Inc., Teltow, Germany) positioned below the monitor. The experiment leader (first author) viewed eye movements of the participant in real time (sampled at 500 Hz) on a separate monitor away from the participant's field of view. During the practice trials, oral feedback was given regarding the participant's eye movements. Participants who violated the fixation instructions during experimental trials—for example, by moving the eyes towards the target or distractor during center fixation trials—received one warning from the experiment leader. Participants who violated the instructions after the warning were excluded from the analyses. Eye movement data were not recorded.

Results

Tracking accuracy was high for both fixating conditions (target disk fixation: $M = 98.6\%$, $SD = 2.2\%$; center screen fixation: $M = 95.85\%$, $SD = 4.7\%$). Only probe events that occurred during trials in which the target was correctly identified were used for the analyses. If the target was not identified correctly, the trial was not repeated, which means that those probe events that occurred during the trial were lost. Only button presses that occurred within 1000 ms after probe presentation were counted as a hit (cf. Flombaum, Scholl, & Pylyshyn, 2008). Out of 24 participants, three were excluded from the analyses as a result of not following the fixation instructions after the first warning. Individual probe detection rates ranged from 11.2% to 45.5% in the target disk fixation condition ($M = 30.5\%$, $SD = 8.1\%$) and from 3.0% to 43.8% in the center screen fixation condition ($M = 19.3\%$, $SD = 11.5\%$). A 2×3 repeated-measures analysis of variance (ANOVA) with fixation (target disk vs. center screen) and probe type (target, distractor, and open space) as factors showed that probes were detected significantly more often on target disk fixation trials compared to center screen fixation trials, $F(1, 20) = 17.77$, $p < 0.001$, $\eta_p^2 = 0.471$. The analysis also revealed a significant effect of probe type, $F(2, 40) = 151.82$, $p < 0.001$, $\eta_p^2 = 0.884$, where target probes were detected most often ($M = 43.8\%$), followed by open space probes ($M = 15.9\%$) and distractor probes ($M = 10.2\%$). Finally, there was a significant interaction between fixation and probe type, $F(2, 40) = 236.67$, $p < 0.001$, $\eta_p^2 = 0.922$, reflecting the fact that on target fixation trials, target probes ($M = 69.6\%$) were detected more often than distractor probes ($M = 4.7\%$) and open space probes ($M = 7.1\%$), while on center fixation trials open space probes ($M = 24.7\%$) were detected more often than both target probes ($M = 17.9\%$) and distractor probes ($M = 15.7\%$). Figure 4 shows the distribution of probe detection rates around targets and distractors for each fixation condition.

An analysis of reaction times for detected probes with fixation (target disk vs. center screen) and probe type (target, distractor, and open space) as factors revealed a significant interaction effect between fixation and probe type, $F(2, 28) = 4.71$, $p = 0.017$, $\eta_p^2 = 0.252$. In the target disk fixation condition, responses to target probes were faster than responses to distractor and open space probes (587 ms vs. 651 ms and 670 ms, respectively), whereas in the center screen fixation condition, responses to open space probes were slightly faster than responses to target and distractor probes (642 ms vs. 660 ms and 672 ms, respectively). Note that our data do not support an analysis of speed-accuracy tradeoffs, as there were no events that could trigger a false alarm, and therefore no reference points to determine reaction times exist.

Next, we compared object probe detection rates at different angles relative to the movement direction of the object, focusing first on target probes only. Because we were not interested in differences between left and right, but specifically wanted to investigate whether probe detection declines (linearly) as probes appear at larger angles away from the movement direction, we looked at absolute angle—that is, we grouped $-45°$ and $45°$, $-90°$ and $90°$, and $-135°$ and $135°$. In an attempt to normalize the data we performed three different data transformations (arc-sin, log, and reciprocal). We saw

