Review TRENDS in Cognitive Sciences Vol.xx No.xx Monthxxxx

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Tracking multiple targets with multifocal attention

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Attention allows us to monitor objects or regions of visual space and select information from them for report or storage. Classical theories of attention assumed a single focus of selection but many everyday activities, such as video games, navigating busy intersections, or watching over children at a swimming pool, require attention to multiple regions of interest. Laboratory tracking tasks have indeed demonstrated the ability to track four or more targets simultaneously. Although the mechanisms by which attention maintains contact with several targets are not yet established, recent studies have identified several characteristics of the tracking process, including properties defining a 'trackable' target, the maximum number of targets that can be tracked, and the hemifield independence of the tracking process. This research also has implications for computer vision, where there is a growing demand for multiple-object tracking.

Multiple target tracking has become a very active area of research not only in human vision but also in computer vision where there is a growing demand for tracking vehicles from surveillance cameras, people in airports, and interactions between people to infer their activities [1,2]. To date, there is little interchange between these two lines of research but future advances should bring the two areas into greater contact.

Tracking by humans relies critically on attention [3,4] but, classically, visual attention selects information from only one location [5–10], acting like a second fovea that roams the visual field independently of eye movements. In 1988, Pylyshyn and Storm [11] convincingly overturned this single focus view by demonstrating continuous tracking of multiple targets (also see Box 1). Their experiments used arrays of identical items that moved within a rectangular area, bouncing off the borders and each other. At the beginning of a trial, some of the items were marked briefly as the targets and they then reverted to being identical to the other items (Figure 1). All items then moved randomly within the target area for the next 7–15 s. To measure performance at the end of the trial, a single item was probed and observers reported whether or not it was a target item. Most subjects were able to keep track of as many as 4 or 5 targets over several seconds. Subjects could not use eye movements alone to follow these multiple targets. Nor could a single focus of attention select a broad region containing the targets without also picking up the distractors in that region. Subject were performing as if more than one focus of attention were available, one to follow each target (Figure 2).

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Models of multiple-object tracking

Several models for multiple-object tracking have proposed since Pylyshyn and Storm first reported their results and five of these are described briefly here: grouping, attention switching, multifocal attention, preattentive indexes (FINSTs), and object files (see [12] for a more detailed review of these models). The grouping and switching proposals require only a single focus of attention. Yantis [3], for example, suggested that all the targets are grouped into one higher order object with each target a vertex in a virtual polygon. Tracking this one changing shape would then require only a single attentional channel. When targets share some common motion [3], they group more strongly and tracking becomes easier. This demonstrates that redundancy in the targets can be exploited by the observer but it is not evidence that grouping is the mechanism of tracking for independently moving targets.

A switching model [3,11,12] also requires only one focus of attention but it must cycle rapidly through the targets, indexing their locations and returning to each before it moves too far away. As attention revisits each remembered location, the nearest item would be taken as the new

Box 1. Learning visual attention

Can we improve our attention skills? Many team sports, video games, and military activities require participants to track multiple targets. A recent study shows that air traffic controllers have higher tracking capacity than undergraduates [4]. Some professional athletes also appear to have exceptional tracking skills. The ice-hockey champion, Wayne Gretzky, for example, was said to keep track of all the players on his and the opponents' team. Do professional sports select for individuals born with exceptional attention skills or do these athletes develop the skills because of extensive practice? Recent research on the effects of playing video games suggests that we may in fact be able to increase our visual attention abilities with certain types of training. Green and Bavelier [46] have shown that video-game players have greater attentional capacities than non-video-game players. They can process information faster and apprehend more information at a glance. They require less in attentional resources for a given target and they have smaller zones of interaction where targets and non-targets would interfere. This advantage for video-game players does not simply reflect a self-selection bias, as non-video-game players trained on a first-person, action video game improved their attention scores with as little as ten hours of playing [46].

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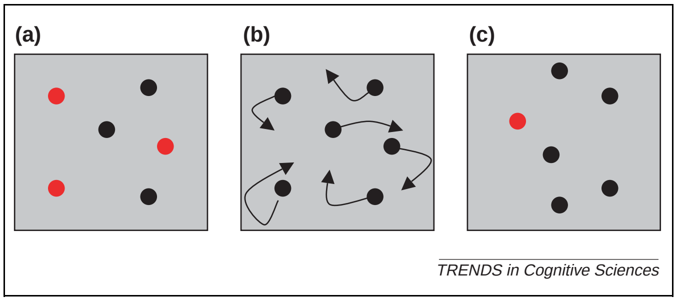

Figure 1. Multiple-object tracking task. (a) Three of the discs are briefly marked (red) to designate them as targets for the tracking task. **(b)** All of the items, now identical, start to move randomly around the display, bouncing off of the borders and each other. **(c)** For a partial report test at the end of a trial, a single, randomly selected item is highlighted and subjects report whether it was a target or not.

position of the target, and that location would be stored for the next cycle. A recent finding of hemifield independence [13] to be discussed near the end of this review has ruled out both grouping and switching models, at least in their simplest form.

