Task-dependent modulation of anticipatory attention

Evidence from Multiple-Object Tracking

Andrea Frielink-Loing

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The research presented in this thesis was carried out at the Radboud University, Donders Institute for Brain, Cognition and Behaviour, and was made possible by an internal grant from the Donders Centre for Cognition.

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Radboud Dissertation Series
ISSN: 2950-2772 (Online); 2950-2780 (Print)

Published by RADBOUD UNIVERSITY PRESS
Postbus 9100, 6500 HA Nijmegen, The Netherlands
www.radbouduniversitypress.nl

Design: Proefschrift AIO | Annelies Lips
Cover: Proefschrift AIO | Guus Gijben
Cover image: Created using Adobe Express
Printing: DPN Rikken/Pumbo

ISBN: 9789465151342
DOI: 10.54195/9789465151342
Free download at: https://doi.org/10.54195/9789465151342

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Task-dependent modulation of anticipatory attention

Evidence from Multiple-Object Tracking

Proefschrift ter verkrijging van de graad van doctor
aan de Radboud Universiteit Nijmegen
op gezag van de rector magnificus prof. dr. J.M. Sanders,
volgens besluit van het college voor promoties
in het openbaar te verdedigen op

maandag 29 september 2025
om 10.30 uur precies

door

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geboren op 14 maart 1986
te Tilburg

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Chapter 1

General introduction

Right now, you are reading these words on the page in front of you, and you are fully focussed on this text. Or are you? Wait, was that the delivery truck? Ooh, a bird just flew by. Hey, you just got that email you were waiting for!

Oh yes, right, you were reading something.

Attention can sometimes be a difficult thing to manage, as you may undoubtedly experience on a daily basis. But that also makes it a very difficult thing to study. The aim of this thesis is to get some insight into how attention is distributed across a visual scene, specifically when multiple moving objects need to be followed simultaneously. In this general introduction, I will first attempt to break down the concept of attention by addressing several distinctions that can be made. Next, I introduce the Multiple Object Tracking paradigm, the task that forms the basis for every study incorporated in this thesis. Finally, I will zoom in on how attention is used and studied throughout this thesis.

What is attention?

When trying to explain to people from outside my field of research (or from outside academia altogether) that I investigated attention, they often ask what attention is. I have never been able to give them a satisfactory answer. That is to say, although *they* may have been satisfied with the answer, *I* never was.

The origin of the word 'attention' as we know it now can be traced back to the late 14th century, literally meaning "to stretch toward" (see also Harper, n.d.). However, it only became a subject of scientific interest on its own in the 17th or 18th century, when the study of Psychology was still a part of the field of Philosophy (Hatfield, 1998). That is not to say that the phenomenon of attending, of being able to focus one's mind on only one or a few sensations around us, wasn't a topic of interest before this time. In fact, already the great minds of Aristotle (4th century BC) and Lucretius (1st century BC) were at some point occupied with wonderings about whether we can actually perceive two things simultaneously, and how 'directing the mind' is necessary to perceive a stimulus clearly.

Attention as a scientific topic has been defined in many different ways, and has been used to describe a broad spectrum of phenomena and mechanisms over the past few centuries. Anderson (2011) even argued that 'there is no such thing as attention', although that may be taking it a bit too far. The term has been muddied by redefinition as individual researchers saw fit, and may have even become a hype word that is merely used to boost interest in publications. Undoubtedly, the way the word 'attention' is used outside academia must have also had its influence on how it is used in research. How often do we say things like "I'm sorry, I didn't hear what you said, I wasn't paying attention", or "my child has a very short attention span", or "I'm attending a class" (which has a whole different meaning, but originates from the same source)?

The fact is that attention is an incredibly broad topic, and should be treated as such. James (1890/1950) beautifully describes it as follows:

> *"Everyone knows what attention is. It is the taking possession by the mind, in clear and vivid form, of one out of what seem several simultaneously possible objects or trains of thought. Focalization, concentration, of consciousness are of its essence. It implies withdrawal from some things in order to deal effectively with others, and is a condition which has a real opposite in the confused, dazed, scatter-brained state which in French is called distraction, and Zerstreutheit in German."*

Simply put: given the sheer number of possible sensations we are exposed to at any given time, we must have a mechanism that enables us to select one or a few of these sensations in order to make sense of anything (or to not go completely mad). Applying this focus can happen in many different ways, as we know from experience. I will discuss some of these ways later, but first I need to address a more important topic related to attention: the senses.

Attention and the senses

An attentional focus can be applied to any of our senses – take for example how a musician can pick out the melody of a single instrument in an orchestra, or a perfumer who can distinguish the most subtle olfactory sensations – as well as to our thoughts. However, for researchers attention is most often associated with vision. This is not surprising, because the visual world is probably the most salient and most chaotic of all, and so our visual system essentially needs a mechanism like attention to even work at all.

Maybe it is for this very same reason that a vast amount of research on attention applies to vision[1]. Not just because it is such a dominant modality, but also because there are so many aspects and phenomena to investigate. The complexity of its underlying mechanisms can keep researchers busy for many decades to come. Attention critically enables us to see and notice things, but its absence (or distraction) can make us miss even the largest of changes. This is best illustrated by the Monkey Business Illusion[2] experiment (Simons & Chabris, 1999), where observers were shown a video of two teams of basketball players and had to count the number of times players from one team passed the ball to each other. Because they were so preoccupied by the counting task, about half of the observers completely missed a person in a gorilla suit walking across the scene (*Figure 1.1*). This phenomenon is called inattentional blindness.

Figure 1.1. Stills of the video used in the original Monkey Business Illusion experiment by Simons & Chabris (1999).

Another closely related phenomenon is change blindness (Rensink, O'Regan & Clark, 1997). This occurs when a visual stimulus (usually a scene with several objects and their surroundings) is alternated with a slightly adapted version (e.g., one object has changed colour), while blank screens or so-called 'mudsplashes' are shown in between alternations (*Figure 1.2*). It often takes observers a long time to notice the change, even if it affects a large portion of the scene.

1. Although a fair amount of research has also been done on attention in auditory perception, see for example the work on selective listening tasks by Anne Treisman and others.
2. If you are not familiar with it, watch the video on YouTube: https://www.youtube.com/watch?v=IGQmdoK_ZfY

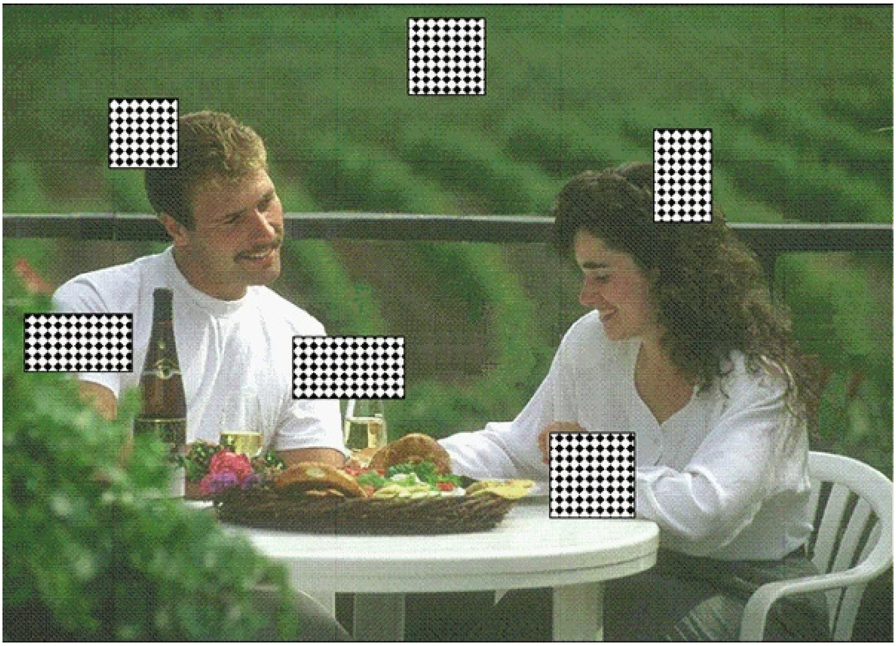


Figure 1.2. Mudsplashes in a picture used in the change blindness paradigm by Rensink, O'Regan and Clark (1997).

In visual attention research, several distinctions are made with regard to how we direct our attention. I will discuss three of these distinctions here: Voluntary versus reflexive attention, object-based versus space-based attention, and overt versus covert orienting.

Voluntary versus reflexive attention

When you consciously and deliberately focus your attention on something, for example when reading a text, we speak of voluntary attention. This is a top-down, goal-driven process, associated with dorsal pathways of the brain's attentional control network. On the other hand, we have reflexive, or stimulus-driven, attention, which is a rapid response mechanism usually triggered by a stimulus or change onset, and is associated with ventral pathways of the attentional control network. Magicians sometimes make use of reflexive attention to distract their audience. But there are also situations where a kind of hybrid or learned form of attentional orienting takes place, for example when playing sports. While voluntary attention can be directed at something without the eyes needing to move towards it (covert orienting, discussed later in this introduction), reflexive attention usually comes with an oculomotor response. The experiments described in this thesis all relied on voluntary attention.

Object-based versus space-based attention

Another distinction that is often made in visual attention research is between object-based attention – i.e., directed towards a whole object, only restricted by its dimensions – and space-based attention – i.e., directed towards a location in space, which can also be part of an object or can contain (parts of) multiple objects. The latter is also often referred to as the attentional spotlight (Posner, Snyder & Davidson, 1980). Although the distinction between object- and space-based attention has long been a subject of dispute among researchers, it is now becoming more and more accepted that both mechanisms may be applied in different contexts, and that they can even be combined into a hybrid form, e.g., an attentional spotlight on a specific part of an object (cf. Scholl, 2009).

Throughout Chapters 2, 3 and 4 of this thesis, we investigated such a hybrid form of space- and object-based attention. Specifically, we looked at a phenomenon called anticipatory attention, where attention is directed at the future location of a moving object rather than at the object itself. This phenomenon will be discussed in further detail later on in this introduction.

Overt versus covert orienting

When you are looking at something, you are automatically directing all your attention to it. Right? Well, not necessarily. If that were the case, we would not be able to attend to more than one thing at the same time. Quite often, we attend to things within our field of vision, but without looking at them directly. Take for example a game of football (or 'soccer', if you will): You have the ball and you're running it all the way across the field towards the goal, when you notice from the corner of your eye that someone from the other team is approaching. You quickly scan the field to find someone from your own team to pass the ball to, then you get your eyes back on the ball, all the while keeping track of the other players from the corners of your eyes, and make the shot towards your team member, who then expertly places the ball in the top left corner of the other team's goal.

In many real-life situations, we divide our attention over multiple things at once. This can be across modalities, but it also happens within modalities. When you attend to multiple things in your field of vision at the same time, you will need both overt orienting – aligning your eyes with an object – and covert orienting – attending to something 'from the corner of your eye'. This distinction was thoroughly reviewed by Posner (1980) and is also the focus of Chapter 2 of this thesis.

Measuring Attention

So how exactly do we know where a person's attention is aimed at? If we are interested in overt attention, we could just track eye movements. Covert attention, however, cannot be measured as directly, and so we need indirect ways that can reliably determine which part of the visual scene is attended at a certain moment in time. For that, we need to remember what attention does: it isolates one or more *things* (locations, objects, features, sounds, etc.) to enhance our perception of them, while suppressing others in order to minimize distraction. This should mean that if something happens at a location that I am currently focussing my attention on, there is a better chance that I detect it than when it happens at an unattended location. This is the basis for the method of *probing* (Poster, 1980).

P300 Speller

In 1988, Farwell & Donchin created a so-called Brain-Computer Interface (BCI) that allowed individuals who are not able to communicate using their motor system to form words on a screen with their brain activity. Using a grid made up of letters that would light up in specific patterns, the attended letter could be picked out by comparing the pattern of P300 peaks in the EEG to the flash pattern of the individual letters.

In a probe detection task, a small object (the probe) is briefly flashed at a certain location in the visual scene, and the viewer is asked to indicate whether they've detected it. The probe should be sufficiently small and flashed briefly enough, that it is hard to detect without the enhancing power of directed, voluntary attention, meaning that we should see a difference in detection rate between attended and unattended locations. This method has been used to determine the allocation of attention in various fields of Psychology, including attentional bias in mental disorders (e.g., Mogg & Bradley, 2005), and visual search (e.g., Kim & Cave, 1995). It is also our method of choice to measure the distribution of attention throughout this thesis.

Multiple Object Tracking: an experimental paradigm

As mentioned at the start of this introduction, the aim of this thesis is to get an insight into how attention is distributed across a visual scene, specifically when multiple moving objects need to be followed simultaneously. To study how we track multiple objects at once, we will make use of a simple task created by Pylyshyn and Storm (1988), in which participants followed several *target* objects among a number of *distractor* objects identical to the targets, while they moved across the visual field for a certain amount of time. Although this task was originally meant to show that humans are able to simultaneously track a subset of items from a larger set of moving identical objects, in the following decades it has been used both in its original form, as well as adapted and expanded, to study a multitude of other phenomena and mechanisms, often related to attention.

The Multiple Object Tracking (MOT) paradigm typically consists of three elements (see also *Figure 1.3*):

- Designation: All the objects are presented on the screen (*Figure 1.3*, *t = 1*), and the objects-to-be-tracked (*targets*) are indicated (*Figure 1.3*, *t = 2*).
- Tracking: The objects move around the screen for a certain amount of time, while the viewer tries to keep track of the targets (*Figure 1.3*, *t = 3*).
- Identification: The viewer performs a target identification task to measure tracking performance (*Figure 1.3*, *t = 4*).

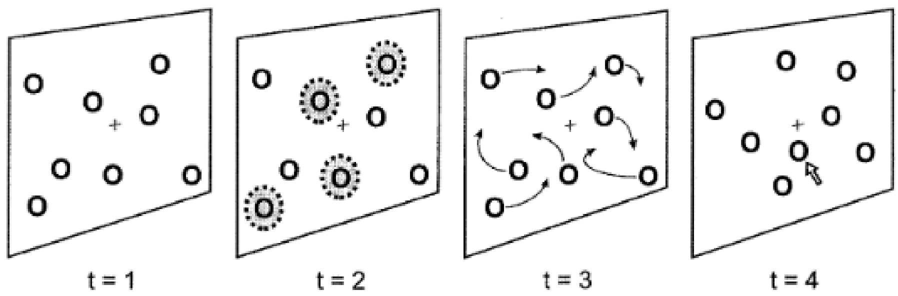


Figure 1.3. A typical timeline for a Multiple Object Tracking task, from Pylyshyn (2004). Time t = 1 corresponds to the initialisation of the display, t = 2 to the Designation phase described above, t = 3 to Tracking, and t = 4 to Identification.

When Pylyshyn and Storm introduced the MOT paradigm in the late 1980s, there was a general assumption among perception researchers that there could only be one region (spotlight) of focal visual attention, meaning that everything that falls within the region is attended to, and anything that falls outside this region is not attended to (cf. the abovementioned space-based attention). Pylyshyn and Storm's finding that viewers can reliably track multiple identical, independently moving objects among a number of distractors, instead revealed the possibility that there can be multiple loci of attention at the same time. They then went on to show that the high tracking performance on the MOT task could not be explained by a purely serial approach, but had to at least partially consist of a parallel, albeit resource-limited, tracking process.

With little or no adjustments, the MOT paradigm was subsequently used to investigate factors that may influence tracking performance. For example, Yantis (1992) manipulated the ease with which the targets could be grouped together, either during the designation phase or during tracking. He found that grouping cues offered only during the designation phase aided tracking in the early stages of an experiment, while grouping cues offered throughout tracking increased tracking performance during the entire task. Oksama and Hyönä (2004) investigated individual differences in tracking ability, and whether tracking performance could be predicted based on an individual's performance on other cognitive tasks. Their results showed that tasks measuring visuo-spatial short-term memory and attention switching ability were good predictors of an individual's performance on the MOT task. As a final example, Howe and Holcombe (2012) showed that tracking performance could benefit from objects moving in a predictable manner (i.e., following linear paths) rather than randomly changing direction every few frames, although this effect could only be found when very few objects (only two) had to be tracked.

Others have adapted the stimulus set by adding objects or obstacles, or by changing the shape of the targets and distractors. One example is the addition of an occluder behind which objects can move, thereby hiding part of the objects' trajectories (Flombaum, Scholl & Pylyshyn, 2008). Using probe detection to determine how attention was being allocated during tracking, Flombaum et al. discovered that more attentional resources were allocated to an occluded object compared to when the object was visible, a finding they referred to as the *attentional high-beams* effect. This finding illustrates that the attentional system not only highlights certain objects or locations, but that there can also be a variation in the *amount* of attentional resources dedicated to items depending on the need.

An example of how the shape of the objects can be varied is given by the work of Alvarez and Scholl (2005). As opposed to the traditional highly symmetric objects (e.g., squares or circles), they introduced stick objects of variable lengths as the targets and distractors. During tracking, probes were flashed at different locations along the objects, in particular the centers and end points, and they found that probes presented at the center of the stick were detected better than those presented on or near the end points. In fact, this effect became stronger (i.e., attention became much more concentrated at the center) as object length increased. This concentration and amplification effect provides strong evidence that attention is (or can be) a combination of object- and space-based attention.

Anticipatory attention

These last two examples show how probe detection can be used in combination with the MOT task to map the distribution of attention with respect to moving objects' locations and even their shapes during tracking. This same technique was used by Vrins (2012) to study the distribution of attention outside the objects' bounds, specifically during brief periods of parallel motion between a target and a distractor. He found that attention is not equally distributed around a tracked object, but forms a rather anisotropic pattern. Although out of scope for his study, Vrins noticed that probed locations in the direction opposite to an object's movement (i.e., trailing the object) were detected less frequently than probes presented more or less in the direction of movement (i.e., ahead of the object). Enough reason for Atsma, Koning and van Lier (2012) to further investigate this seemingly anticipatory pattern of attention.

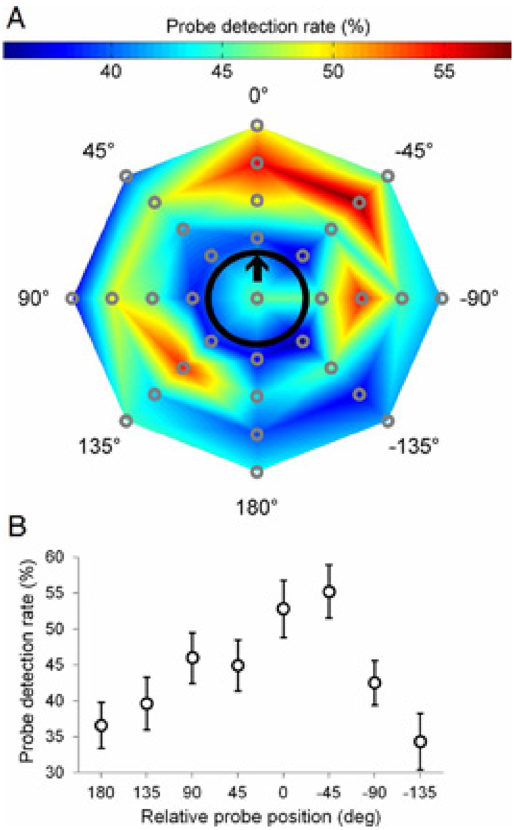


Figure 1.4. Heatmap (A) and plot (B) produced by Atsma et al. (2012) from mean probe detection rates at locations surrounding a tracked moving object.

In a two-part study, Atsma et al. first focused on mapping the distribution of attention around tracked moving objects by combining the classic MOT paradigm with probe detection all around the objects. This produced the heatmap and plot in *Figure 1.4*. These results clearly show that there is an attentional bias towards the direction of movement of an object, even exceeding the object's bounds. Moreover, they are in line with earlier findings by Iordanescu, Grabowecky and Suzuki (2009), as well as others, who found that viewers often overestimated the location at which a tracked object disappeared from the display, in the direction of its prior movement.

Atsma et al. (2012) continued their investigation into anticipatory attention by introducing a new object to the display, a wall against which the objects could bounce or which the objects would move through. Instead of probing all around the object, they focused on two possible paths: the 'straight' path, that the object would move along if it passed through the wall, and the 'bounce' path, which would follow from a reflective interaction with the wall. Because they made the interaction with the wall predictable (i.e., some blocks of trials were 'straight motion' blocks, others were 'bounce' blocks), it was expected that the detection of straight probes would be better during straight motion, and the detection of bounce probes would be better during bounce motion. However, they found that straight probes always had the upper hand, regardless of actual motion (see *Figure 1.5*).

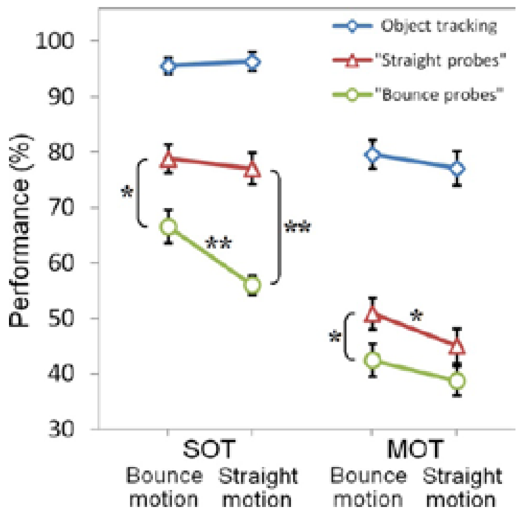


Figure 1.5. Plot from Atsma et al. (2012) comparing probe detection performance on bounce probes and linear probes as a function of object motion.