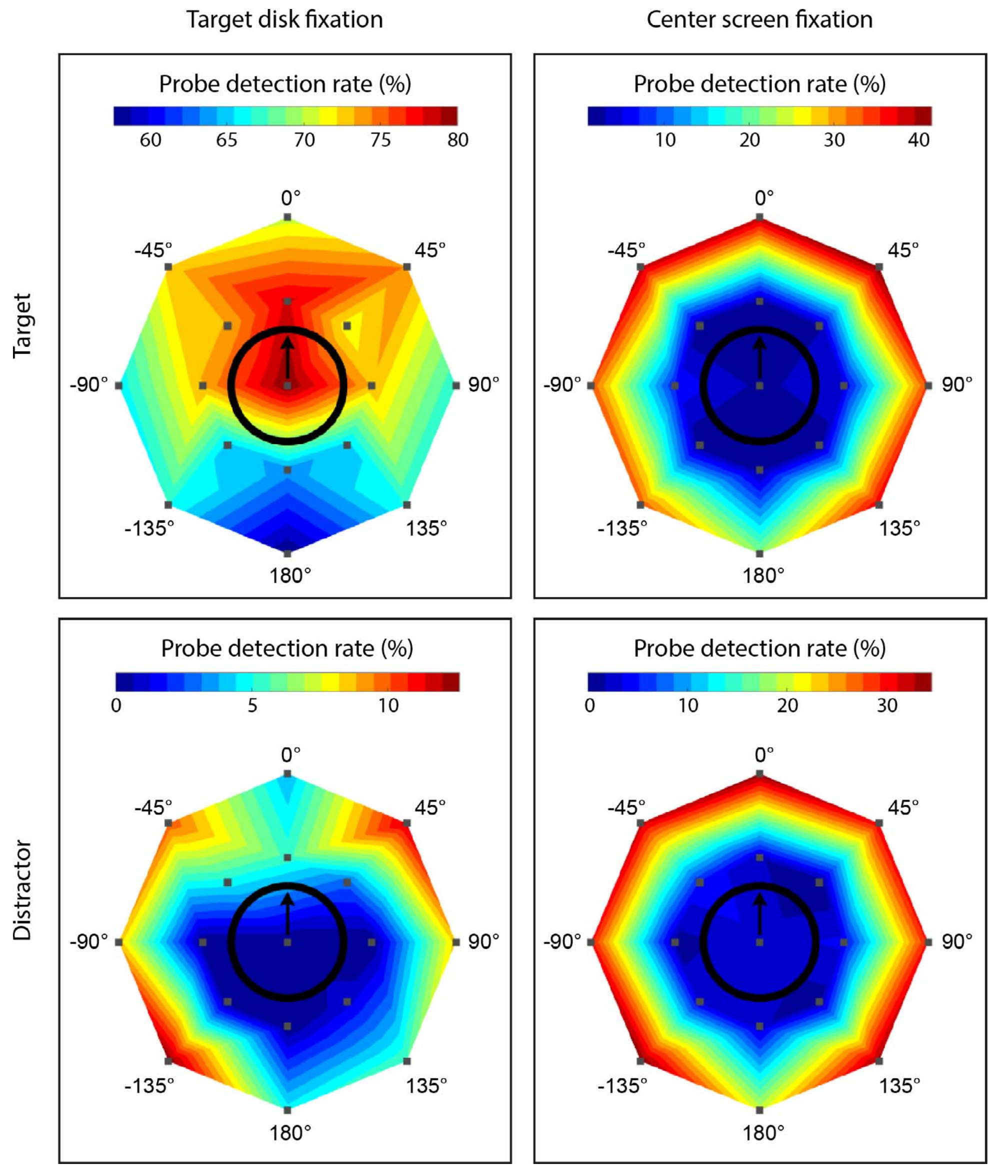

Figure 4. Mean detection rates for target and distractor probes in Experiment 1. Top left: Fixated target. Top right: Nonfixated target. Bottom left: Distractor in target disk fixation condition. Bottom right: Distractor in center screen fixation condition. An object (black circle) is shown with an arrow (not visible during the experiment) depicting its movement direction. Probe locations are shown as gray squares. The individual color coding distribution for each object is shown in the legend above each figure. Note that color ranges are not the same for all objects; for example, for the target in the target disk fixation condition (top left figure), a light green color corresponds to a detection rate of approx. 70%–71%, whereas the same color for the target in the center screen fixation condition (top right figure) corresponds to a detection rate of approximately 23%–25%.

that none of these data transformations improved the normality of the data. We therefore performed a 2 × 2 × 5 repeated-measures ANOVA on the untransformed object probe detection rates, with fixation (target disk vs. center screen), distance (1.65° vs. 3.3°, i.e. near vs. far), and angle (0°, 45°, 90°, 135°, and 180°) as factors. Probe detection rates are shown in Figure 5.

We found a strong significant main effect of fixation, $F(1, 20) = 271{,}54$, $p < 0.001$, $\eta_p^2 = 0.931$, reflecting a higher probe detection rate for fixated targets compared to nonfixated targets. There was also a strong significant main effect of distance, $F(1, 20) = 24.47$, $p < 0.001$, $\eta_p^2 = 0.550$, where probes presented further away from the target were detected more often than probes presented near the target. Mauchly's test indicated that the assumption of sphericity had been violated for the main effect of angle, $\chi^2(9) = 44.66$, $p < 0.001$. Therefore degrees of freedom were corrected using Greenhouse–Geisser estimates of sphericity ($\varepsilon = 0.49$). There was a significant main effect of angle, $F(1.98, 39.53) = 5.26$, $p = 0.010$, $\eta_p^2 = 0.208$. Polynomial contrasts revealed a significant linear trend, $F(1, 20) = 7.35$, $p = 0.014$, $\eta_p^2 =$

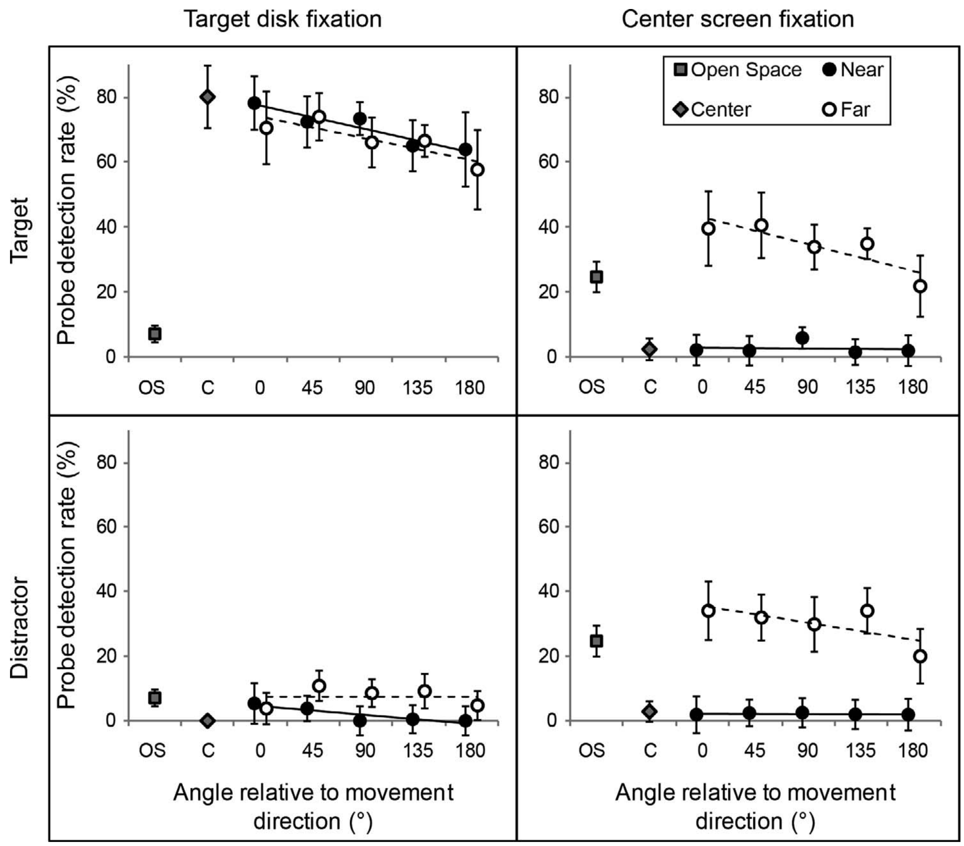

Figure 5. Detection rates for object probes in Experiment 1 in each fixation condition, at both distances and at each angle. Closed circles represent detection rates for probes presented near the object, open circles represent detection rates for probes presented further away from the object. Gray diamonds represent mean detection rates for probes presented at the center of the object. Gray squares represent mean detection rates for open space probes. Trend lines show the relationship between the different angles for each type of attention at each distance. Angle 0 represents the object's movement direction.

0.269, with high detection rates for probes appearing in front of the target (0°) and lower detection rates for probes appearing behind the target (180°).

Furthermore, there was a significant interaction effect between fixation condition and the distance from target to probe, $F(1, 20) = 68.27$, $p < 0.001$, $\eta_p^2 = 0.773$. This effect can be seen in Figure 5. There is a large difference in probe detection rate between probes presented far away from the target and probes presented near the target in the center screen fixation condition, but not in the target disk fixation condition. The analysis also revealed a significant interaction effect between distance and angle, $F(4, 80) = 3.29$, $p = 0.015$, $\eta_p^2 = 0.141$, indicating that the effect of angle is strongest further away from the target compared to near the target. There was no significant interaction effect between attention and angle, $F(4, 80) < 1$. The three-way interaction was also nonsignificant, $F(4, 80) = 1.42$, $p = 0.236$, $\eta_p^2 = 0.066$. To have a further check on the validity of our findings, we also ran a nonparametric analysis. The results do not change the main message reported here.