Multifocal attention assumes that each target attracts an independent focus of attention and these follow the targets as they move (Figure 2). At the end of the trial, subjects will still be attending to the same items that they began with (although now at different locations) and so can identify them as members of the original set. This strategy relies only on classic properties of attention (individuation) but requires that attention can deploy more than one focus.

Pylyshyn's FINST (Fingers of INSTantiation [11,14,15]) model, like switching, depends on indexes but these are not static locations held in memory. Once attached to a target, the index does not have to be refreshed but sticks to the targets as it moves. Pylyshyn's indexes do not require attention to maintain their contact with the targets' locations but they do serve as pointers to allow attention rapid access an object, but only one object at time. The multiple indexes of the FINSTs are clearly similar to the position tracking components of the multifocal attention model, but they differ in that attention has a single focus that is attached to at most one index at any given moment.

Kahneman, Treisman and Gibbs [16] proposed 'object files' to keep track of items of current interest and accumulate information about them as they move and change. The functions of these intermediate representations – selection, tracking, and encoding – are functions classically attributed to attention even in its earliest models [8]. In this sense, 'object files' are more explicit descriptions of the necessary bookkeeping functions of attention. Object-based attention [17,18] has the same conceptual elements as object files, individuating target objects and passing information about the object to more durable representations. If attention can be deployed to multiple objects, then clearly the information encoded for each would have to be maintained separately, as is the case with object files. Object files are therefore not an alternative model to multifocal attention, but a description of some of the constituent processes required by multifocal attention.

Evidence for multiple selection from other tasks

Other paradigms have also demonstrated multiple, spatially separate regions of attention [19,20]. For example, Awh and Pashler [21] were able to produce attentional benefits of precueing at two locations without any benefits at a central location between them. McMains and Somers [22] were able to image two separate peaks of activation in striate and extrastriate cortices corresponding to two attended locations in their task. Earlier work on search in