Outline of the thesis

The aim of this thesis is to study the influence of additional stimuli and tasks on the allocation of attention, ultimately showing that attention can ‘bounce’ under the right circumstances. Specifically, active components are added to the MOT and probe detection task to investigate how different tasks, goals and needs can change the anticipatory role that attention plays in the tight coupling between perception and action. By pushing the limits of the attentional system, we attempt to uncover its flexibility.

Chapter 2 expands on Atsma’s et al. (2012) first experiment, similarly mapping the distribution of attention around tracked objects. In this chapter, a distinction is made between overt and covert tracking, using a single-object tracking task (i.e., either covert or overt tracking of one object) as well as a two-object tracking task (i.e., one covertly tracked and one overly tracked object). For both tasks, we compare the attention mappings of the overtly and covertly tracked objects.

Chapter 3 and 4 expand on Atsma’s et al. second experiment, investigating how different factors can influence the extent to which attention is shifted towards the bounce path ahead of an expected collision.

In Chapter 3, an active component is added to the bouncing task introduced by Atsma et al., turning it into a game resembling Pong. Participants are divided into an active group and a passive (viewing) group, where the former played the game and the latter viewed their recordings. Both groups were tasked with tracking a subset of moving objects, and detecting probes to map the allocation of attention over the bounce and straight paths of objects colliding with the Pong paddle. We compare the performance of both groups, to investigate whether active manipulation of the scene can pull attention towards the bounce path.

In Chapter 4, the active component is taken one step further. In the first experiment, a goal location is added beyond the paddle that needs to be reached by the tracked objects, thereby creating a context in which the future path of the object is relevant. In the second experiment, we refine this paradigm further in order to distinguish between the relevance of the path and the relevance of the goal itself. The third experiment takes a different approach to the goal-directed task, and adds locations that should be avoided in addition to the goals that should be reached.

Chapter 2

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

Text published as: 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.

Data published under: https://doi.org/10.34973/24z2-km86

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 2.1, 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 2.2, 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 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 2.1), or fixate one target while covertly tracking a second target (Experiment 2.2). 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 2.1

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 non-fixated 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 non-fixated 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 grey 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 2.1). One 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° × 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.

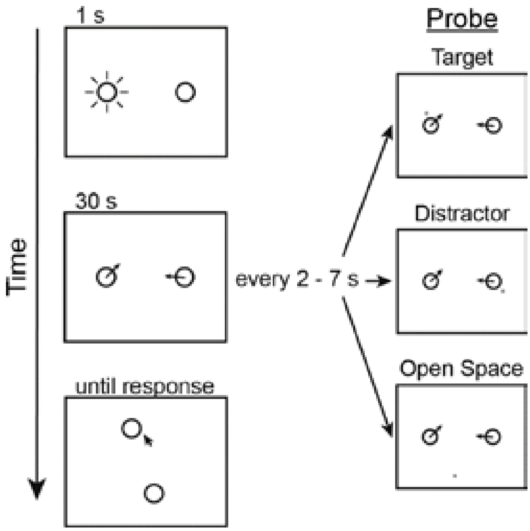


Figure 2.1. Timeline. Each trial started with the indication of the target. Subsequently, both objects started moving for 30 s, during which time probes appeared every 2–7 s. Probes could appear near the target, near the distractor, or in the empty space. When the objects stopped moving, participants had unlimited time to click on the object they remembered to be the target.

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 grey 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 2.2*).

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.

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.

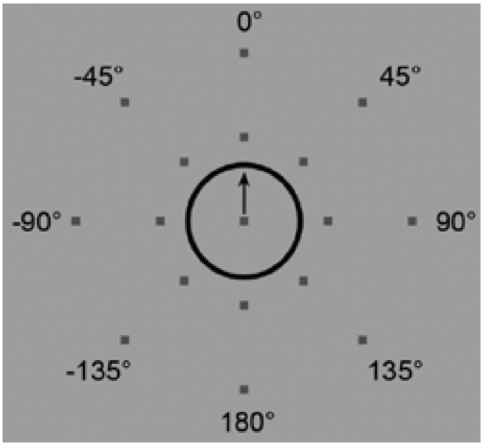


Figure 2.2. The 17 probe locations used in both experiments. An object (black circle, 2.2° diameter) is shown with an arrow (not visible during the experiment) depicting its movement direction. Probe locations are shown as grey squares (0.13°) and are positioned at eight angles and two distances from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

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) × 2 (condition: target disk fixation, center screen fixation) × 17 (location) × 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 × 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 2.3*). 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 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.

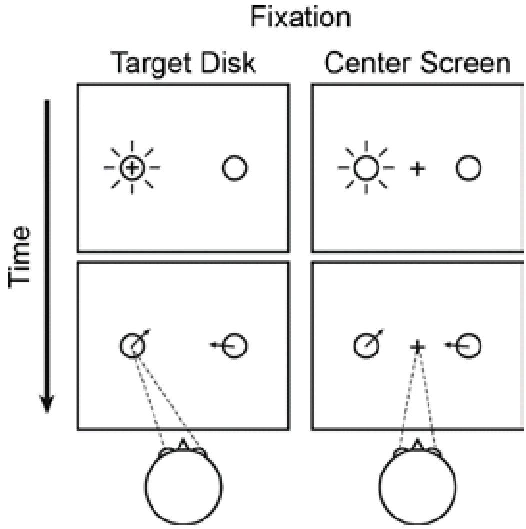


Figure 2.3. Viewing conditions. In the target disk fixation condition (left), a fixation cross appeared inside the target for 1 s during target indication to indicate that the target had to be fixated throughout the trial. In the center screen fixation condition (right), a fixation cross was presented at the center of the display throughout the whole trial to indicate fixation on the center of the screen was required.

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 2.4* 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 trade-offs, as there were no events that could trigger a false alarm, and therefore no reference points to determine reaction times exist.

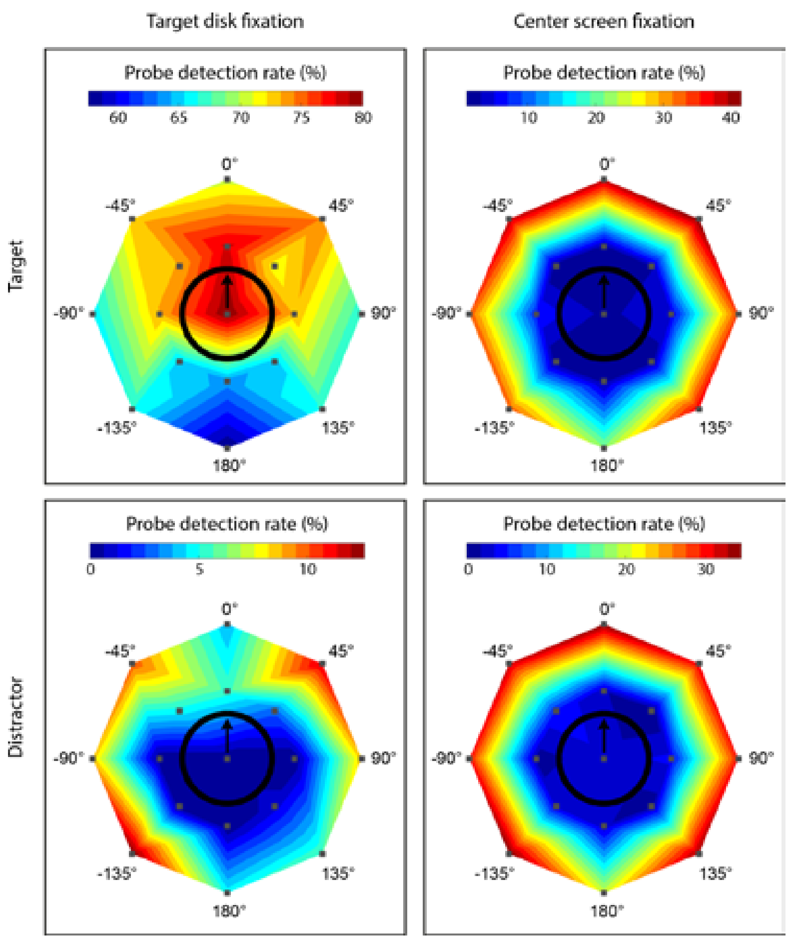


Figure 2.4. Mean detection rates for target and distractor probes in Experiment 2.1. Top left: Fixated target. Top right: Non-fixated target. Bottom left: Distractor in target disk fixation condition. Bottom right: Distractor in center screen fixation condition. An object (black circle) is shown with an arrow (not visible during the experiment) depicting its movement direction. Probe locations are shown as grey squares. The individual colour coding distribution for each object is shown in the legend above each figure. Note that colour 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 colour corresponds to a detection rate of approx. 70%–71%, whereas the same colour for the target in the center screen fixation condition (top right figure) corresponds to a detection rate of approximately 23%–25%.

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 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 2.5*.

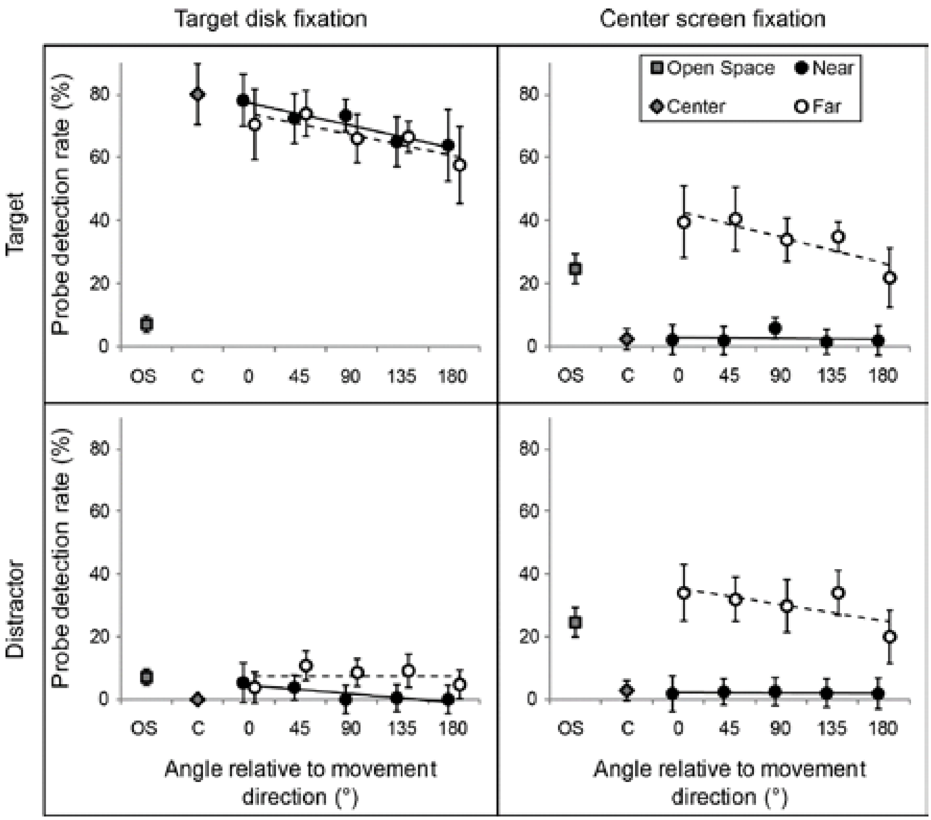


Figure 2.5. Detection rates for object probes in Experiment 2.1 in each fixation condition, at both distances and at each angle. Closed circles represent detection rates for probes presented near the object, open circles represent detection rates for probes presented further away from the object. Gray 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.

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 non-fixated 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, $F(1, 20) = 7.35$, $p = 0.014$, $\eta_p^2 = 0.269$, 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 2.5*. 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 non-fixated 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 non-fixated targets, but probes presented around the fixated target were overall detected much better than probes presented around the non-fixated 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 2.5*). 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 non-fixated targets and high detection rates for center probes on fixated targets support the assumption 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 non-fixated 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 2.2

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 2.1.

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 non-fixated 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 2.1. 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 2.1. Targets and distractors were all identical circular black outlines subtending 2.2° of the visual field, presented on a grey background. Object movement was restricted by a bounding box subtending 25° × 20°. As in Experiment 2.1, 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° × 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 2.1.

During the movement phase, probes (0.13° dark grey 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 2.1 (see also *Figure 2.2*), 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, non-fixated target, distractor) each location was probed six times per participant, leading to 3 × 17 × 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 2.1 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 non-fixated target). As in Experiment 2.1, 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 non-fixated 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, non-fixated 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 non-fixated 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 2.6* shows the distribution of probe detection rates around the fixated and non-fixated 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 analyse the data for the targets, we pre-processed them in the same way as in Experiment 2.1 and used the same 2 × 2 × 5 repeated-measures ANOVA with fixation (fixated vs. non-fixated), distance (near vs. far), and angle (0°, 45°, 90°, 135°, and 180°) as factors. Probe detection rates are shown in *Figure 2.7*. 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 non-fixated 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.

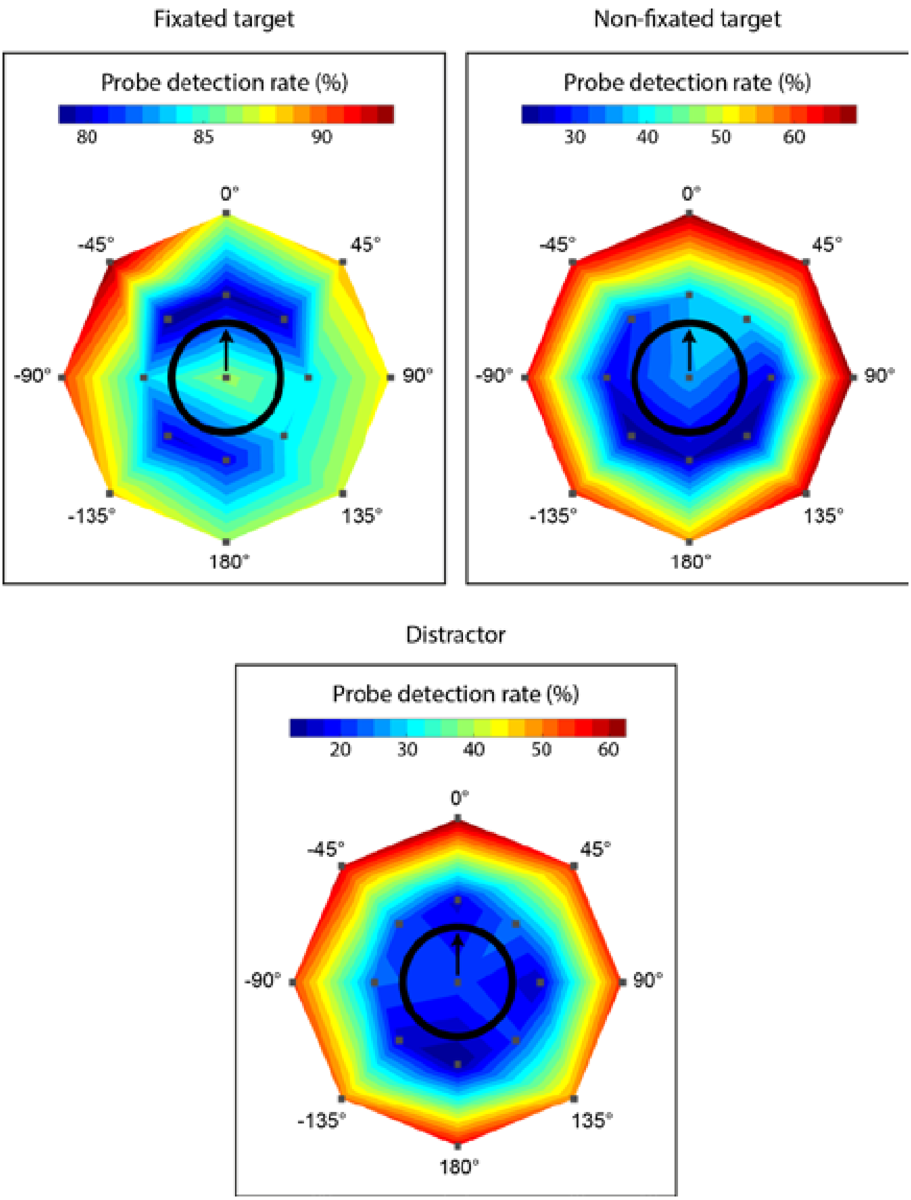


Figure 2.6. Mean detection rates for object probes in Experiment 2.2. Top left: Fixated target. Top right: Non-fixated target. Bottom: Distractor. A target object (black circle) is shown with an arrow (not visible during the experiment) depicting its movement direction. Probe locations are shown as grey squares. The individual colour coding distribution for each object is shown in the legend above each figure. Note that colour 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 colour corresponds to a detection rate of approx. 86%–87%, whereas the same colour for the target in the center screen fixation condition (top right figure) corresponds to a detection rate of approximately 47%–50%.

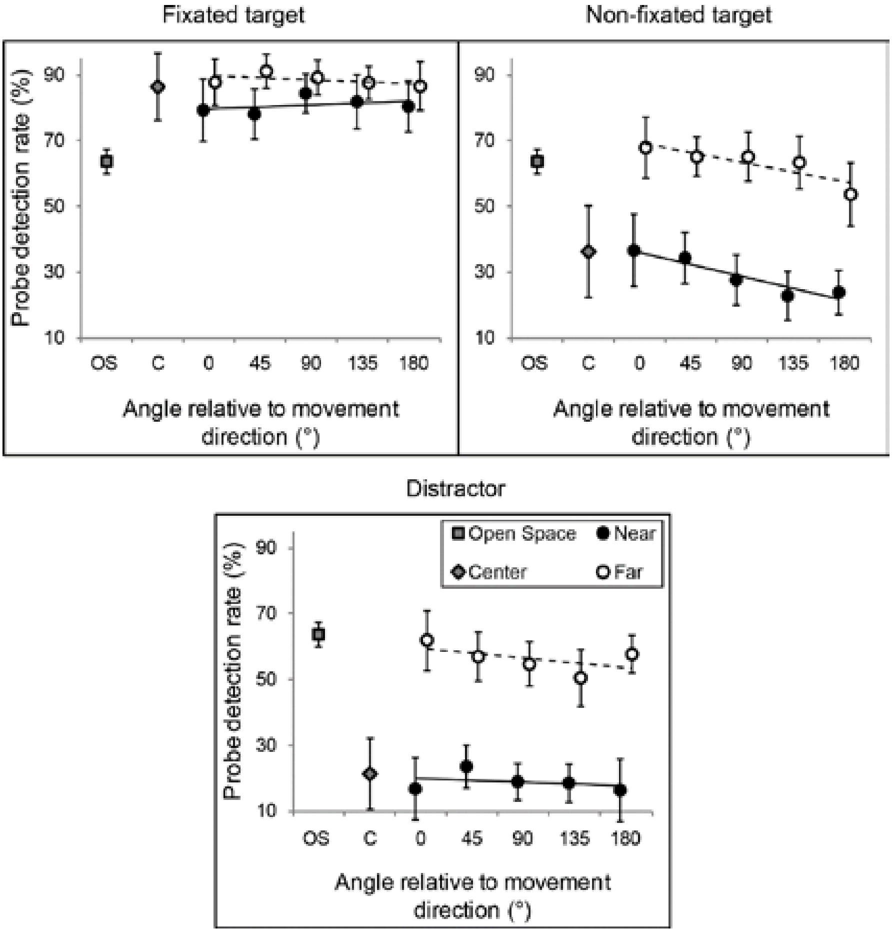


Figure 2.7. Probe detection rates for Experiment 2.2 at each relative angle for each target and combined for the two distractors, at both distances. Closed circles represent detection rates for probes presented near the object; open circles represent detection rates for probes presented further away 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.

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 non-fixated 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 non-fixated 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 2.7* that probe detection rates decrease linearly with increasing angle around non-fixated 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 2.1, 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 2.1, 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 non-fixated targets is 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 non-fixated 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 2.1, probes presented around the fixated target, within or near the fovea, were detected more often than probes presented around the non-fixated target and the distractor. Probes presented near the edge of the non-fixated 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 non-fixated objects and high detection rates for center probes on fixated targets again support that fixation instructions were followed correctly.

With regard to the non-fixated, 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 2.6* 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 2.1). 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 2.2). 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 2.1*.

Table 2.1. Overview of (an)isotropy.

	ATTENTION		
Task	**Target**		
	Overt	**Covert**	**Distractor**
SOT - 1 target - Fixation on target	ANISOTROPY		ISOTROPY
SOT - 1 target - Fixation on center screen		ANISOTROPY	ANISOTROPY
MOT - 2 targets - 1 target fixated (overt) - 1 target not fixated (covert)	ISOTROPY	ANISOTROPY	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.

From Experiment 2.1, 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 2.2 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 2.1, 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 2.2, 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 2.1 and 2.2. 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 2.1 and 2.2, despite the difference in eye movements. Moreover, we find different patterns for the two overtly tracked targets, even though the eye movements were similar.