We additionally performed the same test for the distractor probes to see whether the detection rates for probes around these objects were anisotropically distributed. We found a significant main effect of fixation, $F(1, 20) = 36.04$, $p < 0.001$, $\eta_p^2 = 0.643$, where distractor probes were detected more often on center screen fixation trials compared to target disk fixation trials. We also found a significant main effect of distance, $F(1, 20) = 37.38$, $p < 0.001$, $\eta_p^2 = 0.651$, with higher detection rates for probes presented far from the distractor than for probes presented near the distractor. Mauchly's test indicated that the assumption of sphericity had been violated for the main effect of angle, $\chi^2(9) = 20.47$, $p = 0.016$. Therefore degrees of freedom were corrected using Greenhouse–Geisser estimates of sphericity ($\varepsilon = 0.65$). There was a significant main effect of angle, $F(2.60, 51.97) = 4.24$, $p = 0.013$, $\eta_p^2 = 0.175$. Polynomial contrasts revealed not only a significant linear trend, $F(1, 20) = 9.46$, $p = 0.006$, $\eta_p^2 = 0.321$, but also a significant fourth order trend, $F(1, 20) = 6.36$, $p = 0.020$, $\eta_p^2 = 0.241$, reflecting an overall linear decline from front (0°) to back (180°) with peaks at 45° and 135°. Furthermore, we found a significant interaction effect between fixation and distance, $F(1, 20) = 41.35$, $p < 0.001$, $\eta_p^2 = 0.674$, reflecting the fact that the difference between the two distances is significantly larger in the center fixation condition compared to the target fixation condition. Finally, the three-way interaction was also significant, $F(4, 80) = 3.59$, $p = 0.010$, $\eta_p^2 = 0.152$, indicating that the probe detection pattern was not the same for distractors in the target disk fixation condition and distractors in the center fixation condition. We did not find a significant interaction between fixation and angle, $F(4, 80) = 1.42$, $p = 0.235$, or between angle and distance, $F(4, 80) = 2.39$, $p = 0.058$.

Discussion

We investigated the spread of attention around tracked objects, and more specifically the relative contribution of overt and covert attention with regard to the anticipatory nature of attention, within the context of an SOT task. In this tracking task, we used probe detection performance as a measure of the distribution of attentional resources. We assumed that overt attentional resources are allocated to a fixated target and that covert attention follows a nonfixated target. We found that for both overt and covert conditions probe detection rates were distributed anisotropically around the targets, with a linear decrease from ahead of the target (0°) to behind the target (180°). That is, there was no difference in anisotropy between fixated and nonfixated targets, but probes presented around the fixated target were overall detected much better than probes presented around the nonfixated target. We attribute this large advantage for fixated targets to the fact that probes presented in the vicinity of these targets appeared within, or very close to, the fovea, where visual acuity is high. We also found that object probes that were presented at the smallest distance from the object (i.e., 1.65°) and at the center of the object were greatly suppressed for both objects on center screen fixation trials (see graphs on the right in Figure 5). It is likely that this suppression was caused by the proximity of the object's edge to the probe, as in crowding or surround suppression (Bouma, 1970; Petrov & McKee, 2006). The same effect does not occur for fixated targets, because these appear within the fovea. Moreover, low detection rates for center probes on nonfixated targets and high detection rates for center probes on fixated targets support that participants fixated as instructed throughout the experiment. Furthermore, we saw that the area around distractors was suppressed when viewers were instructed to fixate their gaze on the target, and that this suppression did not occur on center screen fixation trials. We hypothesize that this suppression is a result of a narrow focus on the target when gaze and attention are both fixated on the same, single object. In contrast, the detachment of gaze and attention in the center screen fixation condition might have forced the participants to adopt a much broader focus of the entire scene, which includes both target and distractor. This hypothesis is supported by the fact that detection rates for open space probes, which could appear anywhere within the bounding box, are very similar to detection rates for distractor probes in both fixation conditions. Finally, we found an anisotropic distribution of probe detection rates around distractors.

Based on earlier work by Atsma et al. (2012), we expected to find an anisotropic distribution of attention around the tracked targets in at least one of our fixation conditions. Indeed, we found that overall target probe detection declines as the angle between the probe and the target's movement direction increases, providing evidence for the anticipatory nature of attention. We would expect from the literature that in an MOT task, targets are most often tracked covertly (e.g., using a center-looking strategy; see Fehd & Seiffert, 2008), and that the effect found by Atsma et al. (2012) should therefore primarily be a property of covert attention. However, we did not see a difference in anisotropy, expressed by an effect of angle, between fixated and nonfixated targets. Although this does not give us conclusive information about the relative contributions of overt and covert attention to the anticipatory nature of attention, it does tell us that gaze is not necessary for attention to take motion information into account.

While it appears that during target disk fixation trials the distractor was actively inhibited, as evidenced by low probe detection rates around distractors compared to target probes and open space probes, it seems that during center screen fixation trials participants paid attention to both the target and the distractor. One may note the large differential results in the overt condition and the about similar results for the covert condition when comparing probe detection rates for target and distractors. Considering these results it is important to note that we only considered probe events that occurred during trials where the target was correctly identified (so attention paid to the distractor was not a result of a wrong identification of the target).

Our goal was to investigate the relative contributions of overt and covert attention to the anisotropic distribution of attention around tracked objects in MOT as found by Atsma et al. (2012). The first experiment was designed to investigate these two types of attention in isolation with SOT. One might argue that it becomes difficult to discern overt and covert attention in a task with such a low tracking load, when so few attentional resources are necessary to perform the task. Additionally, when looking at eye movements, the two conditions are not comparable: During overt tracking the eyes are in constant pursuit of the target, while during covert tracking the eyes are always fixated at the center of the screen. We therefore devised a second experiment that deals with both concerns and shows the interplay between overt and covert attention in an MOT setting.

Experiment 2

In our second experiment we looked at the attentional distribution in an MOT task with two targets and two distractors. To make sure that both overt and covert attention are employed, participants had to fixate one target while covertly tracking another. Note that the attentional load in this second task is higher than in the task used in Experiment 1.

Because this task explicitly requires divided attention and the tracking load is higher than in SOT, we expect that the attentional resources used to track the two targets will be utilized more efficiently and will therefore be more focused on the targets than during our first experiment. If the spatial properties of overt and covert attention are different—that is, if one is more anticipatory than the other—then we expect to see this difference reflected in the results of this second experiment. Based on the earlier finding that viewers who perform an MOT task with free viewing do not often look directly at targets but rather fixate on a location near the centroid of all targets (Fehd & Seiffert, 2008), combined with the anisotropic distributions found by Atsma et al. (2012) in MOT and the results from our first experiment in SOT, we hypothesize that the distribution of attentional resources around the nonfixated target (i.e., the covertly tracked target) will be anisotropic. For the fixated target, we consider two possibilities. First, we might find an anisotropic distribution of attentional resources around the target, similar to what we found in the target disk fixation condition in Experiment 1. If so, we may conclude that both overt and covert attention take motion information into account, resulting in anisotropy. Second, attentional resources deployed around the fixated target might be distributed isotropically, suggesting that overt attention by itself does not necessarily take motion information into account when tracking a moving object.

Method

Participants

A new group of 24 participants aged between 18 and 61 ($M = 23.9$, $SD = 8.8$) was recruited through the Research Participation System of the Radboud University. All reported normal or corrected-to-normal vision. Three participants were left-handed. Participants received either course credits or payment after completing the experiment. All procedures conform to the Declaration of Helsinki.

Stimuli and design

Stimuli were largely the same as in Experiment 1. Targets and distractors were all identical circular black outlines subtending 2.2° of the visual field, presented on a gray background. Object movement was restricted by a bounding box subtending $25° \times 20°$. As in Experiment 1, stimuli were created with Matlab for Windows and the Psychophysics Toolbox.

At the beginning of each trial, four circular objects appeared on the screen, one in each quadrant of the bounding box. A fixation cross subtending $0.6° \times 0.6°$ appeared inside one of two target objects and both target objects blinked three times, indicating them as the targets to be tracked. The fixation cross disappeared after the blinking had stopped and all four objects started moving in randomly generated directions for 20 s at a constant speed of 7°/s, similar to Experiment 1.

During the movement phase, probes (0.13° dark gray squares) could appear for 100 ms near one of the targets, near one of the distractors or in open space. Object probes could appear in the same locations with respect to the movement direction as in Experiment 1 (see also Figure 2), and appeared only if objects were at least 7° apart. During probe presentation, the probe moved along with the corresponding object (object probes) or at a speed of 7°/s in a random direction (open space probes).

For every object type (fixated target, nonfixated target, distractor) each location was probed six times per participant, leading to $3 \times 17 \times 6 = 306$ object probes. Additionally, 36 open space probes were presented to each participant, resulting in a total of 342 probes. Probes within a trial were separated by randomized 2–7-s intervals and could not appear in the first or last three seconds of a trial. Due to the restriction that objects needed to be at least 7° apart at probe presentation, the experiment contained an average of 112 trials.

Procedure

Procedures were identical to Experiment 1 with the following exceptions. At the start of each trial, participants received instructions to follow the target containing the fixation cross by fixating it with their eyes (i.e., the fixated target) and to track the other target "with their mind's eye" (i.e., the nonfixated target). As in Experiment 1, eye movement data were monitored, but not recorded. At the end of each trial, both targets had to be identified. Participants were not required to indicate the targets in any particular order. Before the start of the experiment, participants practiced object tracking once and viewed an example of a probe presentation. The whole experiment lasted approximately 65 min, including a break after every 10 trials.

Results

Tracking performance was high for the fixated targets ($M = 98.2\%$, $SD = 4.5\%$) and somewhat lower for the nonfixated targets ($M = 88.9\%$, $SD = 7.4\%$). Only probe events from trials in which both targets were correctly identified were used for our analysis and only button presses that occurred within 1000 ms after probe presentation were counted as a hit. Online fixation control resulted in the exclusion of one participant who did not adhere to the fixation instructions throughout the experiment. Individual overall probe detection rates ranged from 17.4% to 83.5% ($M = 55.5\%$, $SD = 15.4\%$). A repeated-measures ANOVA with probe type (fixated target, nonfixated target, distractor, open space) as the only factor revealed a significant effect, $F(3, 66) = 99.15$, $p < 0.001$, $\eta_p^2 = 0.818$, where probes presented around the fixated target were detected most often ($M = 85.0\%$), followed by open space probes ($M = 66.1\%$), probes presented around the nonfixated target ($M = 45.4\%$), and distractor probes ($M = 36.5\%$). Bonferroni-corrected pairwise comparisons revealed that all probe types differed significantly from each other ($p < 0.001$). Figure 6 shows the distribution of probe detection rates around the fixated and nonfixated targets as well as the distractor.

The analysis of reaction times for detected probes with probe type (overt target, covert target, distractor, and open space) as factors revealed a significant main effect of probe type, $F(3, 66) = 19.86$, $p < 0.001$, $\eta_p^2 = 0.474$. Responses to overt target probes were significantly faster than responses to covert target, distractor, and open space probes (569 ms vs. 608 ms, 623 ms and 611 ms, respectively).

To analyze the data for the targets, we preprocessed them in the same way as in Experiment 1 and used the same $2 \times 2 \times 5$ repeated-measures ANOVA with fixation (fixated vs. nonfixated), distance (near vs. far), and angle (0°, 45°, 90°, 135°, and 180°) as factors. Probe detection rates are shown in Figure 7. There was a significant main effect of fixation, $F(1, 22) = 86.52$, $p < 0.001$, $\eta_p^2 = 0.797$, reflecting higher detection rates for fixated targets compared to nonfixated targets. There was also a significant main effect of distance, $F(1, 22) = 122.70$, $p < 0.001$, $\eta_p^2 = 0.848$, reflecting higher detection rates for probes presented further away from the target compared to close by the target. We also found a significant main effect of angle, $F(4, 88) = 3.49$, $p = 0.011$, $\eta_p^2 = 0.137$, with a significant linear trend, $F(1, 22) = 18.07$, $p < 0.001$, $\eta_p^2 = 0.451$, which showed a general linear decrease of probe detection rate at increasing angles with movement direction.

Next, there was a significant interaction between fixation and the distance between the target and the probe, $F(1, 22) = 39.46$, $p < 0.001$, $\eta_p^2 = 0.642$. The difference in probe detection rates between far and near is larger for nonfixated targets than for fixated targets. We also found a significant interaction between fixation and angle, $F(4, 88) = 2.66$, $p = 0.038$, $\eta_p^2 = 0.108$, which means that the relationship between the different angles is different for the fixated target than for the nonfixated target. Polynomial contrasts revealed a significant linear trend for this interaction, $F(1, 22) = 9.68$, $p = 0.005$, $\eta_p^2 = 0.306$, and we can see from Figure 7 that probe detection rates decrease linearly with increasing angle around nonfixated targets, while detection rates stay the same over all angles around fixated targets. Mauchly's test indicated that the assumption of sphericity had been violated for the interaction effect between distance and angle, $\chi^2(9) = 20.39$, $p = 0.016$. Therefore degrees of freedom were corrected using Greenhouse–Geisser estimates of sphericity ($\varepsilon = 0.72$). The interaction effect was nonsignificant, $F(2.89, 63.59) < 1$. There was also no significant three-way interaction, $F(4, 88) = 1.40$, $p = 0.241$, $\eta_p^2 = 0.060$.