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 2.1 was so easy that participants were very easily distracted by their thoughts, and that Experiment 2.2 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 2.2 than during Experiment 2.1. As a consequence, the apparently isotropic distribution of probe detection rates around the overtly tracked target in Experiment 2.2 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 2.1 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 2.1, 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 2.2, the probe detection rates around distractors are no longer anisotropic, while around the non-fixated 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 non-fixated 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 non-fixated 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 2.2 the detection of probes was better for all probed locations, including those close to the edge of the non-fixated objects, compared to Experiment 2.1. While in Experiment 2.1 detection rates of probes presented near the non-fixated target clearly approached 0%, the performance in Experiment 2.2 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 2.2 compared to Experiment 2.1.

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 2.1) or were moving around (Experiment 2.2). Overtly tracked targets—that is, with eyes moving around following a specific target—revealed either anisotropy (Experiment 2.1) or isotropy (Experiment 2.2). 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.

Chapter 3

Influences of active control on attention allocation in MOT

Text published as: Frielink-Loing, A., Koning, A. & van Lier, R. (2022). Influences of active control on attention allocation in MOT. *Attention, Perception & Psychophysics*, *84*, 671–681. https://doi.org/10.3758/s13414-021-02417-8.

Data published under: https://doi.org/10.34973/vk25-yx32

We investigated the influence of active involvement on the way visual attention is distributed during multiple-object tracking (MOT), specifically when objects bounce, using two experiments modelled after the videogame Pong. In both experiments, participants were either assigned to an active group or a passive group. The active groups were instructed to move a virtual paddle in order to bounce target objects as often as possible. Participants in the passive groups viewed recordings of trials from the active groups. In all conditions, participants were asked to track the target objects and to detect dot probes that briefly appeared on the screen. Using probe detection, we explored the distribution of attentional resources over the linear and bounce trajectories of tracked objects. We found that active involvement can enhance probe detection along the future post-bounce trajectory, but it depends on the difficulty of the task.

Introduction

Every day we are confronted with situations in which we need to pay attention to multiple, often moving, objects at once: soccer practice, your daily bicycle ride to work during rush hour, visiting the playground with your three kids and their friends. Although these are all basically examples of multiple object tracking (MOT), they require varying degrees of involvement. For example, when you're playing soccer, you need to keep track of other players, and, more importantly, a ball to perform actions such as blocking and kicking, respectively. In traffic, you need to keep track of where other vehicles are and where they are going in order to avoid physical interactions as much as possible. Finally, watching children play often requires very little involvement other than making sure they are all still on the playground. In the present study, we attempt to investigate the distinction between various types of involvement in MOT.

There is a general agreement that the attentional system has a limited capacity for simultaneous object tracking (Meyerhoff et al., 2017; Scholl, 2009; Tran & Hoffman, 2016). Early MOT studies estimated that a person can track up to 4 ± 1 moving target objects (e.g., Pylyshyn & Storm, 1988; Scholl et al., 2001), although this number has since been shown to vary with several factors, including object speed (e.g., Alvarez & Franconeri, 2007), density (e.g., Bettencourt & Somers, 2009), grouping (Landry et al., 2001), and viewer expertise (Green & Bavelier, 2006). One of the oldest debates in visual attention research has been whether attention is space- or object-based (Posner, 1980; Pylyshyn & Storm, 1988; Yantis, 1992). Space-based theories pose that attention is directed at an area in visual space, which can hold one or more objects, parts of objects, or no objects. Object-based theories state that attention is directed at perceptual objects. Although the latter has somewhat taken the upper hand (Pylyshyn, 2006; Scholl, 2001), there are some situations in which a space-based form of attention appears more plausible (Cave & Bichot, 1999; Posner et al., 1980), and there is also evidence that suggests attention has both space- and object-based aspects that may be employed simultaneously (Eriksen et al., 1993; Kahneman & Treisman, 1984; Logan, 1996; Scholl, 2009).

After the introduction of the MOT paradigm (Pylyshyn & Storm, 1988), in which viewers track multiple target objects among a number of identical distractors, several mechanisms were proposed to explain how the attentional system could manage multiple items at the same time, including serial (Oksama & Hyönä, 2004) and parallel (Howe et al., 2010) tracking, as well as perceptual grouping (Yantis, 1992). In recent years, research has focused on the spatial distribution of attention at the object level in MOT, both within objects (Alvarez & Scholl, 2005) and in the space surrounding them (Atsma et al., 2012; Frielink-Loing et al., 2017). These studies have suggested that attention is not uniformly spread along the shape of a tracked object, and that attention is even non-uniformly distributed across the space surrounding the objects. Our aim is to expand the findings on attention allocation in the area around tracked target objects, specifically investigating anticipatory patterns of attention, and whether active control might influence these patterns.

The study into anticipatory attention, also referred to as extrapolation or representational momentum (Freyd & Finke, 1984), has produced ambiguous results over the years. Several MOT studies that measured tracking accuracy claim that observers use target location rather than motion information to keep track of objects that are briefly occluded (Franconeri et al., 2012) or disappear and reappear during movement (Keane & Pylyshyn, 2006). However, Franconeri et al. (2012) do point out in their conclusion that their results do not provide evidence against the use of motion extrapolation in target tracking when no occlusion is involved. Computational investigations into the effectiveness of motion extrapolation in MOT have shown that velocity information is not necessary for object tracking (Pylyshyn & Storm, 1988; Zhong et al., 2014), although this does not rule out that human observers actually use motion information to keep track of moving objects. Providing support for the relevance of motion information during object tracking, a study by St. Clair et al. (2010) showed that MOT performance deteriorates when the texture of a tracked target moves in the opposite direction from the target's heading direction. Another MOT study by Iordanescu et al. (2009) showed that localization errors of tracked targets were biased towards the targets' predicted trajectories after disappearance (although the opposite effect was found by a later study; see Howard et al., 2011). Notably, Fencsik et al. (2007) showed that viewers use motion information to keep track of targets at low tracking load as they briefly become invisible during movement, but predominantly use location information at higher tracking load. More recently, we showed that brief probes presented during object movement were detected more often when they were presented ahead of a tracked target compared to when they trailed behind a target, indicating that attentional resources are allocated to future locations of a moving object during tracking (Atsma et al., 2012; Frielink-Loing et al., 2017).

In contrast with the idea of anticipatory attention, the study of Atsma et al. (2012) showed that attention 'does not bounce'. That is, although their results showed that attention is generally allocated ahead of a tracked object, they also found that it does not immediately shift towards the object's new trajectory when a predictable change in direction occurs, for example as a result of an encounter with another object (i.e., bouncing off a wall). Rather, attention more readily continues to extrapolate linearly, not anticipating bounces. Although detection of probes presented in the direction of a bounce appeared to increase when bouncing behaviour did occur, probes presented along the linear extrapolation of an object's original trajectory were detected more accurately in all conditions. However, it seems difficult to reconcile the attentional preference for the linear path over the bounce path with the fact that we are very capable, for example when playing racquetball, of catching a ball after it bounces off a wall. The results found by Atsma et al. may not tell the entire story. That is, the task they used only asked for (passive) observation of moving objects, without the need to manipulate or interact with the objects. Catching a ball requires active involvement, and relies heavily on the interplay between the action and perception systems (Oudejans et al., 1996). The influence that action intentions can have on visual processing has been studied extensively (e.g., Bekkering & Neggers, 2002; Gibson, 1979; Louveton et al., 2012; Witt & Sugovic, 2012). Attention has also been found to be modulated by action (Allport, 1987; Linnell et al., 2005; Tipper et al., 1992; Welsh & Zbinden, 2009). In the context of MOT, Thornton et al. (2014) showed that in an interactive MOT game, where object trajectories had to be pro-actively altered to avoid collisions, participants were capable of controlling more objects than they could track. In other words, the action component increased participants' attentional capacity. The study we present here further investigates the effects of active control in the MOT paradigm on the allocation of attention.

In order to study object tracking with an active component, we adapted the MOT paradigm used in Atsma et al. (2012, Experiment 2) to a game-like paradigm reminiscent of the 1970's video game Pong (see *Figure 3.1*). Participants were either in control of a movable paddle to deflect target objects (active paddle-control, APC), or viewed replays of trials performed by the actively engaged participants (no paddle-control, NPC). The latter groups either tallied target bounces against the paddle (Experiments 3.1 and 3.2), or performed no further action with regard to bounces (Experiment 3.2). As in Atsma et al., all participants were asked to respond to brief probes presented at specific locations surrounding the targets. Based on several studies mentioned above (Allport, 1987; Louveton et al., 2012; Thornton et al., 2014), we expect that active control in the manipulation of an object's trajectory draws attentional resources towards the object's new trajectory. This would be reflected by better detection of probes presented in the direction of the bounce relative to probes presented along the linear extrapolation of the object's motion path prior to the bounce in the APC condition.

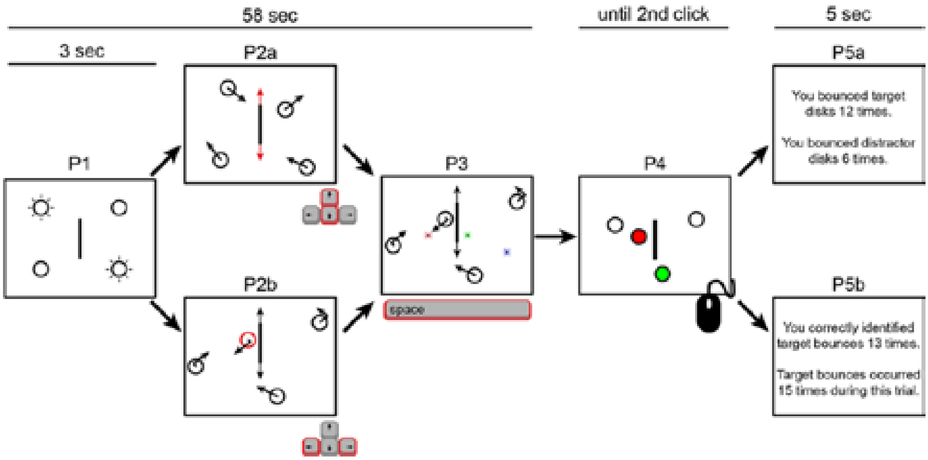


Figure 3.1. Timeline for Experiment 3.1. Each trial started with all objects stationary for three seconds during which the two target objects blinked (300 ms on, 300 ms off, see panel P1). During the following 55 s of the trial, participants in the APC (active paddle-control) condition could move the paddle up and down using the up and down arrow keys to reflect target objects (see panel P2a), whereas participants in the NPC (no paddle-control) condition pressed the left or right arrow keys each time a target object was about to hit the paddle from the left or right, respectively (see panel P2b). Upon impact between an object and the paddle, a probe could appear (see panel P3) either along the object's new direction of movement (Bounce probe, red/leftmost dot), along the object's previous direction of movement (Linear probe, green/middle dot) or at a randomly chosen location within the bounding box (Open space probe, blue/rightmost dot). Participants pressed the spacebar each time they detected a probe. After 55 s, all objects became stationary again, and the participant was prompted to identify the two target objects (see panel P4). Finally, the participant received feedback on performance (see panel P5a/P5b). See text for further details.

With regard to the NPC condition, in Experiment 3.1 we initially moved away from the passive observation task used by Atsma et al. (2012), by adding the instruction to tally target bounces in order to keep the task load consistent with the APC condition in terms of button presses. In Experiment 3.2, we reintroduced the passive viewing task for better comparison to earlier findings. Still, it is important to realize that the tasks presented here are naturally different from the task in Atsma et al.'s second experiment, as they involve an additional moving object in the form of a paddle.

In the following two experiments, we explore the effects of different degrees of passivity in this task. More specifically, in the first experiment we explore an experimental setup to allow a comparison between a task that requires participants to actively influence the display, and a task that requires participants to observe the display. As the experimental task appeared to be relatively easy in terms of probe detection, we then performed a second experiment which included a further refinement of the experimental paradigm to see what happens under more difficult task conditions, and also to allow a better comparison with previous results (Atsma et al., 2012; Frielink-Loing et al., 2017).

Experiment 3.1

Method

Participants. Fifty-three participants (41 female, 12 male; aged 23 ± 4.7) took part in this study and received payment or course credit for their efforts. All participants reported to have normal or corrected-to-normal vision and were naïve with respect to the paradigm and the objective of the study. Forty-two were right-handed. All participants gave informed consent before the start of the experiment, and all procedures were in accordance with the declaration of Helsinki.

Four participants were excluded from analysis due to poor target tracking (correct tracking of all targets in less than 50% of trials). One participant was excluded because she reported not to have seen any probes during the experiment (data showed responses to less than 7% of all probe trials). Excluded participants were replaced to make sure the experimental groups were of equal size. For the analyses, each group contained 24 participants.

We performed a post-hoc check for the required sample size using G*Power, to make sure we had enough participants for a reliable result. Because our main goal was to see whether there was a difference between the detection of probes presented in the bounce direction and the linear direction, and whether this depended on the task of the participant (with or without paddle control), the check was done for a repeated measures, within-between interaction test. We based the expected effect size on our previous study using probe detection (Frielink-loing et al., 2017). Based on these results, and the assumption that the present study investigated a less complex effect, we chose to use an effect size of $f(V) = 0.7$ ($\eta^2 \approx 0.33$) for the calculation. With $\alpha = 0.05$ and Power = 0.95, this yielded a total sample size of 38, or 19 participants per group.

Stimuli and design. A white rectangle subtending 25° × 20° was presented on a black background, acting as a bounding box for the moving objects. Each trial involved two target objects and two distractor objects. The objects were identical circular black outlines subtending 2.2° of the visual field. The paddle was presented as a red 0.5° × 6.0° rectangle with a black outline. Probes were black squares subtending 0.13°. Stimuli were created with Python and presented using PsychoPy software (Peirce, 2007/2009) on a Dell Precision T3610 computer running Windows 7. *Figure 3.1* shows a timeline for one experimental trial.

At the beginning of each trial, the target and distractor objects were randomly assigned to each of the four corners of the bounding box (*Figure 3.1*, see panel P1). The paddle was presented at the center of the bounding box. The two target objects blinked for 3 s, indicating them as the targets to be tracked, after which all four objects started moving in randomly generated directions for 55 s at a constant speed of 6° per second (*Figure 3.1*, see panels P2a/P2b/P3). Object collisions with edges of the bounding box or the paddle produced natural bouncing behaviour (i.e., angle of incidence equals angle of reflection with respect to the normal). Object-object collisions produced unnatural bouncing behaviour, as both objects moved away from each other perpendicular to the line of impact, maintaining their speed of 6° / s. We chose to use this method in order to keep a constant speed (i.e., no transfer of energy upon collision) while preventing objects from 'sticking' together. Upon being asked by the experimenter, participants reported that this bouncing behaviour appeared natural.

During the movement phase of a trial, participants in the APC condition could move the paddle up and down using the arrow keys on a keyboard (*Figure 3.1*, see panel P2a). As long as an arrow key remained pressed by the participant, the paddle moved with a constant speed of 9° / s. The paddle could only move in the vertical direction, and its movement was restricted by the edges of the bounding box. Participants in the NPC group viewed recordings that were played at the same speed. Each time a collision occurred between an object and the paddle, the program randomly triggered one of four types of experimental events described below (*Figure 3.1*, see panel P3), with the exception of collisions that occurred less than 1 s after the last experimental event to ensure enough time for the participant to respond. Half of all events (50%) were NoProbe events, i.e. no probe was shown while a collision still occurred. Note that these NoProbe events were introduced to further increase the unpredictability of probe occurrences. The remaining 50% were Probe events, during which probes could appear along the object's direction of movement (Linear probes, 20% of all events), along the direction of a possible bounce (Bounce probes, 20% of all events), or in open space (Open Space probes, 10% of all events). Linear and Bounce probes appeared at extrapolated locations 4.2° from the center of the object. Probes were presented for 50 ms and moved along with the probed target to maintain their distance with respect to the object. Experimental events were part of the recordings shown to the participants in the NPC group, meaning that they saw the exact same sequence of events as the participant in the APC group whose recordings they viewed.

Procedure. Participants were seated in front of a Benq XL2420Z monitor (resolution of 1920 × 1080 pixels, refresh rate 120 Hz) at a distance of approximately 60 cm and operated a keyboard with low button response latency (1 ms) and a computer mouse to perform the task. All participants were instructed to keep track of the targets and to press the space bar whenever a probe appeared on the screen. Button presses that occurred within one second after each event were recorded. At the end of each trial, participants were asked to identify the targets by clicking on them with the mouse (*Figure 3.1*, see panel P4). To provide feedback, correctly identified targets turned green and distractors turned red when clicked. All participants performed three practice trials of 55 s, followed by as many trials as necessary to obtain measurements from 500 events (250 NoProbe and 250 Probe events). On average, participants performed 33 trials (min. 27, max. 42). The experiment lasted approximately 45 minutes on average and depended on the number of trials needed. After each trial, participants received feedback about the number of object bounces they achieved (APC condition) or identified (NPC condition) during the trial (*Figure 3.1*, see panel P5a/P5b). The next trial started as soon as a button was pressed, giving the participants the opportunity to take self-paced breaks between trials.

We recorded coordinates of all moving objects in the display at each frame from trials performed by participants in the APC group. These were then used to generate the trials for the NPC group. Therefore, we first assigned participants to the APC group until a satisfactory number had been reached before participants were assigned to the NPC group. For each condition, data from 24 participants were recorded.

Active Paddle Control (APC) condition. Participants in the APC condition were instructed to make the targets bounce off the paddle as often as possible and to avoid the distractors by moving the paddle up and down. After each trial, participants received on-screen feedback stating the number of target bounces and the number of distractor bounces they made during the trial (*Figure 3.1*, see panel P5a).

No Paddle Control (NPC) condition. Participants in the NPC condition viewed reconstructions based on the recorded object coordinates of the experiment performed by one of the APC participants as described above. Experimental events were exactly the same as for the recorded participant from the APC condition. NPC participants were instructed to press the left arrow key whenever a target was about to hit the paddle from the left, and to press the right arrow key whenever a target was about to hit the paddle from the right. The button press had to be made before impact, as it would otherwise interfere with the timing of the probe. Participants were not made aware of this reason. After each trial, participants received on-screen feedback stating the number of correctly identified target bounces and the number of actual target bounces in the trial (*Figure 3.1*, see panel P5b).

Results

Events triggered by targets that were not correctly identified at the end of a trial were discarded, because attention was not guaranteed to be directed at the target during those events. This meant that on average 113 out of 500 events were excluded per participant in the analyses. Average probe detection rates and response times (RTs) were determined for NoProbe events (false positives) and for the three types of Probe events (Bounce, Linear and Open Space). We only considered events triggered by target-paddle collisions, because distractor-paddle collisions were far fewer in number and therefore detection rates for those events are considered not to be informative. Only button presses that occurred within 1000 ms after event onset were counted as a hit (cf. Flombaum et al., 2008).

On average, tracking performance was moderately high for all participants (M = 77%, SD = 11.7%) and did not differ between groups (M_{APC} = 78%, M_{NPC} = 76%; $t(46) = -0.57$, $p = .571$). Overall probe detection (i.e., responses to Probe events) was high (M = 75%, SD = 18.1%), indicating that probes were quite salient. False alarm rates (i.e., responses to NoProbe events) were low (M = 2.0%, SD = 1.9%). Detection rates can be found in *Table 3.1*. For the purpose of this study, we were only interested in correctly tracked objects (i.e., targets) and the allocation of attentional resources along the bounce and linear motion paths. Therefore, all further analyses focus only on detection rates for bounce and linear probes associated with target bounces where targets were correctly identified at the end of a trial.

Table 3.1. Probe detection rates for events triggered by target-paddle collisions for both APC and NPC conditions.

	Trial Type			
Experimental Group	**No probe**	**Open space probe**	**Bounce probe**	**Linear probe**
Active Paddle Control	2.4 (2.2)	64.2 (22.6)	76.8 (21.6)	77.7 (19.7)
No Paddle Control	2.4 (2.4)	65.2 (19.2)	82.4 (16.2)	83.2 (17.4)

Notes: Values (in %, with SD in brackets) are based on 46 participants (23 APC, 23 NPC) due to missing values for two participants.

Probe detection. We performed a 2 × 2 repeated-measures analysis of variance (rmANOVA) on target probe detection rates with group (APC vs. NPC) as between-subject factor, and probe type (bounce vs. linear) as within-subject factor (see *Figure 3.2*). The analysis revealed no significant main effects of probe type, $F(1, 46) < 1$, or group, $F(1, 46) = 1.08$, $p = .303$, nor did it show an interaction between type and group, $F(1, 46) < 1$.

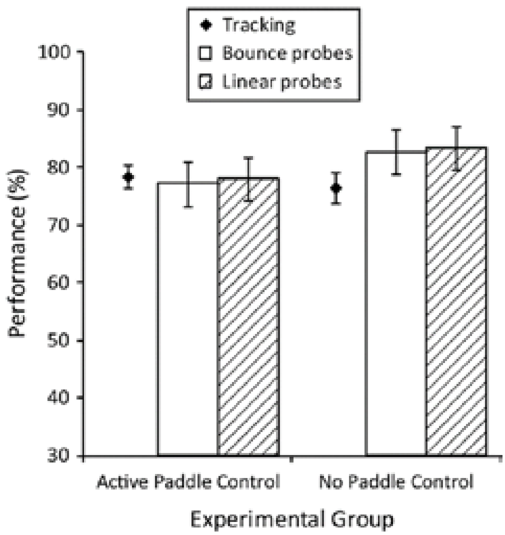


Figure 3.2. Probe detection rates and tracking performance for the active paddle control (APC) group (left) and the no paddle control (NPC) group (right). Error bars depict standard error of the mean (SEM).

Discussion

With this first experiment, we wanted to compare the allocation of attentional resources between participants who actively controlled a paddle in a Pong-like MOT setting (active paddle-control, APC), and participants who viewed the same display but did not actively control the paddle (no paddle-control, NPC). First of all, we hypothesized that active control in the manipulation of object trajectories would result in a shift of attention towards an object's new (future) trajectory, the opposite effect as found by Atsma et al. (2012, experiment 2). Our results do not confirm this hypothesis. More specifically, we find no significant difference between the detection rates of bounce probes and linear probes. We furthermore expected to find a difference in probe detection rates between the APC and the NPC group, given the difference in control between these groups in influencing the visual display. However, we did not find an effect of group, nor did we find an interaction effect between group and probe type.

When comparing our results with those of Atsma et al. (2012), several remarks can be made. For the APC condition, the advantage for linear probes as found in Atsma et al. (who used a task without such action components) has disappeared. However, this also occurred for the NPC task in our experiment, so no conclusion can be drawn so far. One important difference with respect to the results of Atsma et al. stands out, namely the overall high detection rate in the current task (of approx. 80%) as compared to a much lower detection rate in Atsma et al.'s task (approx. 45%). That is, the current task might have been too easy to measure differential results on detecting bounce and linear probes. Indeed, several settings were adjusted compared to Atsma et al. to compensate for the increased difficulty of the task, both benefiting tracking performance and enhancing the detection of probes. For example, we chose a slightly slower object velocity (6°/s, instead of 7°/s) and a smaller area in which the objects could move (25°×20°, instead of 34°×25°) to compensate for the expected increase in tracking difficulty imposed by the Pong-like setting of the game. We also chose a slightly larger probe size (0.13° instead of 0.09°). However, the increase in task difficulty may have been overestimated, and the adjustments could have been disproportional.

In addition, as already mentioned, the task without paddle control (NPC group) used in this experiment was different from the observational task previously used by Atsma et al. (2012). The APC group in the current experiment had to perform two tasks in parallel (i.e., deflect targets with the paddle and respond to probes), and so, in an attempt to match the complexity of button responses between the two groups, we instructed the participants in the NPC group to press a button corresponding to the side of the impact of a target onto the paddle. This means that the participants were not merely passively viewing the scene as in Atsma et al., and this may have even inadvertently put an emphasis on the directionality of the objects.

In order to address the concerns mentioned above, we ran a second experiment in which we adjusted several parameters of the experiment to increase overall probe detection difficulty, and in an attempt to make the NPC condition more passive, we instructed participants in the NPC condition to only press a single button to indicate when a target hit the paddle, independent of its direction. Additionally, we instructed a third group of participants to merely observe the scene while detecting probes, in order to get a viewing condition without any further actions (beside probe detection).

Experiment 3.2

Method

Participants. Sixty participants (35 female, 25 male; aged 25.7 ± 7) took part in this second experiment and received payment or course credit for their efforts. All participants reported to have normal or corrected-to-normal vision and were naïve with respect to the paradigm and the objective of the study. Fifty-three were right-handed. All participants gave informed consent before the start of the experiment, and all procedures were in accordance with the declaration of Helsinki.

Two participants were excluded from analysis because they reported not to have seen a single probe during the entire experiment. Three participants were excluded due to a high false alarm rate (i.e., high response rate to NoProbe events, producing an outlier).

We calculated the required sample size again (a priori) with G*Power with the same considerations as for Experiment 3.1, but now for three groups (APC, NPC-1 and NPC-2, see below). This yielded a required total sample size of 45, or 15 participants per group.

Stimuli and design. Stimuli and design were the same as Experiment 3.1, with the following adaptations.

Tracking difficulty. The size of the bounding box was increased from 25° × 20° to 35° × 27° and object diameter was slightly increased from 2.2° to 2.4°. The appearance of the movable paddle was also adapted to make it stand out less, by changing the colour from red to black and by slightly decreasing its width from 0.5° to 0.3°. In this second experiment, objects moved at a constant speed of 8° / s instead of 6° / s and the paddle moved at a constant speed of 16° / s instead of 9° / s while the up or down arrow key was pressed by the participant. Trial duration was shortened from 55 s to 30 s to decrease the number of lost events in case of a lost target.

Probe saliency. Probe size was decreased from 0.13° to 0.08°. We also chose to probe at two different distances, namely 2.5° and 3.5° from the object's center (instead of 4.2°), which is more consistent with earlier studies (Atsma et al., 2012; Frielink-Loing et al., 2017).

Probe event trigger. Whereas in Experiment 3.1 probe events were triggered by any object colliding with the paddle, in this second experiment probe events were only triggered when one of the targets hit the paddle. This was done to ensure equal numbers of trials for all conditions, since we were only interested in probe detection near tracked objects.

NPC-1 task. In this second experiment, participants in the first no paddle control group were instructed to merely press the right Ctrl button on the keyboard whenever a target object was about to hit the paddle from either side, and to respond to detected probes by pressing the spacebar.

NPC-2 task. A second NPC group was added to control for possible influences of the motoric action of pressing a button when a target approaches the paddle. Participants in this group only pressed the spacebar if they detected a probe, and identified the targets after each trial. Stimuli were the same recordings of the APC group as used for the NPC-1 group.

Procedure. All participants performed three practice trials before completing enough trials to have obtained 400 experimental events (100 NoProbe and 300 Probe events), with equal occurrences of bounce, linear and open space probes (100 events each). On average, 58 trials were needed to trigger all 400 events (min. 52, max. 71). The experiment lasted approximately 45 minutes on average as it depended on the number of trials needed to trigger all events. A break was offered every 5th trial. Button presses that occurred within one second after each event were recorded. Participants were assigned to each condition in the same way as in Experiment 3.1, i.e., the APC condition was run first until a satisfactory number of participants had performed the task. Then, the NPC-1 condition was run with the same number of participants. The NPC-2 condition was added at a later time. For each condition, data from 20 participants were recorded.

Results

Events triggered by targets that were not correctly identified at the end of a trial were discarded. In contrast with Experiment 3.1, we recorded in more detail which target elicited each probe event, allowing us to only discard events that were triggered by poorly tracked targets but more importantly keep those events that were triggered by correctly tracked targets from the same trial. This meant that on average only 26 out of 400 event responses per participant were not considered in the analyses. Average probe detection rates and response times (RTs) were determined for NoProbe events (false positives) and for the three types of Probe events (Bounce, Linear and Open Space). For Bounce and Linear probe events, separate detection rates and RTs were also determined for each probed distance. Only button presses that occurred within 1000 ms after event onset were counted as a hit (cf. Flombaum et al., 2008).

Table 3.2. Probe detection rates.

	Trial Type			
Experimental Group	**No probe**	**Open space probe**	**Bounce probe**	**Linear probe**
Active Paddle Control				
Overall	1.4 (1.7)	9.7 (7.6)	51.7 (26.4)	44.6 (23.2)
2.5°			55.2 (27.1)	44.2 (22.8)
3.5°			48.3 (26.1)	45.0 (24.2)
No Paddle Control-1				
Overall	1.6 (1.8)	7.3 (6.0)	42.3 (24.0)	44.7 (21.6)
2.5°			47.6 (23.6)	43.6 (21.9)
3.5°			37.0 (25.2)	45.6 (22.1)
No Paddle Control-2				
Overall	4.0 (4.1)	14.3 (11.3)	43.9 (25.7)	40.9 (22.2)
2.5°			45.5 (26.7)	38.0 (22.4)
3.5°			42.2 (25.6)	43.8 (22.8)

Notes: For each group, false alarm rates (No Probe events) and detection rates (Probe events) are shown (in %) with standard deviations between brackets.

On average, tracking performance was high for all participants ($M = 92\%$, $SD = 5.2\%$) but there were significant differences between the groups ($M_{APC} = 89\%$, $M_{NPC\text{-}1} = 92\%$, $M_{NPC\text{-}2} = 96\%$; $F(2, 54) = 11.02$, $p < .001$). Overall probe detection (i.e., responses to Probe events) was quite low ($M = 33\%$, $SD = 17.8\%$), indicating that the adaptations we made to the probes succeeded in making them less salient as compared to Experiment 1. False alarm rates (i.e., responses to NoProbe events) were low

(M = 2.3%, SD = 2.9%). In total, we excluded five participants, two who did not detect a single probe, and three whose false alarm rates were higher than their overall probe detection rate. After exclusion based on the abovementioned criteria, data from 55 participants (19 APC, 18 NPC-1, 18 NPC-2) was used for further analysis. Detection rates can be found in *Table 3.2*.

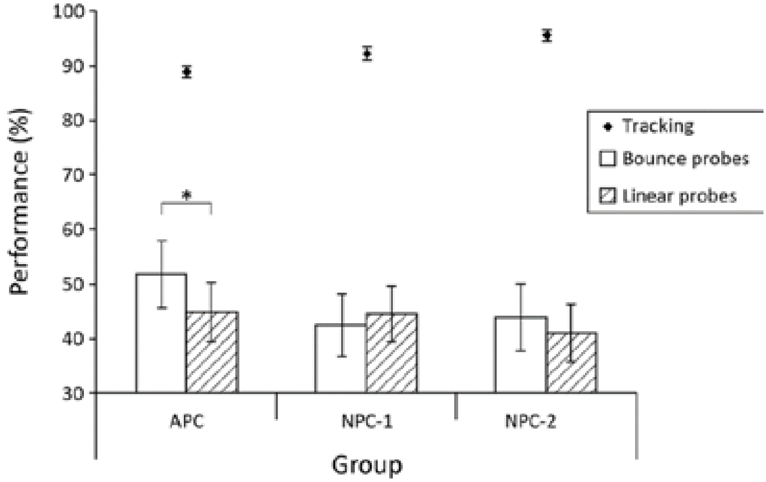


Figure 3.3. Results for Experiment 2. Significant two-way interaction showing probe detection rates as a function of probe type (bounce probes, linear probes) and group. For each group, average tracking performance is also shown. Significant differences between pairs of scores are indicated (*). Error bars depict standard error of the mean (SEM).

Probe detection. We performed a 3 × 2 × 2 rmANOVA with group (APC, NPC-1, NPC-2) as between-subject factor, and probe type (bounce vs. linear) and probe distance (2.5° vs. 3.5°) as within-subject factors (see *Figure 3.3*). This analysis revealed a significant main effect of probe type, $F(1, 52) = 7.05$, $p = .011$, with better detection for bounce probes (M = 46%) than for linear probes (M = 43%). It also showed a significant main effect of probe distance, $F(1, 52) = 8.58$, $p = .005$, reflecting better detection of probes close to the target (M = 46%) compared to further away (M = 44%). There was no main effect of group ($F(1, 52) < 1$). However, we did find a significant interaction between group and probe type, $F(2, 52) = 7.80$, $p = .001$, reflecting a significantly better detection of bounce probes compared to linear probes for the APC group ($F(1, 18) = 17.87$, $p = .001$), and no significant effect of probe type for either the NPC-1 group ($F(1, 17) = 2.14$, $p = .162$) or the NPC-2 group ($F(1, 17) = 2.65$, $p = .122$). There was also a significant interaction between group and probe distance, $F(2, 52) = 5.82$, $p = .005$, with significantly better detection of probes presented close to the target in the APC group ($F(1, 18) = 9.65$, $p = .006$) and in the NPC-1 group ($F(1, 17) = 10.80$, $p = .004$), but no difference between distances in the NPC-2 group ($F(1, 17) < 1$). The analysis also revealed a significant interaction between probe type and distance, $F(1, 52) = 30.14$, $p < .001$, caused by bounce probes being detected better when presented close to the object than further away (49% versus 43%), but the opposite effect for linear probes (42% versus 45%). Finally, there was no three-way interaction, $F < 1$.

Discussion

The purpose of this second experiment was similar to the purpose of our first experiment, namely to compare the allocation of attention during a MOT task between participants who were actively involved in making objects bounce (APC group) and participants who had no control over the display (NPC groups). For this second experiment, we aimed to decrease probe detectability compared to Experiment 3.1 in order to obtain probe detection rates that fall within the same range as found in earlier studies (Atsma et al., 2012; Frielink-Loing et al., 2017). In addition, the task for the NPC-1 group used in this second experiment was adapted compared to Experiment 3.1 such that directionality of the objects was no longer relevant. Finally, a third group (NPC-2) was added to further control for the motor action performed by the NPC-1 group with respect to target-paddle collisions.

Our results showed a main effect of probe type, with better detection of bounce probes compared to linear probes. However, this appears to depend on the degree of control, as we also found a significant interaction between probe type and group. That is, while the APC group showed a significant advantage for bounce probes compared to linear probes, neither NPC group showed a difference between probe types. Furthermore, detection rates for bounce probes appear to be shifted upwards in the APC condition compared to the NPC conditions, while detection rates for linear probes remain roughly the same (see *Figure 3.3*). It appears that the advantage for bounce probes over linear probes in the APC condition is so strong, that it is likely to have been the driving force behind the main effect of probe type.

To explore whether the results found in Experiment 3.2 are significantly different from those found in Experiment 3.1, we performed a post-hoc 2 (Experiment) × 2 (Group) × 2 (Probe type) rmANOVA. For the factor Group, we included the APC groups from both experiments, as well as NPC (Experiment 3.1) and NPC-1 (Experiment 3.2). NPC-2 (Experiment 3.2) was left out, because NPC-1 was more comparable to the NPC condition of Experiment 3.1. The analysis produced a significant main effect of Experiment ($p < .001$), significant two-way interactions between Probe Type and Experiment ($p = .031$) and between Probe Type and Group

(p = .001), as well as a significant three-way interaction (p = .001). As expected, we found a main effect of Experiment, reflecting a higher overall probe detection in Experiment 3.1. Most importantly, the analysis showed a significant three-way interaction, providing support for the observation that the difference in probe detection (bounce versus linear) for the active and passive condition was different between the two experiments.

Overall, our findings suggest that participants who were actively involved in causing objects to bounce off the paddle were more likely to shift their attention towards the bounce path around the moment of impact, whereas more passive viewers of the same display appeared to allocate their attention ahead of the linear trajectory the object was following prior to the impact. We will discuss these findings further with respect to Experiment 3.1 and previous findings in the general discussion below.

General Discussion

We used two experiments to investigate the effects of manipulating object motion trajectories on the allocation of attention ahead of these trajectories. We introduced a 'game-like' version of MOT, in which participants could actively move a paddle up and down the display to deflect objects (active paddle control condition, APC). Other participants viewed replays of trials performed by participants from the first group and indicated when a target-paddle collision was about to occur (no paddle control condition, NPC).

In Experiment 3.1, for participants in the second group (NPC condition) we found much higher probe detection rates as compared to earlier findings (Atsma et al., 2012; Frielink-Loing et al., 2017; ± 75% versus 45-55%). In addition, we found no difference between detection of bounce probes and linear probes for either group at the moment a target object hit the paddle. Under the current experimental settings, we could not replicate previous findings by Atsma et al. (2012), who found that passive observers show diminished attentional anticipation for wall bounces. Note, however that the passive observers in the current study were more actively involved than in Atsma et al.'s experiment. Another crucial difference with Atsma et al. was that in Experiment 3.1 probe detection was very high and almost reached ceiling. We therefore designed a follow-up experiment in which we increased probe detection difficulty to allow for a better comparison with Atsma et al.'s previous task. In Experiment 3.2, the implemented changes revealed differences in detection rates, both within and between groups. We modified the no paddle control condition such that the observers did not have to account for directionality when tallying bounces (NPC-1). Additionally, we introduced a second no paddle control condition in which a new group of participants merely viewed recordings from the APC group while trying to detect probes (NPC-2). We found that bounce probes were overall detected better than linear probes. Importantly, we saw this pattern appear strongly in the active paddle control condition, while in both no paddle control conditions bounce and linear probes were detected equally well.

This study provides support for the hypothesis that active control in a multiple object tracking display influences the way attention is distributed. It should be noted, however, that the differential effects between APC and NPC conditions only appear when probe detection is not easy (with probe detection rates of approx. 40%-50%, similar to Atsma et al., 2012). Interestingly, upon inquiry by the experimenters, participants in both experiments indicated to primarily focus on target tracking and not on probe detection. Moreover, participants reported not to be aware of the timing nor of the placing of the probes throughout the whole experiment session.

Considering that we are comparing different paradigms with each other, it is expedient to take a closer look at the differences between the current results and earlier findings using probe detection paradigms, and to reflect on possible explanatory accounts of the observed differential effects. In contrast with Atsma et al. (2012) we found no advantage for the detection of probes presented along the linear extrapolation of a tracked object's trajectory when a change in its direction (i.e., a bounce) occurred. As expected, when the task involved active manipulation of the paddle (or wall in Atsma et al.) and, with that, the target trajectories, we found an advantage for probes presented along the target's future (bounce) trajectory upon impact with the paddle. A possible reason for that could be that with a moving paddle, in which the position is adjusted by the participant (i.e., the APC condition), the bouncing itself is more salient. Perhaps because in the active condition the future path is of special relevance, given that the paddle position has to be adjusted again for a next possible target-paddle collision.

One could argue that a difference in detection of bounce probes should come with a similar but opposite effect on the detection of linear probes. Indeed, we expected that active involvement would elicit a shift of attention from the more automatic linear extrapolation of an object's trajectory to its anticipated deflection path. However, we do not find such a trade-off in our current results. That is, our results show that there is a heightened sensitivity to the bounce path in the APC condition, while probe detection along the linear path is the same over conditions. The results suggest that active involvement releases additional attentional resources to be dedicated to the execution of the task. Note further that attention might be distributed over the total visual field. With the current paradigm, we determined whether attention is focused on a specific location at a specific moment in time, and how this varies under different circumstances. Our current results support the hypothesis that active involvement modulates the attentional distribution around tracked objects, specifically along bounce and linear paths in the event of a collision.

An earlier study by Thornton et al. (2014) showed that participants were able to avoid collisions between several moving objects by adjusting their future trajectory. They found that viewers could control a higher number of objects during this interactive MOT (iMOT) task than they could track during a regular MOT experiment. These results support our current finding that participants anticipate object trajectories and their coincidence when active involvement is required. Based on Thornton et al.'s findings, it could perhaps also be expected that the participants who were actively involved in deflecting the targets would perform better in terms of target tracking compared to observers. However, we did not find such an advantage for active control in either of the experiments in our current study. This might be explained by the fact that tracking performance in our experiment is already high (around 90%), as the participants in our study only tracked two targets during each trial, far below the average maximum number of 4-6 targets that can be tracked in MOT and iMOT (Scholl, 2009; Thornton et al., 2014). Note that our choice for two targets is based on a reasonable consensus that motion extrapolation may occur at a relatively low tracking load (Fencsik et al., 2007; Howe & Holcombe, 2012; Luu & Howe, 2015; for a review, see Meyerhoff et al., 2017).

The current results support earlier findings that suggest that action can modulate attention (Duncan et al., 1997; Linnell et al., 2005; Tipper et al., 1992). We showed that having an active role in changing the movement paths of tracked objects may lead to heightened sensitivity to extrapolations of these new paths. The difference between conditions with and without paddle control appears when probe detection is difficult enough, i.e., when probe saliency is relatively low, and when the difference in active involvement is large enough between the two tasks. Such task requirements set the right conditions to obtain measurable effects regarding action related modulation of attention.

Chapter 4

Multiple object tracking in the presence of a goal: Attentional anticipation and suppression

Text published as: Frielink-Loing, A., Koning, A. & van Lier, R. (2024). Multiple object tracking in the presence of a goal: Attentional anticipation and suppression. *Journal of Vision*, *24*(5):10, https://doi.org/10.1167/jov.24.5.10.

Data published under: https://doi.org/10.34973/3rt3-hy44

In previous studies, we found that tracking multiple objects involves anticipatory attention, especially in the linear direction, even when a target bounced against a wall. We also showed that active involvement, in which the wall was replaced by a controllable paddle, resulted in increased allocation of attention to the bounce direction. In the current experiments, we wanted to further investigate the potential influence of the valence of the heading of an object. In Experiments 4.1 and 4.2, participants were instructed to catch targets with a movable goal. In Experiment 4.3, participants were instructed to manipulate the permeability of a static wall in order to let targets either approach goals (i.e., green goals) or avoid goals (i.e., red goals). The results of Experiment 4.1 showed that probe detection ahead of a target that moved in the direction of the goal was higher as compared to probe detection in the direction of a no-goal area. Experiment 4.2 provided further evidence that the attentional highlighting found in the first experiment depends on the movement direction toward the goal. In Experiment 4.3, we found that not so much the positive (or neutral) valence (here, the green and no-goal areas) led to increased allocation of attention but rather a negative valence (here the red goals) led to a decreased allocation of attention.