We performed a similar ANOVA for the distractor probes to check for anisotropy, with distance and angle as factors. The main effect of distance was significant, $F(1, 22) = 100.86$, $p < 0.001$, $\eta_p^2 = 0.821$, as probes presented further away from the distractor were detected more often than probes presented near the distractor. There was no main effect of angle, $F(4, 88) < 1$, and no interaction effect, $F(4, 88) = 1.32$, $p = 0.271$.

Discussion

As in Experiment 1, we investigated the relative contributions of overt and covert attention to the anticipatory distribution of attentional resources around tracked objects. In this second experiment, we used an MOT task, leading to a relatively higher attentional load as compared to Experiment 1, in order to look at the interplay between overt and covert orienting when attention needs to be spread between multiple targets. Additionally, in this task eye movements were present for both overt and covert tracking. We found that the spread of attention around fixated targets is rather isotropic, while at the same time, the spread of attention around nonfixated targets is

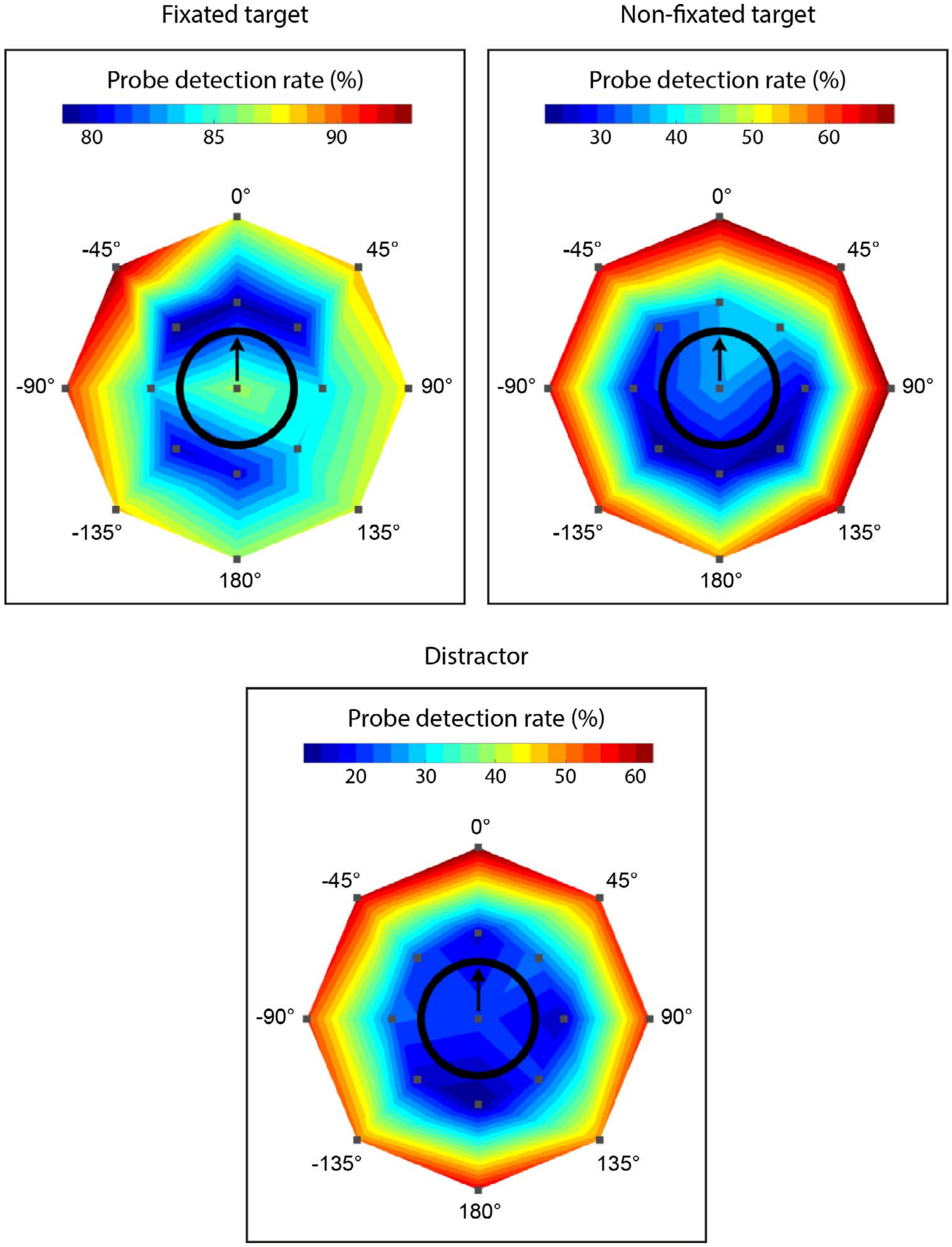

Figure 6. Mean detection rates for object probes in Experiment 2. Top left: Fixated target. Top right: Nonfixated target. Bottom: Distractor. A target object (black circle) is shown with an arrow (not visible during the experiment) depicting its movement direction. Probe locations are shown as gray squares. The individual color coding distribution for each object is shown in the legend above each figure. Note that color ranges are not the same for all objects; for example, for the target in the target disk fixation condition (top left figure), a light green color corresponds to a detection rate of approx. 86%–87%, whereas the same color for the target in the center screen fixation condition (top right figure) corresponds to a detection rate of approximately 47%–50%.

anisotropic, as illustrated by the interaction effect between fixation and the angle relative to the movement direction. Moreover, we found that attention lies mostly ahead of the nonfixated target, as illustrated by a linear decrease of probe detection rates at increasing angle between the probe and the movement direction of the target. Interestingly, we found no anticipatory pattern around the distractors in this second experiment.

As in Experiment 1, probes presented around the fixated target, within or near the fovea, were detected more often than probes presented around the nonfixated target and the distractor. Probes presented near the edge of the nonfixated target and the distractor (i.e., at 1.65°) and at the centers of these objects were also suppressed. We discuss these effects in more detail in the General discussion below. Relatively low detection rates for center probes on nonfixated objects and high