Introduction

Keeping track of moving visual objects in space over time is part of our daily tasks—for example, in doing sports, work, and traversing through traffic. Such multiple object tracking (MOT) tasks usually involve multiple objects of interest that must be tracked simultaneously. This means that we need to be able to divide our attention over several loci that often move independent from each other. Perhaps unsurprisingly, we are quite able to do so, even when the objects that have to be tracked look identical (Pylyshyn & Storm, 1988). However, there is a limit to how many objects we can keep track of (Alvarez & Franconeri, 2007; Cavanagh & Alvarez, 2005; Scholl, 2009). We previously proposed that the ability to track multiple objects is aided by not only attending to the current locations of objects but also taking into account their trajectories (Atsma, Koning, & van Lier, 2012; Frielink-Loing, Koning, & van Lier, 2017). Using probe detection, we showed that attention is indeed projected ahead of objects in anticipation of their future locations during MOT, especially when objects are tracked covertly (Frielink-Loing et al., 2017). Following the finding of Atsma et al. (2012) that attention does not "bounce" during passive viewing (i.e., that it does not shift to a new trajectory in anticipation of a predictable change of direction following a collision), we found that, when the task involved active interaction with the tracked objects, attention was shifted more toward the "bounce" path, when measured under the right conditions (Frielink-Loing, Koning, & van Lier, 2022). Therefore, in the present study, we investigated whether the context in the form of a goal is able to further direct attention toward the future trajectory of the object.

There are several ways in which allocation of attention can be measured and mapped. The original MOT task, developed by Pylyshyn and Storm (1988), has often been applied as a tool to investigate mechanisms of attention. In the original paradigm, a target flash identification task was used during the movement phase to measure how many targets participants could track simultaneously. Tracking performance is also often measured after each motion phase either by randomly highlighting an object and asking, "Was this a target or not?" (e.g., Yantis, 1992), or by requiring the participant to select all objects they believed were targets (e.g., Keane & Pylyshyn, 2006). In recent years, MOT has been used for closer investigation into the way attentional resources are distributed over the visual scene when observers perform a MOT task, not just between objects but also across the object surface and in the area surrounding them (e.g., Alvarez & Scholl, 2005; Atsma et al., 2012; Flombaum, Scholl, & Pylyshyn, 2008; Frielink-Loing et al., 2017; Frielink-Loing et al., 2022). This requires a different type of measurement than tracking performance.

For a more direct measure of where attentional resources are allocated during tracking, we make use of probe detection (Drew, McCollough, Horowitz, & Vogel, 2009; Posner, 1980). Specifically, we briefly present tiny dot probes at specific locations with respect to moving objects and compare probe detection rates between these locations to determine how attention is allocated during object tracking. This technique relies on the idea that attention lowers the threshold for stimulus detection (cf. Posner, 1980); thus, by measuring probe detection at multiple but specific locations with respect to a moving object, we can map the distribution of attention in and around a tracked object. In earlier studies, we used this technique to show that attention is distributed anisotropically around tracked objects (Atsma et al., 2012), specifically during covert tracking (Frielink-Loing et al., 2017), and that allocation of attention can be modulated by active interaction (Frielink-Loing et al., 2022). These findings suggest that attention is focused ahead of a moving target object, thereby appearing to take into account not just the current location of the object at each time point but also its predicted future trajectory.

In addition to active involvement, it seems likely that the relevance of the trajectory of an object also influences the allocation of attention; that is, naturally, if the trajectory of a target object is unpredictable (e.g., Howe & Holcombe, 2012), then using motion information to predict its future location (extrapolation) will not help tracking. Under such circumstances, one needs to attend to the current location of an object in order to be able to successfully track it. Conversely, when an object moves predictably (e.g., in a straight line), its future path can be anticipated (Atsma et al., 2012), although a computational investigation showed that extrapolation is not necessary for object tracking (Zhong, Ma, Wilson, Liu, & Flombaum, 2014). Moreover, and more relevant for the current study, what if the task is not only to keep track of objects but also to manipulate their movement such that they may approach, or avoid, a certain location or another object? After all, in real life, object tracking, generally, is a means to an end; we use it to be able to anticipate or to manipulate (objects in) our environment. In fact, a study by Thornton, Bülthoff, Horowitz, Rynning, and Lee (2014) showed that participants are very good at controlling object movements to avoid collisions during an interactive MOT task (iMOT) and can even control more objects than they can track during a regular MOT task.

Here, we present a form of interactive MOT employed in a paradigm where target objects must hit a goal in order to score points (Experiments 4.1 to 4.3), allowing us to investigate the distribution of attention in a new context. Additionally, we investigate the influence of goal valence (i.e., whether a goal should be approached or avoided; Renton, Painter, & Mattingley, 2019) on the allocation of attention around tracked objects (Experiment 4.3). In Experiment 1, participants performed a MOT task where they controlled a movable "goal" with which they were instructed to deflect (or "catch") tracked objects. During the MOT task, as objects collided with a static wall at the center of the screen, a probe could appear either along the extrapolation of its pre-collision path (where the object would never go, because it always bounced off the wall) or along its post-collision path (cf. Atsma et al., 2012). We compare probe detection rates for these two probe locations (the so-called linear and bounce probes) in situations when the target object was moving toward the goal and when it was moving away from the goal. We expected to see enhanced attention anticipating an imminent collision between the object and the goal, measured as a relatively high detection rate for bounce probes compared to linear probes as the object moved toward the goal. No such difference in probe detection rates is expected when a tracked object is moving away from the goal.

In Experiment 4.2, the goal area was confined to a smaller part of the screen, which allowed us to distinguish whether proximity between the probe and the goal, or anticipation of scoring a point, could account for the enhanced probe detection for the "goal" probes in Experiment 4.1. In a third experiment, the goals were fixed in the corners of the display, and the participants were given control over the permeability of the static wall in the center of the screen (i.e., whether objects would bounce off or move through it). In the first two experiments, where objects always bounced, only bounce probes would appear in an actual future location of the object, but this third experiment allowed for investigation of the distribution of attention around a tracked object where both linear probes and bounce probes could appear in the future location of the object. We again expected to find enhanced allocation of attention along the path of an object moving toward a positive reward goal. Additionally, we expected to see a suppression of probes along the path between the object and a negative reward goal.

Experiment 4.1

Method

Participants. Thirty-two participants (27 females, five males; 23 ± 3 years old) took part in this experiment and received payment or course credit for their participation. Twenty-seven participants were right-handed. All reported to have normal or corrected-to-normal vision and were naïve with respect to the nature and objective of the study. Procedures were in accordance with the tenets of the Declaration of Helsinki, and all participants gave written informed consent before the start of the experiment.

Stimuli and design. A white rectangle subtending 25° × 20° was presented centrally on a black background, acting as a bounding box. On each trial, four identical objects were presented, two targets and two distractors. Objects were black circular outlines, 2° in diameter, and were randomly assigned to a corner of the bounding box (*Figure 4.1*, panel P1). A black vertical wall, 0.1° wide and 10° high, was presented at the center of the screen. A grey horizontal bar subtending 12.5° × 0.4° appeared centred along either the top or bottom wall of the bounding box and served as the goal in the experiment. Whether the goal appeared at the top or the bottom of the bounding box was randomly determined at the beginning of each trial.

At the start of each trial, the two target objects blinked on and off for 3 seconds to indicate that they were the objects the participant should keep track of (*Figure 4.1*, panel P1). Next, all four objects started moving in randomly generated directions for a duration of 20 seconds at a constant speed of 8°/s (*Figure 4.1*, panel P2). Upon encountering one of the four edges of the bounding box, the wall in the middle of the screen, or the goal, objects would bounce off naturally (angle of reflection equals angle of incidence as measured to the normal).

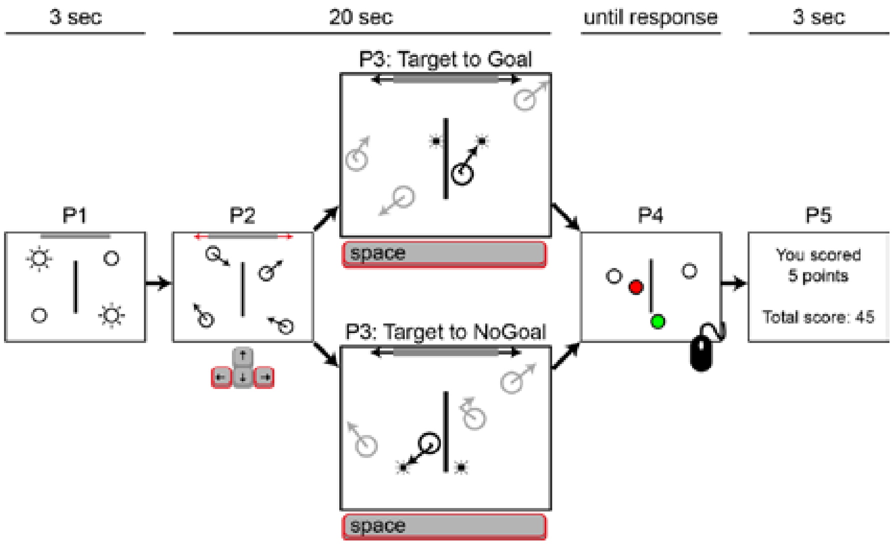


Figure 4.1. Timeline for Experiment 4.1. Each trial started with identification of the targets that had to be tracked by having them blink on and off for 3 seconds (panel P1). The goal (gray horizontal bar) appeared at either the top or bottom of the screen (randomly chosen at the start of each trial). Next, targets and distractors started moving while participants controlled the movable goal to intercept the targets by pressing the left and right arrow keys on a standard keyboard (panel P2). Whenever a target hit the vertical wall at the center of the screen, a probe could appear along the linear trajectory of the target, on the bounce trajectory (panel P3) or at a random location within the bounding box (see main text). Depending on the direction of the target with respect to the location of the goal, these probes were marked as goal probes (panel P3, top) or no goal probes (panel P3, bottom). At the end of the trial, participants were asked to identify the targets using the mouse (panel P4) and received feedback on the number of interceptions they made (panel P5).

During the movement phase of a trial, participants could move the goal left or right by pressing the left or right arrow keys on a standard QWERTY keyboard. The bar moved at a constant speed of 16°/s left or right while the arrow key remained pressed, and its movement was restricted by the edges of the bounding box. Whenever a collision occurred between a target object and the vertical wall at the center of the screen, one of four possible experimental events could occur: a probe was shown along the bounce trajectory of the object (Bounce probe, 30% of events), a probe was shown along the linear extrapolation of the heading direction of the object before the collision (Linear probe, 30% of events), a probe was shown at a random location within the bounding box (Open Space probe, 20% of events), or no probe was shown (No Probe event, 20% of events). Bounce and Linear probes (for examples, see *Figure 4.1*, panel P3) could appear at one of three distances (2.4°, 3.2°, or 4.0°) from the center of an object. Probes were presented for 50 ms and moved along with the probed target to maintain their distance with respect to the object.

The Bounce and Linear probes were additionally categorized as Goal or No Goal events, depending on whether the target object that triggered the event was at that moment moving towards (Goal) or away (No Goal) from the horizontal wall containing the goal. Goal probes (bounce or linear) thus always appeared between the target object and the goal (in *Figure 4.1*, panel P3, top); No Goal probes (bounce or linear) thus always appeared between the target object and the horizontal wall not containing the goal (in *Figure 4.1*, panel P3, bottom). In case of a Goal event, we also recorded whether the target subsequently reached the goal (hit) or not (miss).

Procedure. Participants were seated in front of a liquid-crystal display monitor (resolution of 1920 × 1080 pixels and refresh rate of 120 Hz), and they operated a standard QWERTY keyboard and computer mouse. Participants were seated on a fixed chair approximately 60 cm from the screen. Stimuli were created and presented with PsychoPy 1.90.2 (Peirce, 2007; Peirce, 2009), running on a Dell Precision T3610 computer (Dell, Round Rock, TX) with Windows 7 (Microsoft, Redmond, WA).

At the start of the experiment, participants received instructions to track two out of four identical objects, which were indicated at the beginning of each trial, and to deflect the two target objects as often as possible with the movable goal. They were told that they would receive points each time they "caught" a target object, and at the end of each trial their total score would be presented (*Figure 4.1*, panel P5). Participants were also instructed to press the space bar each time they detected a small, brief dot probe on the screen. Responses to probes within 1000 ms after presentation were recorded. If no response was given within that time window, the probe was considered undetected. At the end of the movement phase of each trial, participants were asked to identify both targets using the mouse (*Figure 4.1*, panel P4). To provide feedback on their tracking performance, correctly identified targets turned green and distractors turned red when selected.

All participants first performed five practice trials of 20 seconds, followed by as many trials as necessary to obtain measurements for 400 events (320 Probe events and 80 No Probe events). Participants performed 95 trials on average (minimum 90, maximum 100), with the exception of two participants who performed 54 and 88 trials, respectively, due to technical problems causing the experiment to stop prematurely. The experiment lasted approximately 50 minutes, depending on the number of trials needed to complete data collection, including a break after every fifth trial.

Results

Overall tracking performance was determined for each participant by calculating the average number of correctly identified targets over all trials. Mean tracking performance was moderate to high for most participants (*M* = 66%; *SD* = 14%; range, 47%–92%). Only events triggered by targets that were correctly identified at the end of a trial were considered for analysis to ensure that participants attended to the correct object during probe presentation. As a result, 144 out of 400 events were discarded on average per participant. Average probe detection rates were determined based on the responses to the remaining events. Only button presses that occurred within 1000 ms after event onset were counted as a hit (cf. Flombaum et al., 2008). Participants could be excluded for not seeing probes (less than 5% total probe detection for probe events relevant for analysis), high false alarm rate (measured as outliers), and low tracking performance (below or at chance level, 50%). Eight participants were excluded from analysis because their total probe detection rate for the Bounce and Linear probe events was lower than 5%.

Table 4.1. Experiment 1 probe detection results.

	Goal	No goal
Bounce probe	24.7 (2.6)	19.2 (2.5)
Linear probe	24.1 (2.9)	22.5 (2.7)

Notes: Mean probe detection rates are expressed as percent (SE) based on 24 participants.

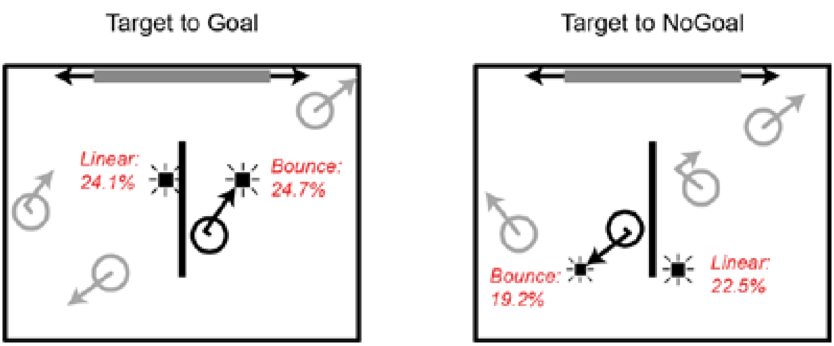


Figure 4.2. Mean probe detection rates superimposed on the situation sketch from Figure 4.1 (panel P3). Probe sizes represent their relative detection rate and do not reflect presentation size during the experiment.

For the remaining 24 participants, overall probe detection (i.e., responses to Probe events) was low to moderate (*M* = 19%; *SD* = 9.5%; range, 5%–45%). False alarm rates ranged from low to high (*M* = 5.3%; *SD* = 5.0%; range, 0%–17%), with no statistical outliers (the criterion for an outlier used here is that its value falls above the third quartile + 1.5 times the interquartile distance). *Table 4.1* and *Figure 4.2* show detection rates for the Bounce and Linear probes. Note that, because target objects that were heading toward the wall with the goal were almost always caught by the participant, we only considered probes triggered by target objects that were moving toward and eventually hit the goal (Goal events) and probe events triggered by target objects that were moving toward the opposite wall (No Goal events). Finally, due to data sparsity, we decided to collapse the results over probing distance for further statistical analyses.

Probe detection. A 2 × 2 repeated-measures analysis of variance (ANOVA) with probe type (Bounce, Linear) and object heading (Goal, No Goal) as the within-subject factors and probe detection rate as the dependent variable revealed a significant main effect of object heading, $F(1, 23) = 5.87$, $p = 0.024$, $\eta^2 = 0.203$, $1 - \beta = 0.641$, with higher detection rates for probes triggered by target objects moving toward the goal than by target objects moving away from the goal ($M_{Goal} = 24.4\%$, $M_{NoGoal} = 20.9\%$). There was no main effect of probe type ($F < 1$), and no significant interaction between probe type and object heading ($F = 2.33$, $p = 0.141$).

Discussion

For this first experiment, we used an interactive form of MOT including a goal to investigate whether the distribution of attention around a tracked object would differ when the tracked object moved toward the side where the movable goal was located compared to when it moved away from the goal. We indeed found a main effect of object heading, as probes were detected more often when a tracked object was moving toward the goal than when a tracked object was moving away from the goal, which shows that the presence of a goal does modulate the distribution of attention around tracked objects. We did not find a main effect of the type of probe (bounce vs. linear) nor an interaction effect between object heading (toward a goal vs. away from a goal) and the type of probe (bounce vs. linear). This means that here attention was enhanced when a probe was presented in the area between the tracked object and the goal, irrespective of whether the probe appeared in the bounce direction of the tracked object or along its linear direction.

The current study expands on research by Atsma et al. (2012), who found that attention does not shift toward the post-bounce trajectory when an object is colliding with an obstacle. In this first experiment, attention was rather equally distributed over the linear and bounce trajectories. The results show that attention is generally enhanced when a tracked object approaches a goal compared to when a tracked object does not approach a goal. Still, this can be interpreted in two ways:

either the object moving toward the goal side of the box (top/bottom) enhances attention or the presence of the goal itself does. In order to distinguish between these two possible explanations, we performed a second experiment.

Experiment 4.2

We adapted the task from Experiment 4.1 such that the goal could only move along half the width of the bounding box, essentially allowing participants to only deflect objects on either the right or left side of the screen (see *Figure 4.3*). We expected to see one of two possible outcomes: (a) both Bounce and Linear probes presented when an object bounces off the central wall heading toward the goal (e.g., toward the top-right quadrant; see probes B1 and L1 in *Figure 4.3*) are detected better than probes presented when the object bounces on the other side (e.g., toward the top-left quadrant; see probes B2 and L2 in *Figure 4.3*), which would indicate a rather object-centred enhancement of attention, versus (b) probes presented in the quadrant where the goal is located (B1 and L2) are detected better compared to probes presented in the quadrant where the goal is not located (B2 and L1), which would imply a more goal-centred enhancement of attention.

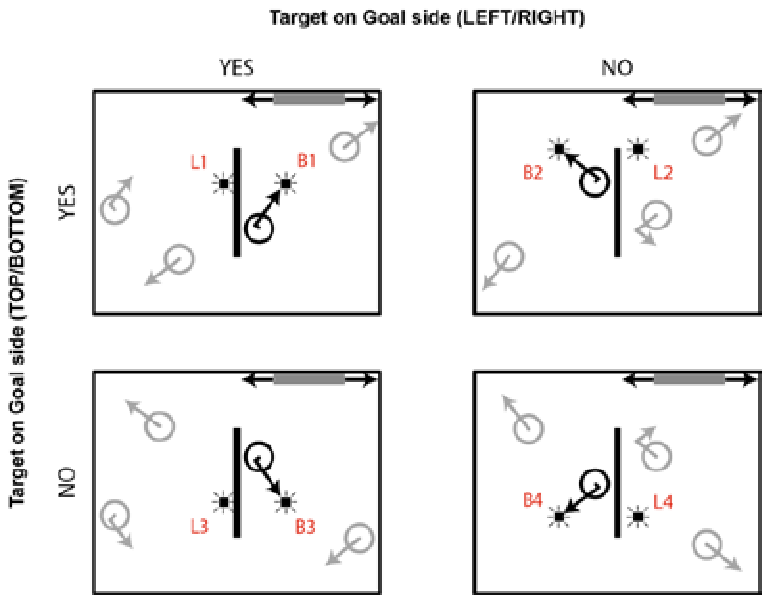


Figure 4.3. Probe types in Experiment 4.2 for probe events triggered by target objects moving toward the horizontal wall containing the goal. For illustration purposes, the goal is restricted to the upper right corner of the bounding box.

Method

Participants. Twenty-seven new participants (21 females, five males, one other; 25 ± 12 years old) took part in this experiment and received payment or course credit for participation. All reported to have normal or corrected-to-normal vision and were naïve with respect to the nature and objective of the study. Procedures were in accordance with the tenets of the Declaration of Helsinki, and all participants gave written informed consent before the start of the experiment.

Stimuli and design. All stimuli were identical to those presented in Experiment 4.1, except for the goal, which now subtended a quarter of the width of the bounding box (6.25°). The goal could appear along either the top or bottom wall of the bounding box, centred on either the right or left half of the wall. The location of the goal was determined at random at the start of each trial by the PsychoPy program and was recorded along with the data that were collected. The movement of the goal was restricted to one-half of the bounding box by the program.

Procedure. The procedure for this experiment was nearly identical to the procedure for Experiment 4.1, with the additional instruction that the goal could only be moved along one-half of the wall of the bounding box. This also meant that, if an object could not be caught due to this restriction, it would not be counted as a miss. Participants performed 97 trials on average (minimum 92, maximum 106). The experiment lasted approximately 64 minutes, depending on the number of trials needed to complete data collection, including a break after every fifth trial.

Results

Overall tracking performance was determined for each participant by calculating the average number of correctly identified targets over all trials. Mean tracking performance was moderate to high for most participants (M = 75%; SD = 12%; range, 50%–94%). Only events triggered by targets that were correctly identified at the end of a trial were considered for analysis to ensure that participants attended to the correct object during probe presentation. As a result, 99 out of 400 events were discarded on average per participant. Average probe detection rates were determined based on the responses to the remaining events. Only button presses that occurred within 1000 ms after event onset were counted as a hit (cf. Flombaum et al., 2008). Exclusion criteria can be found in the Results section of Experiment 4.1. During a session with one participant, the experiment stopped prematurely due to a technical error, and the results for this participant were lost. Three participants were excluded from analysis because they formed an outlier on false-alarm rate (for the exclusion criterion, see the Results section in Experiment 4.1) or because their tracking performance was at chance level (~50%). For the remaining 23 participants, overall probe detection (i.e., responses to Probe events) was high (*M* = 65%; *SD* = 13.9%; range, 23%–89%). False-alarm rates were low (*M* = 1.3%; *SD* = 1.5%; range, 0%–5%). *Table 4.2* and *Figure 4.4* show detection rates for the Bounce and Linear probes.

Table 4.2. Experiment 4.2 probe detection results.

		Goal side (Left/Right)	
		Yes	**No**
Goal side (Top/Bottom)			
Yes	Bounce probe	75.8 (3.2)	75.0 (3.2)
	Linear probe	67.5 (3.4)	72.3 (3.2)
No	Bounce probe	69.6 (3.8)	72.1 (3.4)
	Linear probe	64.0 (2.9)	62.4 (3.1)

Notes: Mean probe detection rates are expressed as percent (SE) based on 24 participants. Note that goal side refers to the location of the tracked object, not the probe.

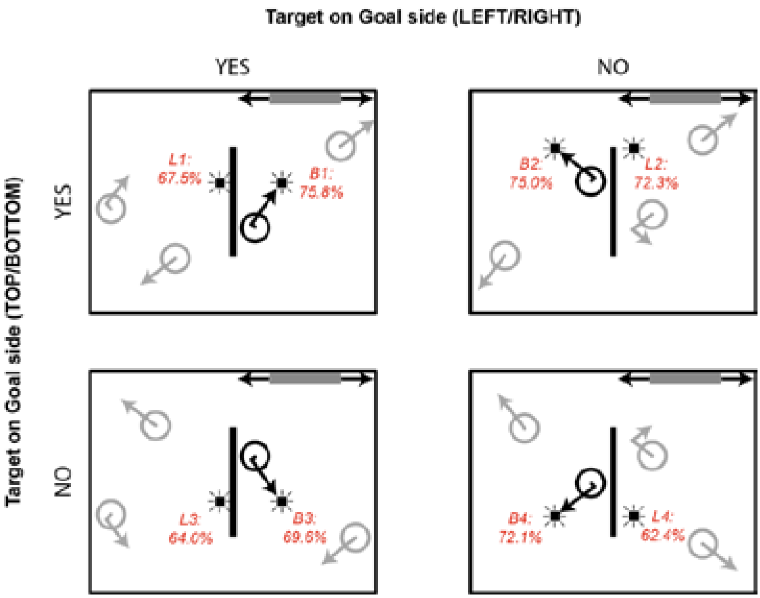


Figure 4.4. Mean probe detection rates superimposed on the situation sketch from Figure 4.3.

Probe detection. In order to test our two hypotheses, we performed a 2 × 2 repeated-measures ANOVA with object near goal (yes, no) and probe near goal (yes, no) as within-subject factors and probe detection rate as the dependent variable. Specifically, looking at *Figure 4.4*, probes B1 and L1 belonged to the target at the same side of the goal (i.e., object near goal: yes), whereas probes B2 and L2 belonged to the target on the opposite side of the goal (i.e., object near goal: no). Similarly, in *Figure 4.4*, probes B1 and L2 were presented at the same side of the goal (probe near goal: yes), whereas probes B2 and L1 were presented at the opposite side of the goal (i.e., probe near goal: no). The analysis revealed a main effect of probe near goal, $F(1, 22) = 4.61$, $p = 0.043$, $\eta_p^2 = 0.173$, $1 - \beta = 0.537$, with higher detection rates for probes that appeared in the goal corner of the bounding box. There was also a significant interaction between object near goal and probe near goal, $F(1, 22) = 11.06$, $p = 0.003$, $\eta_p^2 = 0.335$, $1 - \beta = 0.888$. As can be seen in *Figure 4.4* (top row), mean probe detection was lowest when the object approached the central wall on the side where the goal was located, but the probe was not near the goal (see L1 in *Figure 4.4*)—that is, a linear probe irrelevant to the task. In contrast, both bounce probes (B1 and B2 in *Figure 4.4*) and the linear probe near the goal (L2 in *Figure 4.4*) yielded similar detection rates. There was no significant main effect of object near goal ($F = 2.54$, $p = 0.125$).

Discussion

This second experiment was created to investigate the relative contributions of attention to the tracked object (target) and attention to the part of the bounding box containing the goal, which together might have contributed to the main effect of object heading in Experiment 4.1. That is, in Experiment 4.2, with the same vertical wall in the center of the screen, but now restricting the range of the moveable goal to the left or right side of the display, we could additionally distinguish the situation where the tracked object was heading toward the wall where the goal was located, as well as it being on the side of the vertical wall where the goal was located, from the situation where the tracked object was heading toward the wall where the goal was located but on the other side of the vertical wall (to where the goal could not be moved).We expected one of two outcomes: (a) a rather object-centred enhancement of attention, reflected by a higher detection of probes triggered by an object moving on the side where the goal could catch it (B1 and L1 in *Figure 4.3*); or (b) a more goal-centred enhancement where probes presented in the “quadrant” of the display of the goal are detected better (B1 and L2 in *Figure 4.3*).

What we can conclude from Experiments 4.1 and 4.2 so far is that goals appear to have an enhancing effect on probe detection. However, the interaction effect we found here suggests that in this second experiment there was neither an overall object-centred enhancement of attention nor an overall goal-centred enhancement of attention. That is, the results appear to be driven mainly by the lower probe detection for the condition in which the object was near the goal while the probe was presented on the opposite side (i.e., L1 in *Figures 4.3* and *4.4*). Or, stating it otherwise, the actual bouncing path of the object toward the goal apparently attenuated attention to the no-goal side. The following aspects should be noted here, which we will deal with in Experiment 4.3. First, whereas bounce probes are always on the same side of the vertical wall as the goal, this is not the case for linear probes. Naturally, this imbalance is the result of the targets always bouncing and never "going through" the wall. Experiment 4.3 was set up to deal with this imbalance by allowing the targets to also go through the wall. More specifically, wall permeability could be manipulated by the participant in Experiment 4.3. Second, following the influence of action on probe detection (Frielink-Loing et al., 2022), it seems plausible that this imbalance is further strengthened by the action that has to be taken on the goal. Thus, in Experiment 4.3, action and goals are decoupled; that is, just as in Frielink-Loing et al. (2022), we introduced a task in which the action occurs in the area of the central wall. The goals are still located in the corners of the box, but they will be static (although changing position from trial to trial). The action will be such that both Bounce probes and Linear probes appear at the quadrant toward which the object might be heading. The trick is to introduce an action task in which the wall can be made permeable by the participant when needed, triggered by the positioning of the goals that have to be reached, or avoided.

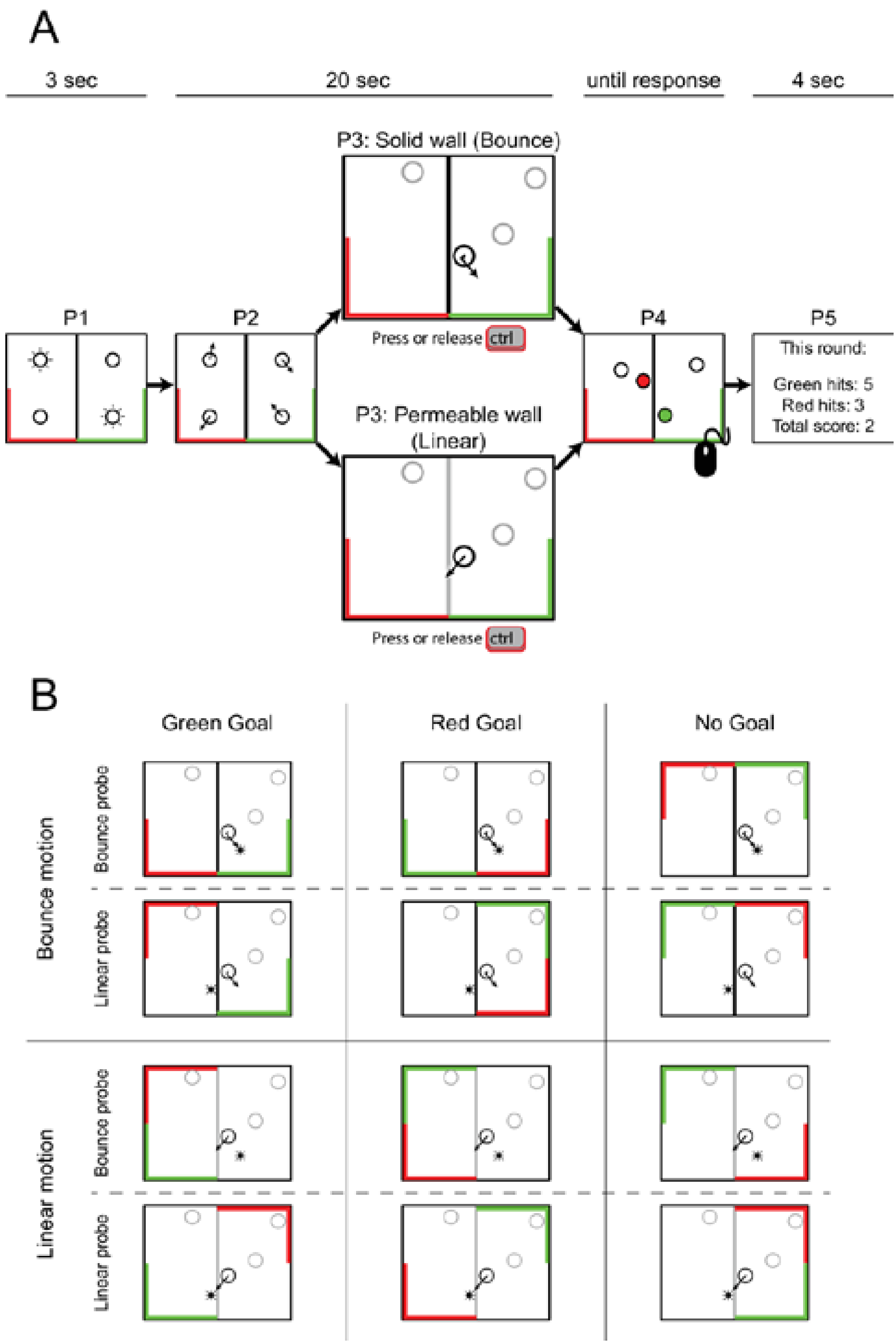
Experiment 4.3

In this third experiment, we again employed a MOT paradigm in which two target objects among two distractor objects had to be tracked while at the same time probes must be detected. Instead of moving the goal around on the screen, attracting attention, the goal was now fixed in one of the corners of the bounding box. The vertical wall in the middle of the bounding box was extended to span the entire height of the box and could be made permeable or solid by the participant by pressing or releasing a button. To make the task as challenging as the previous tasks, a second "goal" was added that was to be avoided instead of hit. When a target object hit a positive goal, a point was gained; when a target object would hit a negative goal, a point was subtracted. For example, when a target object approached the central vertical wall as it was heading in the direction of a positive goal, it paid for the participant to make the wall permeable, allowing the object to continue along its path and hit the positive goal, resulting in a scored point. Similarly, to provide another example, when a target object approached the central wall as it was heading in the direction of a negative goal, it paid for the participant to make the wall solid, allowing the object to bounce off to avoid the negative goal, thereby avoiding the subtraction of a point. Within this design, both bounce probes and linear probes can appear in the direction of actual movement of the tracked object following an action of the participant (as they can make the wall permeable or solid). In sum, this task allows us to investigate the distribution of attention around tracked objects when they must be made to approach certain areas of the display and avoid others, by either moving through or bouncing off a wall as manipulated by the participant. We expect that probe detection is modulated by goal presence. More in particular, probe detection for objects moving toward a positive goal may be higher than toward a negative goal. The addition of neutral goals may then act as a baseline condition to decide whether it is in fact an enhancement or rather a suppression effect.

Method

Participants. Thirty-one new participants (25 females, six males; 24 ± 5 years old) took part in this third experiment and received payment or course credit for participation. All reported to have normal or corrected-to-normal vision and were naïve with respect to the nature and objective of the study. Procedures were in accordance with the tenets of the Declaration of Helsinki, and all participants gave written informed consent before the start of the experiment.

Stimuli and design. The bounding box and circular objects were identical to those presented in Experiments 4.1 and 4.2. A black vertical wall, 0.2° wide, divided the bounding box into two compartments. One green goal (positive) and one red goal (negative), each subtending 12.5° along a horizontal border and 10° along an adjacent vertical border, were randomly assigned by the computer program to a corner of the bounding box on every trial (*Figure 4.5A*, panel P1). The goals could be assigned to any corner of the box, as long as they did not overlap. *Figure 4.5B* depicts all possible positions of the goal and no-goal areas and shows (non-exhaustive) examples of Bounce and Linear probe events as the object moves toward the green goal, red goal, or no-goal area. Depending on an action of the participant (who could decide to make the wall permeable or solid when a target was about to hit the wall by pressing or releasing a single button), the object continued along its motion path and thus went "through the wall" (linear motion), or the object bounced off the wall naturally (bounce motion), with the angle of reflection being equal to the angle of incidence as measured to the normal.


A
3 sec
20 sec
until response
4 sec
P3: Solid wall (Bounce)
P1
P2
P4
P5
Press or release ctrl
This round:
Green hits: 5
Red hits: 3
Total score: 2
P3: Permeable wall
(Linear)
Press or release ctrl
B
Green Goal
Red Goal
No Goal
Bounce motion
Bounce probe
Linear probe
Linear motion
Bounce probe
Linear probe

< **Figure 4.5**. Illustration of the timeline (A) and conditions (B) for Experiment 4.3. (A) Each trial started with an identification of the targets to be tracked (panel P1). Next, targets and distractors started moving (panel P2). Participants controlled the permeability of the centralized wall by pressing or releasing the right Ctrl key on a standard keyboard in order to be able to manipulate the targets and let them reach the green goal but avoid the red goal (bottom panel in panel P3 shows the permeable wall as grey for illustrative purposes; the wall did not change colour during the experiment). At the end of the trial, participants were asked to identify the targets using the mouse (panel P4). Panel P5 shows example feedback on the number of times targets had hit the green and red goals and also the total score (i.e., subtracting the red hits from the green hits). (B) For each trial the positions of the green and red goals were randomly assigned to two corners of the box. With the remaining two corners of the box not being assigned a colour (i.e., the neutral goals), this resulted in the 12 shown displays, each with a unique goal configuration. Next, the participant could manipulate the permeability of the centralized wall by pressing and releasing a button, shown as black (solid) or grey (permeable) in the figure (note that, in the experiment, the wall remained black throughout). The top two rows show the centralized wall in black, indicating that whenever an object would collide with the centralized wall the object would bounce off of it. The bottom two rows show the centralized wall in grey, indicating that whenever an object would collide with the centralized wall the object would continue along its motion path. Finally, the (non-)permeability of the centralized wall and the locations of a presented probe (left or right of the wall) and an object that is about to collide with it (coming from the left or the right) resulted in probes being labelled as either a Bounce probe or a Linear probe, as shown in the figure. In all displays, the objects not colliding with the wall are shown in grey for illustrative purposes.

At the start of each trial, two target objects blinked on and off for 3 seconds to indicate that they were the objects the participant should keep track of (*Figure 4.5A*, panel P1). Next, all four objects started moving in randomly generated directions for a duration of 20 seconds at a constant speed of 8°/s (*Figure 4.5A*, panel P2). Upon encountering one of the four edges of the bounding box or the (solid) wall in the middle of the screen, objects would bounce off naturally (angle of reflection equals angle of incidence as measured to the normal).

During the movement phase of a trial, participants could control the permeability of the vertical wall using the right Ctrl key on a standard QWERTY keyboard. How wall permeability could be toggled was counterbalanced, with half of participants having to press the Ctrl key and the other half of participants having to release the Ctrl key to let an object pass through. Each time a target object collided with the central wall, one of four experimental events could occur similar to Experiments 4.1 and 4.2 (i.e., Bounce, Linear, or Open Space Probe event or No Probe event). The chance of each event occurring was the same as in Experiments 4.1 and 4.2. Bounce and Linear probes could appear at the same three distances as used before (2.4°, 3.2°, or 4.0° from object center), and probes were again presented for 50 ms, moving along with the probed target to maintain their distance with respect to the object. For each event, the motion of the target was saved (through the wall or bounced off), as well as the presence and type of goal in both the corner the object approached and the corner the object avoided (green, red, or no goal) (*Figure 4.5B*).

Procedure. At the start of the experiment, participants received instructions to track two out of four identical objects, which were indicated at the beginning of each trial. They were informed that their task was to maximize their score by letting the two targets hit the green goal and avoid the red goal as often as possible by manipulating the permeability of the wall. No instructions were given regarding the distractor objects. Participants were informed that they would receive one point for each time a target hit the green goal and that they would lose a point each time a target hit the red goal. At the end of each trial their scores were presented onscreen (*Figure 4.5A*, panel P5). Crucially, participants were also instructed to press the space bar each time they detected a small, brief dot probe on the screen. Responses to probes within 1000 ms after presentation were recorded. If no response was given within that time window, the probe was considered undetected. At the end of the movement phase of each trial, participants were asked to identify both targets using the mouse (*Figure 4.5A*, panel P4). To provide feedback on their tracking performance, correctly identified targets turned green and distractors turned red when selected.

All participants received detailed instructions onscreen, as well as a brief demo explaining wall permeability and probe presentation. They then performed five practice trials of 20 seconds, followed by as many trials as necessary to obtain measurements for 600 events (480 Probe and 120 No Probe events). Thus, participants performed 75 trials on average (minimum 50, maximum 85). The experiment lasted approximately 45 minutes, depending on the number of trials needed to complete data collection, including a break after every fifth trial.

Results

Overall tracking performance was determined for each participant by calculating the average number of correctly identified targets over all trials. Mean tracking performance was high for most participants (*M* = 82%; *SD* = 15%; range, 49%–97%). Only events that belonged to correctly identified targets were considered for analysis to ensure that participants attended to the correct object during probe presentation. As a result, 193 out of 600 events were discarded on average per participant. Average probe detection rates were determined based on the responses to the remaining events. Only button presses that occurred within 1000 ms after event onset were counted as a hit (cf. Flombaum et al., 2008). Eight participants were excluded from analysis because their total probe detection rate for Bounce and Linear probe events was lower than 5% or because their tracking performance was at chance level.

For the remaining 23 participants, overall probe detection (i.e., responses to all Probe events, including Open Space probe events) was low to moderate ($M = 24\%$; $SD = 14.4\%$; range, 4%–54%). False alarm rates were low ($M = 1.6\%$; $SD = 1.8\%$; range, 0%–7%). We collapsed the results over probing distance for further analyses to overcome data sparsity. *Table 4.3* shows the mean detection rates for all probes, split over the approached goal (green, red, or no goal) and the type of motion (bounce or linear).

Table 4.3. Experiment 4.3 probe detection results.

	Green goal	Red goal	No goal
Bounce motion			
Bounce probe	32.8 (3.4)	18.2 (5.6)	33.7 (3.8)
Linear probe	33.8 (3.7)	22.5 (4.9)	30.0 (3.4)
Linear motion			
Bounce probe	16.2 (4.5)	6.0 (2.7)	15.6 (3.9)
Linear probe	16.6 (4.7)	11.8 (4.2)	14.4 (3.7)

Notes: Mean probe detection rates are expressed as percent (SE) based on 23 participants. Results are split over the type of goal that was approached (green, red, or no goal) and which interaction with the wall preceded it (bounce or linear motion).

Probe detection. We performed a 2 × 2 × 3 repeated-measures ANOVA with move type (bounce, linear), probe type (Bounce, Linear), and goal type (green, no goal, red) as within-subject factors. Due to missing values (specifically for red goal events, as participants avoided hitting these goals), data of only 17 participants could be analysed. There was a significant main effect of move type, $F(1, 16) = 25.30$, $p < 0.001$, $\eta_p^2 = 0.613$, with a higher detection rate for probes presented when a target bounced off the wall compared to when a target went through the wall. We also found a significant effect of goal type, $F(2, 15) = 6.38$, $p = 0.010$, $\eta_p^2 = 0.458$. Probes that were presented when a target moved toward a goal with a negative valence (i.e., the red goal) were detected significantly less compared with probes presented when a target moved toward either a positive goal (green) or a neutral goal (no goal). No other significant effects were found (all $p > 0.2$).