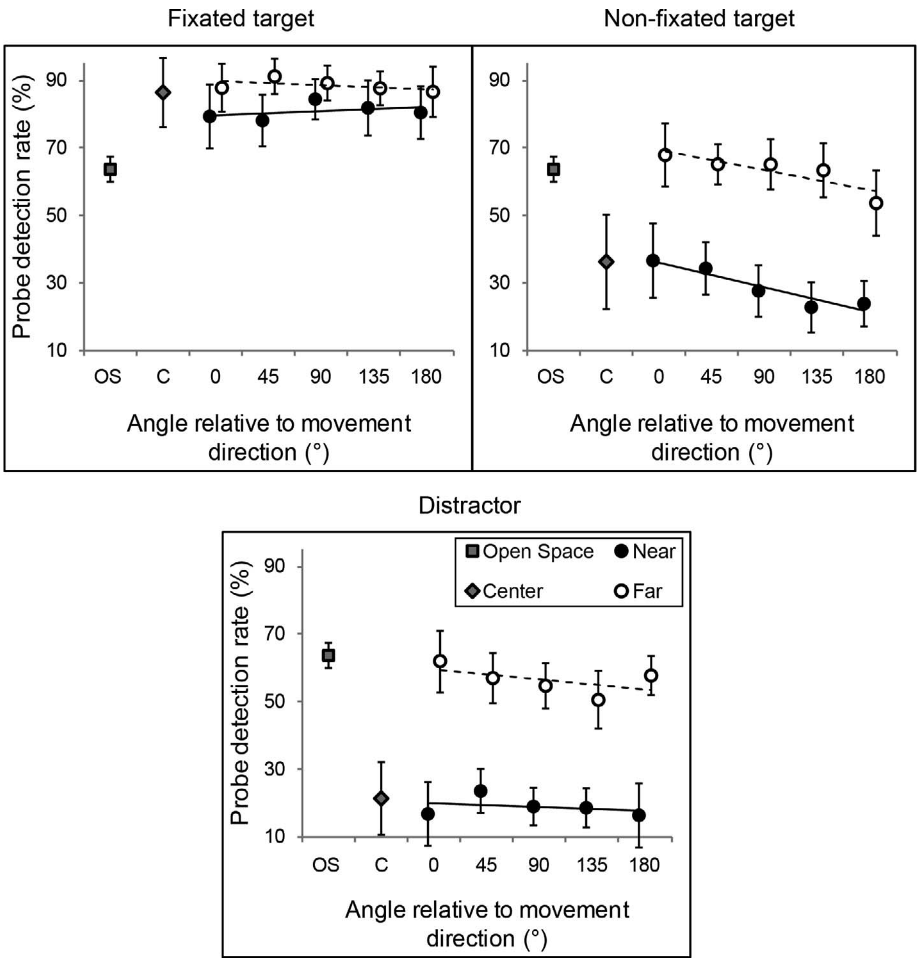

Figure 7. Probe detection rates for Experiment 2 at each relative angle for each target and combined for the two distractors, at both distances. Closed circles represent detection rates for probes presented near the object; open circles represent detection rates for probes presented further away from the object. Gray diamonds represent mean detection rates for probes presented at the center of the object. Gray squares represent mean detection rates for open space probes. Trend lines show the relationship between the different angles for each type of attention at each distance. Angle 0 represents the object's movement direction.

detection rates for center probes on fixated targets again support that fixation instructions were followed correctly.

With regard to the nonfixated, covertly tracked target, we see a distribution of attention very similar to the anticipatory distribution of attention found by Atsma et al. (2012, experiment 1) when freely tracking three targets amongst three distractors (compare the top right plot in Figure 6 above and Atsma et al., figure 2A, p. 4). However, with regard to the fixated, overtly tracked targets the attentional distribution was found to be isotropic. It is likely that in the experiment by Atsma et al., where three targets had to be tracked, viewers tracked the targets covertly most of the time (see also Fehd & Seiffert, 2008). Although a direct comparison between the current study and the study by Atsma et al. is difficult, it should be noted that the detection rates we find for covertly tracked targets, averaged over the two distances (1.65° and 3.3°), also lie within the same range as those found by Atsma et al. at a distance of 3.0° (both approximately 35%–55%).

When we introduced this second experiment, we hypothesized that covert attention would be distributed anisotropically. This is indeed what our results show. For overt attentional resources, we considered that they could be distributed either anisotropically or isotropically around the target. We found the latter, which suggests that in the setting of this second experiment, where two targets needed to be tracked instead of one, overt attention by itself does not take motion information into account.

General discussion

In this study, we investigated the relative contributions of overt and covert orienting with regard to the distribution of attention directed at moving targets. First, we investigated the distributions of overt and covert attention near tracked targets using an SOT task (Experiment 1). We found that for both overtly tracked and covertly tracked targets, the probe detection distributions were anisotropic—that is, attentional resources were not equally divided over the probed space around the target—with more of the resources deployed ahead of the moving target. Next, we combined overt and covert attention in a MOT task (Experiment 2). There, we found that probe detection was clearly distributed anisotropically around non-fixated targets with a similar pattern as found in the first experiment, whereas probe detection was more homogeneous in the probed space around the fixated target. These main results are summarized in Table 1.

From Experiment 1, we could conclude that attention directed at moving objects always uses information about the object's movement direction, independent of whether the object is attended overtly or covertly. This appears to be in line with previous studies that showed that both overt (Khan et al., 2010) and covert (Luu & Howe, 2015; Shiori et al., 2000; Shiori et al., 2002; Szinte et al., 2015) attention might take movement information into account. Our findings from Experiment 2 suggest that movement information is only used when an object is tracked covertly, also in line with abovementioned studies regarding covert attention, but with a different outcome for overt attention (Lovejoy et al., 2009; Watamaniuk & Heinen, 2015). Both findings individually appear to agree with previous studies using free-viewing MOT (Atsma et al., 2012; Fencsik et al., 2007; Howe & Holcombe, 2012; Iordanescu et al., 2009), where the relative contributions of overt and covert attention were not known. However, when tracking n targets at once, viewers will automatically need to track at least $n - 1$ objects in a covert manner at any given time, because gaze (and therefore overt attention) can only be directed at one location at a time. In fact, viewers often adopt a center-looking strategy when more than two targets need to be tracked (Fehd & Seiffert, 2008), which involves only covert attention. The apparent anticipatory attentional processing of moving targets found in free-viewing MOT studies can therefore be independent of gaze (as our first experiment suggests), or it can specifically be a property of covert attention (as in our second experiment).

Although the results from both our experiments appear to be consistent with previous research (Atsma et al., 2012; Fencsik et al., 2007; Franconeri et al., 2012; Howe & Holcombe, 2012; Iordanescu et al., 2009; Keane & Pylyshyn, 2006; Khan et al., 2010; Lovejoy et al., 2009; Luu & Howe, 2015; Szinte et al., 2015; Watamaniuk & Heinen, 2015), they do not seem to be consistent with each other. Obviously, the two experiments we have described here were not exactly the same. We will discuss some of the differences that might explain the seemingly conflicting results. First, eye movements could have been an issue (Luu & Howe, 2015; Zhong, Ma, Wilson, Liu, & Flombaum, 2014). In Experiment 1, overt tracking required our participants to move their gaze along with the target, while covert tracking required them to keep their gaze stationary and directed at the fixation cross. In Experiment 2, covert tracking was always done while the eyes were moving, because gaze simultaneously followed the overtly tracked target on every trial. If this difference in eye movements would have influenced our results, we would see a difference between the covertly tracked targets from Experiments 1 and 2. For the overtly tracked targets in both experiments, the eye movements would have been essentially the same, namely following the target. However, our results show similar probe detection patterns around the covertly tracked targets in Experiments 1 and 2, despite the difference in eye movements. Moreover, we find different patterns for the two overtly tracked targets, even though the eye movements were similar.

	Attention		
	Target		
Task	Overt	Covert	Distractor
SOT One target Fixation on target	Anisotropy		Isotropy
SOT One target Fixation on center screen		Anisotropy	Anisotropy
MOT Two targets One target fixated (overt) One target not fixated (covert)	Isotropy	Anisotropy	Isotropy

Table 1. Overview of (an)isotropy. *Notes*: This table shows the main overview of findings with regard to (an)isotropy of probe detection rates for all objects in both experiments. SOT = single-object tracking; MOT = multiple-object tracking.

Second, the amount of attentional resources dedicated to the task might have been different between the two experiments. For both overtly tracked and covertly tracked targets, we see that the overall probe detection rate was higher in the second experiment compared to the first. Moreover, the feedback we received from several participants in both experiments suggests that tracking the objects in Experiment 1 was so easy that participants were very easily distracted by their thoughts, and that Experiment 2 was more challenging and engaging. We therefore speculate that participants focused their attention more strongly (i.e., dedicated more attentional resources) toward tracking each target during Experiment 2 than during Experiment 1. As a consequence, the apparently isotropic distribution of probe detection rates around the overtly tracked target in Experiment 2 might be a kind of ceiling effect. Such a ceiling effect could mask any anticipatory pattern that might have been visible otherwise. To further explore whether the isotropic distribution is to be attributed to a ceiling effect, we performed an additional analysis in which we compared participants with relatively low probe detection rates to participants with relatively high detection rates using a median split. Now, we found an isotropic distribution around overtly tracked targets for both groups, even though the average detection rate of the low detectors was around 70%. Additionally, we performed the same analysis for the overtly tracked targets in Experiment 1 and found that the distribution of probe detection rates was consistently anisotropic for both participants with a relatively high detection rate and participants with a relatively low detection rate. These additional results support the conclusion that anisotropy around covertly tracked targets is fairly robust, whereas overt attention is much more flexible and sensitive to the specific task requirements.

Additionally, a possible effect of the difference in task difficulty can be seen in the distribution of probe detection rates around the distractors. In Experiment 1, we see similar patterns around the target and the distractor in center screen fixation trials. More specifically, they share a similar anisotropic pattern. In Experiment 2, the probe detection rates around distractors are no longer anisotropic, while around the nonfixated target the anisotropy remains. A possible explanation for this phenomenon is that during SOT, when tracking was relatively easy, participants also inadvertently allocated some left over attentional resources to the distractor. This could even serve a purpose, such as anticipating interactions between the objects. We would expect to see this during center screen fixation, where gaze and attention are to a certain degree detached from each other, and participants supposedly adopt a broader focus of the scene, but not during target fixation trials, where gaze and attention form a narrow focus on the tracked target. In MOT, when more attentional resources had to be dedicated to the task, the additional tracking of the distractor would require effort and therefore would be more detrimental to task performance. In our second experiment, detection rates for distractor probes are still almost as high as detection rates for probes presented near the nonfixated target, but the pattern around distractors is no longer anisotropic.

We further highlight the following observation: In both experiments, we saw that the probe locations close to the edge and in the center of the nonfixated objects had very low detection rates compared to the probe locations further away from the objects. It appears that the detection of these probes was somehow suppressed. We suggest that this could have been the result of a suppression effect caused by the proximity of the target, such as surround suppression (e.g., Petrov & McKee, 2006; Petrov, Popple & McKee, 2007). Interestingly, this effect was also reported by Atsma et al. (2012), which is the reason why we chose to use two probe distances instead of only one. It should, however, also be noted that in Experiment 2 the detection of probes was better for all probed locations, including those close to the edge of the nonfixated objects, compared to Experiment 1. While in Experiment 1 detection rates of probes presented near the nonfixated target clearly approached 0%, the performance in Experiment 2 for comparable probes revealed a clear anisotropic detection pattern. The generally higher probe detection rates support the idea that the amount of attentional resources dedicated to the task was higher in Experiment 2 compared to Experiment 1.

Note that we assume that a high detection rate of probes at a certain location reflects a high amount of attentional resources allocated to that location: When we attend to a certain location, we are better at detecting a transient stimulus at that location compared to when we do not attend to that location (Posner, 1980). One could argue that probe detection is facilitated by a top-down process, such as hypothesis testing: First, a probe is detected tentatively, and second, attention shifts towards the probe's presumed location to confirm its presence. The first step of initial detection would then not necessarily have to be anisotropic. However, as we do find anisotropy in probe detection rates around some of the attended objects in both experiments, the additional process of hypothesis testing has to be responsible for the bias towards the movement direction of the objects. Given the design of our experiments and the fact that probes appeared with equal probability at each angle and each distance, as well as the fact that object probes always remained stationary with respect to the object during the 100 ms of presentation, this process would already have to be anisotropically biased. That is to say, also in this alternative explanatory account, attention is leaning ahead of the moving object. This conclusion is in line with our initial, more parsimonious, explanation of our findings.

In sum, our goal was to investigate how far anticipation is a property of overt or covert attention, or both. The results can be summarized as follows. Covertly tracked targets showed anisotropy, regardless of whether the eyes were fixating at one point on the screen (Experiment 1) or were moving around (Experiment 2). Overtly tracked targets—that is, with eyes moving around following a specific target—revealed either anisotropy (Experiment 1) or isotropy (Experiment 2). From this it appears that the attentional distribution is rather independent of eye movements. All in all, we conclude that covert attention always takes motion information into account when keeping track of objects, while overt attention is more flexible and its anticipatory nature is much more task-dependent.

Keywords: multiple-object tracking, *visual attention*, *anticipation*, *overt attention*, *covert attention*, *attention allocation*

Acknowledgments

We thank our colleagues Mathieu Koppen for advice on statistics and Jeroen Atsma for helpful input and advice, as well as two anonymous reviewers for their helpful comments and suggestions.

Data are available from the Donders Institute for Brain, Cognition and Behaviour repository at http://hdl.handle.net/11633/di.dcc.DSC_2017.00019_079.

Commercial relationships: none.
Corresponding author: Andrea F. Frielink-Loing.
Email: a.frielink@donders.ru.nl.
Address: Montessorilaan 3, 6525 HR Nijmegen.