Valence. In the final analyses we also take into account the effect of avoiding (or missing) a (no-)goal area as a result of controlling the permeability of the central wall. That is, we performed an additional analysis in which we considered not only the properties of the quadrant of the box which the target was heading toward (green goal, red goal, or no goal) but also the properties of the quadrant at the same side (top or bottom) which the target then was not heading toward as a result of the decision and the corresponding action of the participant to make the wall permeable or not. As an example, a participant might choose to let a target bounce off the wall to make it head toward a no-goal area to avoid it hitting the red goal. Another possible situation was that a target was accidentally allowed through the wall toward the red goal, but it would have otherwise reached the green goal if it had bounced (although this situation occurred far less than the first example). *Table 4.4* shows how the combinations of reached and avoided goal (or no-goal) area could be classified in terms of reward and punishment. The various combinations suggest various strengths regarding approaching or avoiding a specific direction and the attentional resources ahead of the target in that direction (as reflected by the probe detection rate). We labelled each combination with a specific valence value. So, if a target (as a result of the permeability response of the participant) headed toward a green goal to avoid a no-goal (as in *Figure 4.6*, bottom left), the probe detection in that direction was labelled with a single plus (+), and similarly so when the target headed toward a no-goal area to avoid a red goal (as in *Figure 4.6,* third row right). When a target headed toward a green goal to avoid a red goal (as in *Figure 4.6*, top left) a double plus (++) was assigned to that cell. The cells with a negative valence were defined in a similar way. In the situation where a target headed toward a red goal to "avoid" a no-goal area (by a wrong permeability response as in *Figure 4.6*, bottom center) a single minus (–) label was assigned, and similarly so when the target headed toward a no-goal area to "avoid" a green goal (as in *Figure 4.6*, bottom right). When a target headed toward a red goal to "avoid" a green goal (as in *Figure 4.6*, top center), the corresponding cell received a double minus (– –). Finally, when a target was heading toward a no-goal area to "avoid" another no-goal area (as in *Figure 4.6*, top right), this was assigned a zero (0). Note that the green/green and red/red combinations are not possible with this paradigm, because there is always only one green goal and one red goal. Using this classification, we could determine whether there was an effect of valence of the combined situation (area reached plus area avoided). Additionally, by comparing to baseline (0), it can be made clear whether a positive outcome gives enhanced attention or a negative outcome gives suppressed attention.

Table 4.4.

		Reached		
		Green	**No Goal**	**Red**
Avoided	Green	-	Neg (-)	Neg (--)
	No Goal	Pos (+)	Pos/neg (0)	Neg (-)
	Red	Pos (++)	Pos (+)	-

Note: Classification of reward/punishment for different combinations of (no-)goal area reached or avoided.

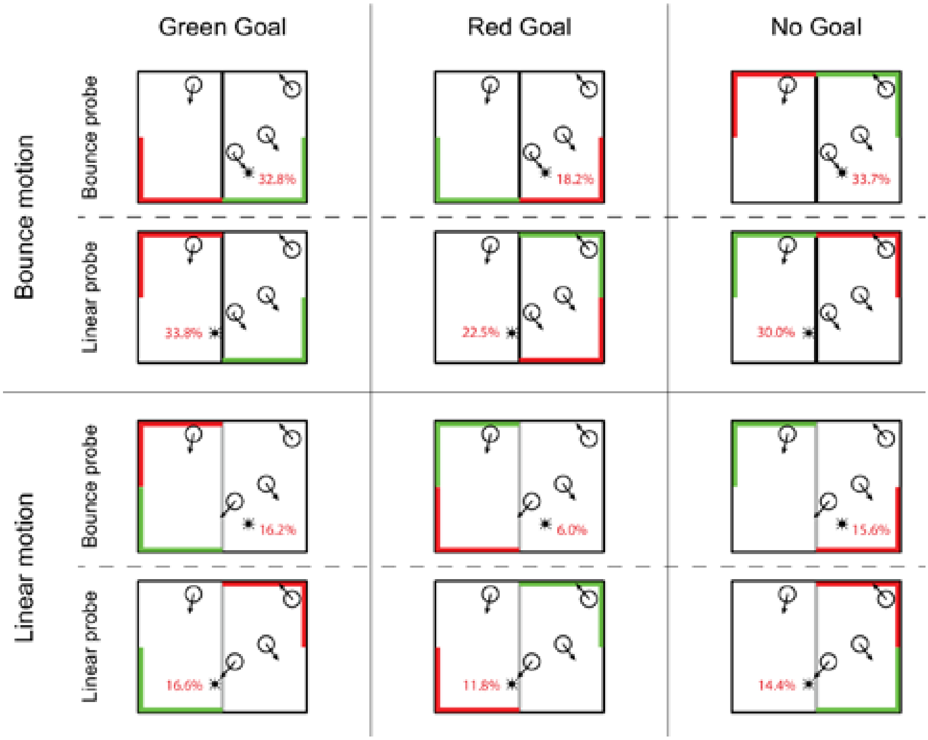


Figure 4.6. Results of Experiment 4.3 superimposed on the situation sketch from Figure 4.5. Note that these situation sketches are not exhaustive; that is, there were multiple goal configurations possible for each item in the table. For example, in the bottom-right corner, the probed object was let through the wall to reach a no-goal area, thereby missing the green goal. Alternatively, the two goals might be switched and the object could have avoided the red goal. For the results depicted here, these two examples would describe the same situation.

Table 4.5 shows mean detection rates for the categories introduced in *Table 4.4*. We pooled the mildly positive (+) combinations together, as well as the mildly negative (–) combinations, and performed a one-way ANOVA with five levels (– –, –, 0, +, ++). Because Mauchly's test indicated that the assumption of sphericity had been violated for the main effect of valence, $\chi^2(9) = 48.96$, $p < 0.001$, degrees of freedom were corrected using Greenhouse–Geisser estimates of sphericity ($\varepsilon = 0.45$). There was a significant effect of valence, $F(1.78, 39.15) = 6.19$, $p = 0.006$, $\eta_p^2 = 0.220$, indicating that there was a difference in probe detection between the different levels. At closer inspection, comparing each level with the next (i.e., comparing – – with –, – with 0, 0 with +, and + with ++), there was only a significant difference between – and 0 ($p < 0.001$).

Table 4.5. Probe detection rates for different combination of (no-)goal area reached or avoided.

		Reached		
		Green	**No Goal**	**Red**
Avoided	Green	-	16.3 (4.4)	16.4 (4.6)
	No Goal	24.6 (3.1)	26.8 (3.0)	13.8 (2.9)
	Red	27.1 (3.1)	25.7 (3.5)	-

Note. Mean probe detection rates in % based on 23 participants (SE between brackets).

Discussion

In this third experiment, we presented a different approach to an interactive MOT task than the one used in Experiments 4.1 and 4.2. Importantly, objects were now able to move through the central vertical wall, as well as bounce off. We found a main effect of move type (linear or bounce) in the current experiment, with higher probe detection rates when the object bounced off the obstacle wall than when it went through. This effect was also found by Atsma et al. (2012) when only one target needed to be tracked, but not during multiple object tracking (with three targets). This effect may be caused by the uncertainty that is introduced with the change in direction after a bounce. Viewers might need to perform an extra check or stay on the object longer to update its new trajectory when a bounce is expected, whereas this would not be necessary when its trajectory remains the same (i.e., when the object moves through the wall). In a future study, eye-tracking data might shed further light on this.

Another advantage of the current paradigm is the addition of a negative (red) goal. This not only makes it possible to compare the effects of reward and punishment on attention allocation but also provides a kind of baseline measurement from interactions with the no-goal areas. As expected, probe detection was significantly lower when an object moved toward, and eventually hit, a red goal. What's more, we saw a clear divide between negative valence (– and – –) on the one hand and neutral and positive valence (0, +, and ++) on the other hand. With the 0 level (neutral) acting as baseline, this is an indication that probe detection is suppressed in a negative (punishment) situation rather than enhanced in a positive (reward) situation (see below).

General discussion

We investigated the effect that the presence of a goal might have on the spatial distribution of attention during MOT, specifically upon the moment a tracked object interacts with a wall (i.e., bounces off or passes through). We conducted three experiments using different forms of interactive MOT, where participants had to make tracked objects hit a goal object or area as often as possible by manipulating part of the display. In Experiment 4.1, participants could move a goal bar along one of the horizontal edges of the screen in order to catch the tracked target objects. In Experiment 4.2, the movement of the goal was restricted to only one-half of that horizontal edge. In Experiment 4.3, participants manipulated the permeability of a vertical wall that divided the screen in order to make the objects pass through or bounce off to either reach a green (positive reward) goal or avoid a red (negative reward) goal.

In Experiment 4.1, we saw an overall increase in probe detection on the side of the screen where the goal was situated. There did not appear to be any dissociation between the type of probe, Bounce or Linear, but for both cases there was an enhancement of attentional focus when the goal was in sight. In Experiment 4.2, we replicated the attentional enhancement for probes presented in the direction of the goal, with a higher resolution than in Experiment 4.1 by restricting the goal area. Additionally, we found a significant advantage for probes presented along the actual future path of the object (i.e., Bounce probes), indicating anticipatory attentional allocation. With Experiment 4.3, we found results similar to those of Experiments 4.1 and 4.2, as we also found lower probe detection when the target avoided a green goal to subsequently hit a no-goal area, compared with when the target avoided a no-goal area to subsequently hit the green goal. From this result alone, one might assume that the upcoming impact with the goal enhances the allocation of attention to the tracked object. However, when we increased the range of possible scenarios by introducing a negative reward in Experiment 4.3, turning the "no-goal" event into a neutral baseline, we saw that it is not so much enhancement of attention toward a (positive) goal but rather suppression of attention toward an area of negative reward.

A similar suppression effect in MOT was described by Pylyshyn (2006) on non-target objects, or what we refer to as distractors in the current study. Using a dot probe technique similar to the one we used here, with open space probes serving as a baseline, he found that non-targets were suppressed compared to target objects during MOT. A more recent study by Renton et al. (2019) even showed attentional suppression of avoidance-relevant items, both in a concurrent approach–avoidance task and when comparing attentional selection toward task-relevant objects between separate approach and avoidance tasks. In principle, non-target objects and non-goal-related areas (e.g., the no-goal side in Experiment 4.1) share the feature of not being directly relevant for the task, and attending to them would be unnecessary and possibly detrimental. Moreover, suppressing irrelevant elements of the display might even optimize performance on the task. However, when a situation should be actively avoided (for example, a target reaching the red goal in Experiment 4.3), we might expect to see less suppression or even enhancement around this area, as it is an area of interest. Instead, we saw suppression, especially when the outcome of an event was negative. This can be explained by the timing of the probe—at the moment the object touches the wall, when a mistake can no longer be corrected—and by the fact that there are two targets to track; that is, the participant may have already moved on to a situation they can still control. It is important to note here that participants tended to prioritize scoring points over detecting probes, so their main concern was to make sure the objects hit the green goal and avoided the red goal. We should also point out here that participants were not aware of the timing of the probes.

The current study shows that event valence, in the form of achieved reward or avoided punishment, on the one hand, and missed reward or achieved punishment, on the other hand, influences the allocation of attention during object tracking. Although we do not know exactly how positively our participants experienced the given reward or how negatively they experienced the punishment used, the paradigm used in Experiment 4.3 enabled us to define a ranking with increasing levels of valence that can be compared. Our findings are in line with previous studies investigating the effects of reward on attentional control (Anderson, Laurent, & Yantis, 2011; Hickey, Chelazzi, & Theeuwes, 2010), and complement our previous findings on anticipatory allocation of attention during multiple object tracking (Atsma et al., 2012; Frielink-Loing et al., 2017; Frielink-Loing et al., 2022).

Chapter 5

Summary and Discussion

The aim of this thesis was to investigate whether and how additional stimuli and tasks presented during a Multiple Object Tracking (MOT) task would influence the allocation of attention. We were ultimately keen to find out whether attention can 'bounce' under the right circumstances, following up on the finding by Atsma et al. (2012) that attention does not 'anticipate' the bounce path of a moving object.

We started off in Chapter 2 by making the distinction between overt and covert object tracking, during both single- and multiple-object tracking tasks. By mapping participants' performance on a probe detection task to specific locations surrounding the tracked objects, similar to Atsma et al. (2012), we were able to visualize how attention is distributed around the object during tracking. The resulting attentional heatmaps clearly showed patterns indicative of anticipation (or 'attending ahead'), with increased allocation of attention ahead of the object, for both overtly and covertly tracked objects during single-object tracking. During multiple-object tracking, we only saw such an anticipatory pattern appear around covertly tracked objects, but not overtly tracked objects. These results indicate that the distribution of attention can be independent of eye movements, and 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.

In this chapter, we used measurements of probe detection performance to map the distribution of attention around tracked moving objects, and found that, especially for covertly tracked objects, probe detection was relatively low within and close to the object, and was significantly higher in the area surrounding the object (see *Figures 2.4* and *2.6*). Moreover, the attentional distribution in the outer ring showed a clear pattern of anisotropy. Although the relatively low probe detection close to the object may have been the result of a suppression effect, this is a clear indication that attention extends beyond the visual bounds of an object, providing evidence for a combination of object- and space-based attention. This formed an important premise for Chapters 3 and 4, where we investigated whether we could induce a spatial shift of this object-linked attentional spotlight in anticipation of a change in direction.

In Chapter 3, we took the task that led Atsma et al. (2012) to their conclusion that 'attention doesn't "bounce"', and created a variation that required active engagement to the task, essentially changing 'viewers' into 'players'. Comparing probe detection performance of both bounce and linear probes from these active participants with the performance of passive viewers, we concluded that the task of actively manipulating the scene can actually pull attention towards the bounce path of a tracked object. Moreover, the enhanced attention towards the bounce path during the active task did not happen at the expense of attentional resources being directed towards the linear path, but rather seemed to come from an additional boost in attention directed towards the tracked object's future path.

Finally, in Chapter 4 we created even more context by adding goals – post-bounce areas where the objects should go (or which should be avoided) in order to score points. In two experiments, participants could manipulate the location of the goal in order to 'catch' the objects, while in a third experiment participants manipulated the object's trajectory itself. Even though the results did not reveal the expected attentional shift towards the bounce path of a tracked object, which we did see in Chapter 3, there was an attentional shift towards the location of the goal. What's more, when an area had to be avoided there was a clear attentional suppression around objects moving towards this area, indicating that tracked objects that move towards a location of negative valence are suppressed, similar to the suppression of distractor objects found in earlier studies (cf. Pylyshyn, 2004/2006).

Anticipation is a key component in our investigations. MOT was classically used with unpredictable motion, where objects randomly changed direction every few frames. However, without predictability there is little to anticipate. In the real visual world things mostly move in a predictable way due to all kinds of physical laws – inertia, friction, reflection and many other rules and effects apply to all objects that have a mass and a surface – but also due to the laws that we set as humans, such as traffic rules. The fact that feinting moves are so effective to trick an opponent in sports already shows how much we rely on this predictability. This is why in all experiments described here we chose to use predictable motion in our stimulus designs.

All experiments in this thesis were based on the Multiple Object Tracking paradigm, or MOT, which has proven to be a powerful tool for the investigation of all kinds of attention-related phenomena. It is a paradigm that can easily be adapted, for example by changing the size or shape of the objects (Scholl, Pylyshyn & Feldman, 2001), adjusting motion speed (Alvarez & Franconeri, 2007), or manipulating the way the objects move across the screen (Yantis, 1992). Adding obstacles and extra tasks also works quite well with MOT, as we've demonstrated in this thesis. However, as with any experimental paradigm, adaptations need to be made with care, and the added degrees of freedom must be taken into account when analysing the data. Such adjustments also make it difficult to directly compare performances on different variations of the paradigm. For example, there is a clear difference in average probe detection performance between Experiment 3.2 and Experiment 4.1, presumably caused in large part by the more challenging task in the latter which also directed some attention away from the probing 'hot spot' near the central wall in the display.

This inter-experiment variation comes on top of the relatively large variation in performance we see between participants within the same experiment, both on object tracking and probe detection. Object tracking performance for individual participants almost always covered the full range between chance level (50% in all experiments discussed here) and 100%, on each experiment, and sometimes even dropped below chance, while overall probe detection performance could range between 0% and 90% for individual participants within a single experiment. Some participants had incredible difficulty keeping track of the target objects, while others found it very easy. Some could not see the probes appearing on the screen unless we would freeze the screen and point them out during practice trials, while others would detect almost every probe under normal experiment conditions. Thresholding for probe saliency was considered as an option to get the variance on probe detection down. However, there are multiple factors that could affect detectability of probes in these tasks, and while one person would profit from a minute change in probe size, another could benefit more from a slightly longer presentation time but would require a much larger change in size to achieve the same effect. This is why the decision was eventually made to avoid introducing such complex variations.

The reader might ask why we did not just track eye movements. Although eye fixations are often equated with directing visual attention, tracking eye movements will only tell part of the story – overt attention can be measured this way, but not covert attention. Because we investigated divided attention in a dynamic setting, which is intrinsically (partly) covert, one cannot rely on measurements of eye movements. In fact, the proportion of overt orienting towards each individual object during tracking automatically decreases as the number of target objects that need to be tracked increases, given that we are not able to fixate on multiple, spatially separated objects at the same time (unless they move very close to each other). The combination of MOT and probe detection has therefore instead provided a reliable method to measure and map attention in situations where covert tracking dominates (Alvarez & Scholl, 2005; Atsma et al., 2012; Flombaum et al., 2008). Despite the variations in performance discussed above, the effects demonstrated throughout this thesis were strong enough to show significant differences between conditions.

In accordance with previous findings (Alvarez & Scholl, 2005; Atsma et al., 2012; Iordanescu et al., 2009), we have provided evidence for a form of attentional orienting that is not entirely object-based but also not entirely space-based. What we have measured here are attentional resources that are dynamically allocated to the space surrounding an object, moving along with it and attuning to things that might be relevant to the movement of the object or an additional task, such as an upcoming change in direction or another object. These dynamic changes in allocation may be necessary for reliable object tracking, to have a prediction of where the object will probably be a moment later while we switch our gaze to another tracked object. Alternatively, they might aid in performing an additional task, for example to predict the outcome of a certain action as in Experiment 4.3. In either case, attention sticks to an object, but is not bound by the object's visual boundaries nor does it hold a fixed shape. Rather it fans out or zooms in on the object, or occupies a different location relative to the object, depending on the task at hand.

Attention remains an incredibly complex phenomenon to understand and to study, and it is clear that there is still so much to investigate. Other paradigms can be considered as well to study the role of actions and goals on attention (see e.g., Trentin, Olivers & Slagter, 2024). For the topic of attentional distribution during target tracking using an MOT task, it would be worthwhile to move towards more real-world situations, for example using traffic simulations or displaying scenes of real sports matches instead of moving abstract shapes. These situations could give much better insight into how items in a scene are naturally selected as 'targets' and how predictability plays a role in tracking. To gain better insights into how the attentional system can be trained and adapted to deal with complex tracking situations, there should be more research into how expert groups, like traffic controllers (Metzger & Parasuraman, 2006) and gamers (Green & Bavelier, 2006), divide their attention. Finally, to get a more complete picture of how attention is actually distributed over a dynamic scene without burdening participants with longer experiments, it could be very interesting to apply the P300 measure used in Farwell & Donchin's (1988) spelling brain-computer interface to probe multiple locations of the scene at once.

Conclusion

In this thesis we have shown how attentional resources are allocated in varying ways depending on the task at hand, revealing the incredible flexibility of the visuo-attentional system. Covert attention is consistently concentrated ahead of a tracked object's motion path, whereas overt attention is not (Chapter 2). Active manual interaction with task-relevant objects leads to increased attention along the object's post-bounce path as an object interacts with an obstacle, whereas passive viewing does not elicit such an anticipatory shift (Chapter 3). And finally, attention is attracted to reward goals as tracked objects move towards them, but oppressed as objects move towards a forbidden section (Chapter 4). Given these findings, it can be said that tasks that involve multiple object tracking demand continuous modulation of attention, anticipating the object's future path when necessary, based on the complexity of the situation such that it can facilitate choosing the right actions to successfully perform the task at hand.

Appendices

References

Dutch Summary

Research Data Management

About the author

Donders Graduate School

Acknowledgements

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Samenvatting

Voor dit proefschrift heb ik onderzoek gedaan naar het fenomeen aandacht, specifiek naar hoe mensen hun aandacht in het visuele veld verdelen over meerdere bewegende objecten tegelijk. Hieronder volgt een beknopte samenvatting van de verschillende experimenten die wij hiervoor hebben uitgevoerd en onze bevindingen die tot dit proefschrift hebben geleid. Allereerst zal ik het hoofdbegrip aandacht en enkele andere basisbegrippen kort inleiden.

Wat is aandacht?

Hoofdstuk 1 van dit proefschrift geeft een uitgebreide wetenschappelijke inleiding van het fenomeen aandacht. Aandacht is een mechanisme dat wij in het dagelijks leven vaak voor lief nemen. We merken het meteen wanneer het niet goed werkt, zoals bij ADHD, of wanneer je iets probeert te doen terwijl je heel moe bent. Maar als ons aandachtsmechanisme helemaal niet zou bestaan, zouden we helemaal niets meer kunnen. Alle sensaties zouden ongefilterd en op volle sterkte binnenkomen. Je hersenen zouden alles dat je ziet en hoort tegelijk proberen te verwerken. Stel je eens voor dat je dan door een stad als New York of Mumbai zou moeten navigeren!