Footnote

[1]Against the walls of the bounding box, a natural bounce means that the angle of incidence equals the angle of reflection. In object-to-object collisions, $v_{new} = w_r + v_t$ and $w_{new} = v_r + w_t$, where v_{new} and w_{new} are the resulting velocity vectors of the two objects involved after the collision, v and w are the object velocities prior to collision, v_r and w_r are the orthogonal components of v and w parallel to the line of collision and v_t and w_t are the orthogonal components of v and w perpendicular to the line of collision.

References

Alvarez, G. A., & Cavanagh, P. (2005). Independent recourses for attentional tracking in the left and right visual hemifields. *Psychological Science*, *16*(8), 637–643.

Alvarez, G. A., & Franconeri, S. L. (2007). How many objects can you track? Evidence for a resource-limited attentive tracking mechanism. *Journal of Vision*, *7*(13):14, 1–10, doi:10.1167/7.13.14. [PubMed] [Article]

Alvarez, G. A., & Scholl, B. J. (2005). How does attention select and track spatially extended objects? New effects of attentional concentration and amplification. *Journal of Experimental Psychology: General*, *134*(4), 461–476.

Atsma, J., Koning, A., & van Lier, R. (2012). Multiple object tracking: Anticipatory attention doesn't "bounce." *Journal of Vision*, *12*(13):1, 1–11, doi:10.1167/12.13.1. [PubMed] [Article]

Bouma, H. (1970). Interaction effects in parafoveal letter recognition. *Nature*, *226*, 177–178.

Brainard, D. H. (1997). The Psychophysics Toolbox. *Spatial Vision*, *10*, 433–436.

Cavanagh, P., & Alvarez, G. A. (2005). Tracking multiple targets with multifocal attention. *Trends in Cognitive Sciences*, *9*(7), 349–354.

Fehd, H. M., & Seiffert, A. E. (2008). Eye movements during multiple object tracking: Where do participants look? *Cognition*, *108*, 201–209, doi:10.1016/j.cognition.2007.11.008.

Fencsik, D. E., Klieger, S. B., & Horowitz, T. S. (2007). The role of location and motion information in the tracking and recovery of moving objects. *Perception & Psychophysics*, *69*(4), 567–577.

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

Franconeri, S. L., Pylyshyn, Z. W., & Scholl, B. J. (2012). A simple proximity heuristic allows tracking of multiple objects through occlusion. *Attention, Perception & Psychophysics*, *74*, 691–702.

Howe, P. D. L., & Holcombe, A. O. (2012). Motion information is sometimes used as an aid to the visual tracking of objects. *Journal of Vision*, *12*(13):10, 1–10, doi:10.1167/12.13.10. [PubMed] [Article]

Iordanescu, L., Grabowecky, M., & Suzuki, S. (2009). Demand-based dynamic distribution of velocities during multiple-object tracking. *Journal of Vision*, *9*(4):1, 1–12, doi:10.1167/9.4.1. [PubMed] [Article]

Keane, B. P., & Pylyshyn, Z. W. (2006). Is motion extrapolation employed in multiple object tracking? Tracking as a low-level, non-predictive function. *Cognitive Psychology*, *52*, 346–368.

Khan, A. Z., Lefèvre, P., Heinen, S. J., & Blohm, G. (2010). The default allocation of attention is broadly ahead of smoot pursuit. *Journal of Vision*, *10*(13):7, 1–17, doi:10.1167/10.13.7. [PubMed] [Article]

Kleiner, M., Brainard, D. H., & Pelli, D. G. (2007). What's new in Psychtoolbox-3? Perception, *36*, ECVP Abstract Supplement.

Lovejoy, L. P., Fowler, G. A., & Krauzlis, R. J. (2009). Spatial allocation of attention during smooth pursuit eye movements. *Vision Research*, *49*(10), 1275–1285.

Luu, T., & Howe, P. D. L. (2015). Extrapolation occurs in multiple object tracking when eye movements are controlled. *Attention, Perception & Psychophysics*, *77*, 1919–1929, doi:10.3758/s13414-015-0891-8.

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

Pelli, D. G. (1997). The Videotoolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision*, *10*, 437–442.

Petrov, Y., & McKee, S. P. (2006). The effect of spatial configuration on surround suppression of contrast sensitivity. *Journal of Vision*, *6*(3):4, 224–238, doi: 10.1167/6.3.4. [PubMed] [Article]

Petrov, Y., Popple, A. V., & McKee, S. P. (2007). Crowding and surround suppression: Not to be confused. *Journal of Vision*, *7*(2):12, 1–9, doi:10. 1167/7.2.12. [PubMed] [Article]

Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology*, *32*(1), 3–25.

Pylyshyn, Z. W. (2004). Some puzzling findings in multiple object tracking: I. Tracking without keeping track of object identities. *Visual Cognition*, *11*(7), 801–822.

Pylyshyn, Z. W. (2006). Some puzzling findings in multiple object tracking (MOT): II. Inhibition of moving nontargets. *Visual Cognition*, *14*(2), 175–198.

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

Ramachandran, V. S., & Anstis, S. M. (1983). Extrapolation of motion path in human visual perception. *Vision Research*, *23*, 83–85.

Scholl, B. J. (2001). Objects and attention: the state of the art. *Cognition*, *80*, 1–46.

Scholl, B. J. (2009). What have we learned about attention from multiple object tracking (and vice versa)? In D. Dedrick & L. Trick (Eds.), *Computation, cognition, and Pylyshyn* (pp. 49–77). Cambridge, MA: MIT Press.

Scholl, B. J., Pylyshyn, Z. W., & Feldman, J. (2001). What is a visual object? Evidence from target merging in multiple object tracking. *Cognition*, *80*, 159–177.

Shioiri, S., Cavanagh, P., Miyamoto, T. & Yaguchi, H. (2000). Tracking the apparent location of targets in interpolated motion. *Vision Research*, *40*, 1365–1376.

Shioiri, S., Yamamoto, K., Kageyama, Y., & Yaguchi, H. (2002). Smooth shifts of visual attention. *Vision Research*, *42*, 2811–2816.

Szinte, M., Carrasco, M., Cavanagh, P., & Rolfs, M. (2015). Attentional trade-offs maintain the tracking of moving objects across saccades. *Journal of Neurophysiology*, *113*(7), 2220–2231, doi:10.1152/ jn.00966.2014.

Watamaniuk, S. N. J., & Heinen, S. J. (2015). Allocation of attention during pursuit of large objects is no different than during fixation. *Journal of Vision*, *15*(9):9, 1–12, doi:10.1167/15.9.9. [PubMed] [Article]

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

Zhong, S., Ma, Z., Wilson, C., Liu, Y., & Flombaum, J. I. (2014). Why do people appear not to extrapolate trajectories during multiple object tracking? A computational investigation. *Journal of Vision*, *14*(12):12, 1–30, doi:10.1167/14.12.12. [PubMed] [Article]