Dankzij aandacht kunnen we ons concentreren op de dingen die belangrijk zijn, en uitfilteren wat niet belangrijk is. Aandacht zorgt ervoor dat alleen datgene dat op dit moment belangrijk is helemaal wordt verwerkt. De rest komt nog steeds wel binnen, maar wordt alleen op een lager niveau verwerkt. Deze achtergrondruis kan soms wel 'inbreken', de aandacht opeisen, bijvoorbeeld een heel hard geluid, een onverwachte flits, of wanneer je in het geroezemoes op een feestje ineens je naam hoort. Maar we kunnen door die ruisonderdrukkende functie van aandacht zelfs hele bijzondere dingen missen. Dit wordt heel mooi geïllustreerd in de Monkey Business Illusion (zie hoofdstuk 1).

Aandacht kan dus goed selecteren, maar het heeft ook een versterkende functie, die ook weleens wordt vergeleken met een spotlight. Wanneer je ergens aandacht voor hebt, vallen je meer bijzonderheden aan datgene op dan wanneer je er niet specifiek aandacht aan schenkt. Je zult bijvoorbeeld eerder opmerken dat een auto zijn knipperlicht aan zet wanneer je je aandacht op die auto gericht hebt dan wanneer je je aandacht ergens anders op richt.

Enkele basisbegrippen uitgelegd

Waar je je aandacht op gericht hebt hoeft niet per se gelijk te staan aan waar je op dat moment naar kijkt. We maken onderscheid tussen *overte* aandacht, wanneer

*

je zowel je blik als je aandacht op iets richt, en *coverte* aandacht, wanneer je je aandacht ergens op richt zonder er naar te kijken. Denk bijvoorbeeld aan een potje voetbal, waarbij je je oog op de bal wilt houden, maar ook de andere spelers in de gaten moet houden.

Het is dus ook mogelijk om je aandacht op meerdere dingen tegelijk te richten. Een methode geïntroduceerd door Ron Storm en Zenon Pylyshyn in 1988, genaamd Multiple Object Tracking (*MOT*), heeft dit heel mooi kunnen aantonen. Zij lieten mensen kijken naar een scherm waarop een aantal identieke vierkantjes zigzag door elkaar bewogen. Deze proefpersonen kregen de opdracht om een aantal van deze vierkantjes specifiek in de gaten te houden. Hieruit bleek dat men zeker wel vier objecten tegelijk kan volgen zonder ze kwijt te raken, zelfs al zijn ze omgeven door een aantal andere, identieke objecten. In dit type experimenten noemen we de te volgen objecten *targets*, en de overige objecten noemen we *distractors*.

In ons eigen onderzoek zetten we deze *MOT*-methode in om een beeld te krijgen van waar men de aandacht op richt tijdens het volgen van objecten. Omdat alle objecten identiek zijn, vereist het volgen en voortdurend onderscheiden van een subset hiervan (de *targets*) een tactische verdeling van aandacht. We maken gebruik van de eerdergenoemde spotlight-functie van aandacht om precies in kaart te brengen hoe deze verdeeld is door middel van het kort tonen van probes: piepkleine, moeilijk te detecteren puntjes. Door deze veelvuldig op specifieke locaties rondom de verschillende bewegende objecten te tonen en de deelnemers te vragen op een knop te drukken wanneer zij zo'n *probe* waarnemen, kunnen we een soort hittekaart construeren. Plekken waar *probes* vaak worden gedetecteerd zitten meer in de spotlight dan plekken waar *probes* veel minder vaak worden gezien. Plekken waar probes vaak worden gedetecteerd krijgen van ons op de hittekaart een rode kleur. Plekken waar probes minder vaak worden gedetecteerd krijgen een blauwe kleur (zie bijvoorbeeld Figuur 2.4, in hoofdstuk 2).

Door *MOT* en *probe detectie* met elkaar te combineren, hebben wij de verdeling van aandacht in verschillende situaties in beeld kunnen brengen met behulp van zo'n hittekaart.

Experimenten en bevindingen

In hoofdstuk 2 laten we zien dat tijdens *covert* volgen van *targets* de aandacht een beetje voor het object uit ligt. Deelnemers doorliepen drie verschillende scenario's in willekeurige volgorde. In het eerste scenario volgden zij één enkel *target* met hun ogen (*overte* aandacht). In het tweede scenario volgden zij één *target* met alleen hun aandacht (*coverte* aandacht) terwijl zij hun blik gefixeerd hielden op het midden van het scherm. In het derde scenario moesten twee *targets* worden gevolgd, waarbij het ene target *overt* moest worden gevolgd en het andere *covert*. In alle scenario's waren er evenveel *distractors* als *targets*, en hadden de deelnemers de taak om zowel de *target(s)* te volgen als *probes* te detecteren. Vervolgens brachten wij in kaart hoe vaak *probes* werden gedetecteerd op verschillende plekken ten opzichte van de bewegingsrichting van ieder *target* (zie Figuren 2.4 en 2.6). Hierbij zagen we dat aandacht bij *covert* gevolgde targets, zowel in het scenario met één *target* als in het scenario met twee *targets*, een eindje voor het bewegende object uit ligt. Bij *overt* gevolgde objecten lag de spotlight veel meer op het object zelf, vooral wanneer maar één *target* gevolgd hoefde worden. Deze patronen impliceren dat, wanneer minder vertrouwd kan worden op pure visuele informatie, er meer gebruik wordt gemaakt van additionele informatie, zoals de bewegingsrichting van het object waarop geanticipeerd kan worden.

In hoofdstuk 3 zien we dat het 'vooruitkijkend' patroon uit hoofdstuk 2 sterker is wanneer een deelnemer een actieve taak heeft in het beïnvloeden van waar de objecten naartoe bewegen. We deelden de deelnemers op in een actieve groep en een passieve groep. De actieve deelnemers kregen de opdracht om niet alleen twee *targets* te volgen, maar ook met de pijltjestoetsen op het toetsenbord een balkje in het midden van het scherm op en neer te bewegen om de *targets* er zo vaak mogelijk vanaf te laten kaatsen. Op het scherm bevonden zich ook weer twee identieke *distractors*. De bewegingen van het balkje en de objecten op het scherm werden opgenomen, en deze opnames werden getoond aan de groep passieve deelnemers. Zij hoefden enkel de *targets* te volgen, en als tegenhanger van de actieve taak van de andere groep bij te houden hoe vaak een target van het balkje af kaatste. Beide groepen kregen tijdens de taak ook weer de opdracht *probes* te detecteren, die deze keer altijd werden getoond wanneer een *target* tegen het balkje aan botste. Soms verschenen ze op een plek waar het *target* heen zou zijn gegaan als het dwars door het balkje heen had gekund (deze noemen we *lineair*), en soms op een plek waar het *target* uiteindelijk echt naartoe stuiterde (deze noemen we *bounce*). Hierbij bleek dat de passieve deelnemers vaker *lineaire probes* zagen dan *bounce* probes, ondanks het feit dat het *target* nooit door het balkje heen kon gaan en de *lineaire probes* dus altijd op een plek verschenen waar het *target* nooit zou komen. Daarentegen zagen de actieve deelnemers wel vaker *bounce probes* dan *lineaire probes*. Hieruit concluderen we dat actieve deelnemers meer rekening houden met waar het object naartoe gaat, en dus beter anticiperen op het traject dat het object gaat volgen. Anders gezegd, ons aandachtssysteem kan beïnvloed worden door de acties die van ons verwacht worden in een bepaalde taak.

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In hoofdstuk 4 laten we zien dat aandacht nog verder vooruit kan worden getrokken wanneer er tijdens een actieve taak, zoals beschreven in hoofdstuk 3, ook nog moet worden gezorgd dat *targets* naar een bepaald doel bewegen. Hiervoor hebben we verschillende experimenten uitgevoerd waarbij deelnemers door slim te spelen punten konden verdienen met het raken van doelen. De doelen bevonden zich altijd aan de rand van het scherm, maar de probes werden al getoond wanneer de *targets* een lijn in het midden van het scherm raakten, zoals in hoofdstuk 3. De resulterende patronen in *probe detectie* laten niet zozeer een verschil zien tussen *bounce* en *lineaire probes*, maar tonen wel aan dat het doel zelf veel aandacht trekt, dus dat het gebied tussen het *target* en het doel, ongeacht of het *target* ook echt richting het doel zal gaan, relatief veel aandacht krijgt. Daarnaast zien we dat, wanneer er een negatief doel wordt toegevoegd waarmee punten kunnen worden verloren, aandacht juist sterk kan worden onderdrukt. Hiermee is wederom de enorme flexibiliteit en taakafhankelijkheid van ons aandachtssysteem aangetoond.

Conclusie

Bovenstaande resultaten laten zien dat het anticiperend vermogen van ons aandachtsmechanisme flexibel is en op verschillende manieren wordt ingezet in uiteenlopende situaties. Aandacht kan zelfs 'meestuiteren' wanneer een gevolgd object op het punt staat van richting te veranderen, maar of dit ook echt gebeurt hangt erg af van de situatie.

Alle experimenten in dit proefschrift maken gebruik van een combinatie van dezelfde twee technieken: Multiple Object Tracking en probe detectie. Deze combinatie is een beproefde methode in onderzoek naar verschillende eigenschappen van aandacht, en biedt een krachtig middel om de verdeling van aandacht in kaart te brengen. Met de kennis uit eerdere onderzoeken konden we de taak ook stapje voor stapje verder uitbreiden om steeds complexere effecten te testen.

Een volgende stap zou zijn om een vergelijkbaar onderzoek in een 'echte wereld' situatie op te zetten. Het onderzoek dat in dit proefschrift beschreven staat kan een basis vormen voor dergelijk onderzoek. Denk aan een experiment waarbij deelnemers in een 3D simulatie een potje tennis spelen of verkeerssituaties naspelen – allebei situaties waarbij bewegende objecten moeten worden gevolgd en waar context een rol kan spelen in waar men de aandacht richt. Wij verwachten dat ons onderzoek een waardevolle bijdrage kan leveren aan toekomstig onderzoek naar aandacht, misschien zelfs aan de ontwikkeling van zulke 'echte wereld' experimenten, en dat daarmee de kennis over hoe aandacht werkt verder kan worden uitgebreid.

Research Data Management

This research followed the applicable laws and ethical guidelines. Research Data Management was conducted according to the FAIR principles. The paragraphs below specify in detail how this was achieved.

Ethics and privacy

This thesis is based on the results of research involving human participants, which was conducted in accordance with relevant national and international legislation and regulations, guidelines, codes of conduct and Radboud University policy. The privacy of the participants in these studies was warranted by the use of fully anonymous data. Informed consent was obtained from participants to collect and process their data for this research project.

Data collection and storage

Data for Chapters 2, 3 and 4 was collected on lab computers and immediately moved to secure network storage of the research institute after collection, either via a USB stick or via a direct connection to the secure storage facility. The data was subsequently removed from the lab computers. During processing and analysis, the data was stored on the secure network storage of the department. Raw data chapters 3 and 4 has been archived in separate Data Acquisition Collections (DACs) on the Radboud Data Repository. Processed data, scripts and additional documentation for these chapters are archived in separate Research Documentation Collections (RDCs) on the Radboud Data Repository.

Informed consent was obtained on paper following the procedure of the faculty and were archived in the central archive of the institute for 10 years after termination of the studies.

Data sharing according to the FAIR principles

The anonymous, processed data, as well as programming scripts for data collection and processing from Chapters 2, 3 and 4 have been made available through Data Sharing Collections (DSCs) on the Radboud Data Repository. All datasets are accompanied by a readme-file with information about the research project and a description of the files present in the dataset. All data has been made available in open access and will remain available for at least 10 years after publication. The table below details the persistent identifiers and applicable licenses for the data and research documentation of each chapter.

Ch.	DAC	RDC	DSC	DSC License
2			https://doi.org/10.34973/24z2-km86	RU-DI-HD-1.0
3	https://doi.org/10.34973/5wxh-c679	https://doi.org/10.34973/bqmj-4q80	https://doi.org/10.34973/vk25-yx32	CC-BY
4	https://doi.org/10.34973/zsdx-5402	https://doi.org/10.34973/hvpv-k427	https://doi.org/10.34973/3rt3-hy44	CC-BY

DAC = Data Acquisition Collection, RDC = Research Documentation Collection,
DSC = Data Sharing Collection

About the author

Andrea Frielink-Loing was born in Tilburg, the Netherlands, on 14 March 1986. In 2004 she moved to Nijmegen to study Molecular Life Sciences at Radboud University, but did not finish the Bachelor's. Instead, after a brief hiatus, she started a Bachelor's in Artificial Intelligence in 2007 from which she graduated in 2010 with a thesis on learning a new language through subtitles. This was followed by a Research Master's in Cognitive Neuroscience at the Donders Institute in Nijmegen, with a specialization in Perception, Action and Control. For her Master's thesis under supervision of Rob van Lier, Arno Koning and Floris de Lange, she investigated the modulation of neural activity in category-selective regions, such as the Fusiform Face Area and the Parahippocampal Place Area, by both subjective and physical disappearance of images.

After a brief period working as a business engineer at IT-company Blueriq (then: Everest), Andrea started a PhD under supervision of Rob van Lier and Arno Koning on the topic of anticipatory attention in 2014. She finalized her PhD thesis in 2025.

During the end of her PhD contract, Andrea started working as a research data project officer at the Donders Center for Cognition, supporting researchers in part of their research administration and data management. In 2020 she started working as a Data Steward at Radboudumc.

Andrea currently lives in Malden, the Netherlands, with her husband Jens and their two sons, Seb and Brenn.

Donders Graduate School

For a successful research Institute, it is vital to train the next generation of scientists. To achieve this goal, the Donders Institute for Brain, Cognition and Behaviour established the Donders Graduate School in 2009. The mission of the Donders Graduate School is to guide our graduates to become skilled academics who are equipped for a wide range of professions. To achieve this, we do our utmost to ensure that our PhD candidates receive support and supervision of the highest quality.

Since 2009, the Donders Graduate School has grown into a vibrant community of highly talented national and international PhD candidates, with over 500 PhD candidates enrolled. Their backgrounds cover a wide range of disciplines, from physics to psychology, medicine to psycholinguistics, and biology to artificial intelligence. Similarly, their interdisciplinary research covers genetic, molecular, and cellular processes at one end and computational, system-level neuroscience with cognitive and behavioural analysis at the other end. We ask all PhD candidates within the Donders Graduate School to publish their PhD thesis in de Donders Thesis Series. This series currently includes over 750 PhD theses from our PhD graduates and thereby provides a comprehensive overview of the diverse types of research performed at the Donders Institute. A complete overview of the Donders Thesis Series can be found on our website: https://www.ru.nl/donders/donders-series

The Donders Graduate School tracks the careers of our PhD graduates carefully. In general, the PhD graduates end up at high-quality positions in different sectors, for a complete overview see https://www.ru.nl/donders/destination-our-former-phd. A large proportion of our PhD alumni continue in academia (>50%). Most of them first work as a postdoc before growing into more senior research positions. They work at top institutes worldwide, such as University of Oxford, University of Cambridge, Stanford University, Princeton University, UCL London, MPI Leipzig, Karolinska Institute, UC Berkeley, EPFL Lausanne, and many others. In addition, a large group of PhD graduates continue in clinical positions, sometimes combining it with academic research. Clinical positions can be divided into medical doctors, for instance, in genetics, geriatrics, psychiatry, or neurology, and in psychologists, for instance as healthcare psychologist, clinical neuropsychologist, or clinical psychologist. Furthermore, there are PhD graduates who continue to work as researchers outside academia, for instance at non-profit or government organizations, or in pharmaceutical companies. There are also PhD graduates who work in education, such as teachers in high school, or as lecturers in higher education. Others continue in a wide range of positions, such as policy advisors, project managers, consultants, data scientists, web- or software developers, business owners, regulatory affairs specialists, engineers, managers, or IT architects. As such, the career paths of Donders PhD graduates span a broad range of sectors and professions, but the common factor is that they almost all have become successful professionals.

For more information on the Donders Graduate School, as well as past and upcoming defences please visit:

http://www.ru.nl/donders/graduate-school/phd/

Acknowledgements

This is the hardest part to write of this entire thesis, and for that reason also the part I'm writing last. I wish I had written it sooner, because I know I'm going to forget to thank people who do deserve it. If you are reading this and you are disappointed at not finding your name, please know that it doesn't mean I'm not grateful for you being part of my life.

I want to start off thanking my supervisors, **Rob** and **Arno**. I can't believe you stuck with me all these years. Not just the eleven years spent on my PhD, because our journey together already started before that, during my Master's. Without your never-ending support, I wouldn't have been able to make it this far. There were times I thought about quitting, because I simply couldn't find the energy and time to work on my thesis while juggling a new job and a household with two kids, and also trying to spend some time on my hobbies. You were always there to pull me out of these moments of doubt, to cheer me on, to push me so I would make it to the finish. I made it, guys. Thanks to you.

Tessa, thank you for sharing an office with me for four years. I'm happy we could share so many stories and experiences, having both become moms during our time at the Donders. I couldn't have asked for a better office mate, thank you. And now you're on my manuscript committee, how cool is that!

Vanessa, **Jolanda** and **Karin**, thank you for all your support in figuring out all the administrative stuff that comes with having a real grown-up job. And thank you more for all the laughs, all the talks, all the jokes, and all the love. I spent far too much time at your desks, but it was worth it.

Thank you **Miriam** and **Maaike**, for giving me an opportunity to discover how important and fulfilling research support is. Working with you prepared me for the work I do now, and hope to do for a long time.

Thanks also to all the other people who passed through the Perception and Awareness lab, in particular **Xuyan**, **Chayada**, **Yagmur**, **Simon-Jan** and **Jordy**. Thank you for all the great presentations, discussions, the sharing of knowledge, and of course also all the fun, laughs and great conversations.

Thanks to my fellow PhD representatives, with a special shout-out to **Ricarda**, **Jana**, and **Marpessa**.

I also want to thank all the other people whose offices I frequented, regularly ran into at the coffee machine, and had the occasional lunch with. This is where I will definitely forget to name people, because it's been a while. **Miles**, **Nynke**, **João**, **Suhas**, **Willeke**, **Max**, **Katrin**, and everyone else at the DCC, thank you!

And of course, my wonderful paranymphs, **Wendy** and **Jordy**! Of course I can never forget you! Thank you for the fun, the lunches, the nerding, the amazing friendship and the love! Whatever happens, you guys will always be dear to my heart.

Natuurlijk wil ik ook iedereen bedanken die het leven buiten werk fijn en mooi heeft gemaakt. Popkoor **Switch** en **Wired Voices**, zonder muziek is er geen leven, bedankt dat ik bij jullie mijn creativiteit kwijt kon en kan.

De **Dexters**, ik hou van jullie, wat heerlijk dat we altijd weer bij elkaar kunnen komen, ook na elkaar meer dan een jaar niet te hebben gezien, en het toch altijd fijn en gezellig is. De **Strabrechters**, in het bijzonder **Jesper** en **Eva**, jullie zijn geweldig.

Familie **Loing** en **Marcelis**, wat fijn om zo'n hechte familie om me heen te hebben die lief en leed met elkaar deelt. Mijn **schoonfamilie**, bedankt voor al jullie steun en jullie interesse in wat ik doe (de vraag 'hoe gaat het eigenlijk met je PhD' was een vast onderdeel op verjaardagen de afgelopen jaren).

Pap, **mam**, jullie hebben mij mijn hele leven altijd gesteund in wat ik doe. Ik hoop dat ik hetzelfde geduld en vertrouwen kan geven aan mijn eigen kinderen. Zonder jullie was dit alles sowieso nooit gelukt. 'Dankjewel' is niet voldoende. Ik hoop dat jullie weten hoe belangrijk jullie voor mij zijn en hoeveel ik van jullie houd.

Jens... wat zal ik zeggen? Jouw niet-aflatende steun en vertrouwen waren essentieel om dit punt te bereiken. Je moedigde me aan om op Ton af te stappen om hem te vragen of ik mijn bachelorscriptie bij hem mocht doen. Dit wakkerde mijn interesse in onderzoek aan. Je steunde me toen ik koos voor de CNS Master. Je stond achter me toen ik mijn goede IT-baan (met leasebak) inruilde voor een PhD. Je gaf me de tijd om aan mijn thesis te werken toen ik alles in mijn eigen tijd moest doen, ook toen ons leven steeds voller en drukker werd. Nu ik dit boek eindelijk (letterlijk) kan afsluiten, komt er weer meer ruimte om te genieten van ons prachtige gezinnetje.

Seb en **Brenn**, jullie hebben op dit moment nog geen idee wat dit alles inhoudt, maar dat komt nog wel, mijn slimme mannekes. Jullie geven kleur aan het leven, en zo ontzettend veel liefde. Ik hou van jullie.

*

Oh ja, en onthoud: papa is misschien wel de grappigste thuis, maar mama is de slimste. Ik kan het bewijzen.

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