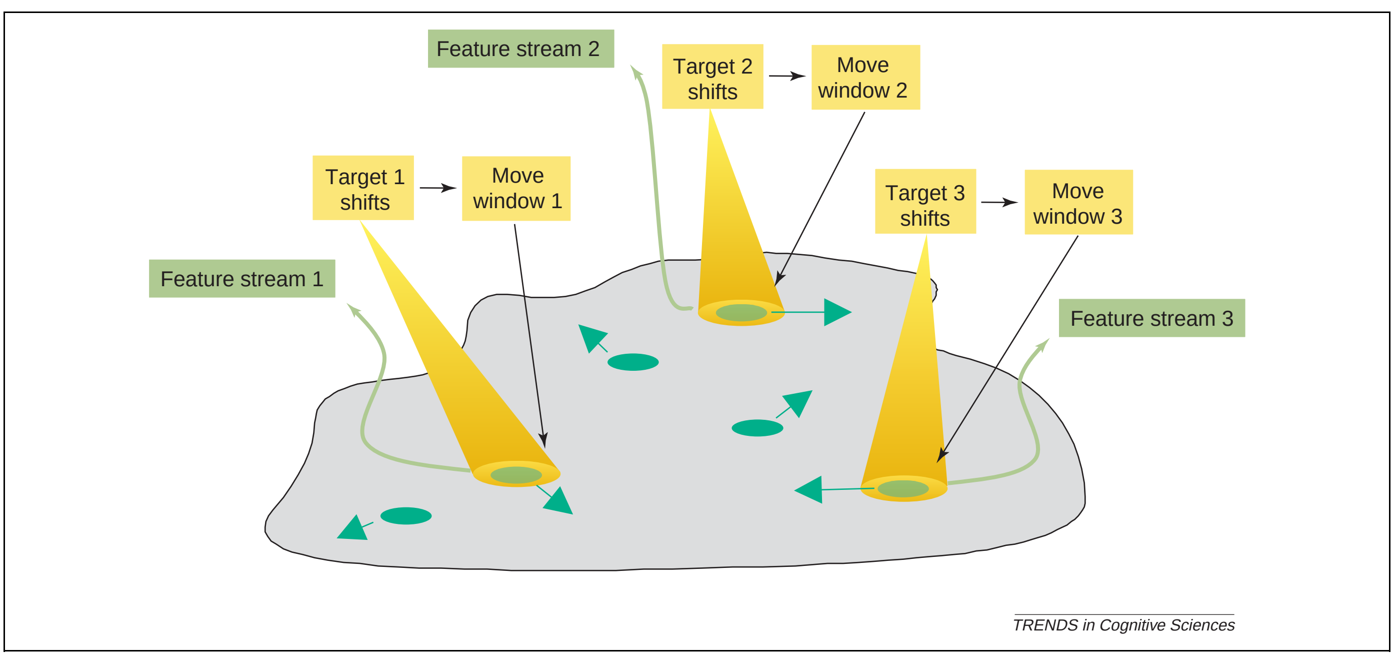

Figure 2. The multifocal model. In this model, attention maintains several streams of concurrent selection. Each target is tracked by an individual focus of attention where a control process keeps a region of selection centered over the target as it moves and an encoding stream takes information from the target and passes it on to higher processes. Three of these selection channels are shown here, each comprising a position tracker and an output stream of features. An alternative model based on attention-switching would have one selection stream that jumps sequentially from target to target. (See text for descriptions of three other tracking models: grouping, FINSTs, and object files.)

visual arrays by Fisher [23] also proposed up to 4 input channels for attention.

Tracking capacity

Pylyshyn's early results suggested that the limit for tracking independent targets was 4. A recent study [24] shows that arraying the targets in depth increases this capacity somewhat. According to Oksama and Hyona [12], however, there is a lot of variability in the tracking capacity across individuals. They tested 201 subjects and reported that the tracking capacity on trials lasting 5 s was distributed uniformly between 2 to 6, with a mean of 4 (capacity dropped for longer tracking durations). In a second experiment, subjects had to retain the identities of targets that were revealed at the start of a trial and then hidden as the items moved. They tracked between 2 and 6 items with no distractors and at the end of a trial reported the original identity of a randomly probed item. In this case, capacities were distributed in a narrower normal distribution centered at 4, a limit the authors attributed to visual short term memory rather than to tracking processes.

Capacity limits on feature encoding

Several studies have shown that the feature information available from tracked targets can be very restricted. For example, if the targets are given particular feature values like color or shape and these change at different moments during the task [25,26], these feature values are less well retained than location information. In cases where subjects are capable of accurately tracking as many as 4 items, they notice feature changes to targets only half of the time [25] despite accurate tracking. When identities do not change over time, however, subjects can retain the identities of ~4 targets during tracking [12] when there are no distractors but fewer if distractors are also present [27]. These studies suggest that continuous transfer of feature information is not an automatic consequence of tracking the targets' locations. The total selection capacity must be shared among input streams, whether they are attended concurrently (multifocal attention) or sequentially (switched attention or FINSTs). If there are several targets, they must share the available capacity and, at the limit, each will be reduced to encoding no more than the location required to perform the tracking task.

Spatial and temporal limits

In addition to the number of targets, several other factors increase the difficulty of the tracking. When targets and distractors are too close, it becomes difficult to individuate the targets and maintain tracking. This difficulty in selection of an individual item from a dense array, despite the clear visibility of the items, has been attributed to the coarse acuity of attention [28,29] or, alternatively, to obligatory feature averaging [30,31]. Because of these spacing limits on selection, tracking becomes impossible for displays spanning less than about 1/16th of a degree [29] where the dots are clearly seen but frustratingly impossible to follow. This limit to tracking is the same no matter how many targets are being tracked showing that this spatial limit is independent of the capacity limit. Targets can also move too fast to be tracked. Accurate tracking of even one target moving on a circular path breaks down for speed greater than 1 to 2 revolutions per second [32].

Attention benefits for targets

There is an advantage for detection of briefly presented probes [15] or identity changes [25] when they appear on targets rather than non-targets. This is evidence that attention is allocated to some or all of the targets and a more detailed analysis of data like these could resolve the issue. Specifically, in the switching and FINST models, attention is on only one target at a time and so the probability of a probe benefiting from attention drops with the reciprocal of the number of targets. In the multifocal model, the total capacity must be shared among the targets and the prediction is the same. The distribution of benefits will be very different in the two cases, however, but these studies did not provide this analysis. For now, the available data do not favor either type of model over the other.

What is tracked in multiple-object tracking?

Recent evidence from Scholl, Pylyshyn and Feldman [33] suggests that the basic unit of tracking is the object. They took a multiple-object tracking display where subjects could successfully track about 4 square targets among distractor squares (Figure 3a,b). They then joined the squares in target-distractor pairs so that each target was now one end of a bar shaped, extended object (see Figure 3c,d). Subjects were unable to track these same 4 target ends when they were parts of the bars. The

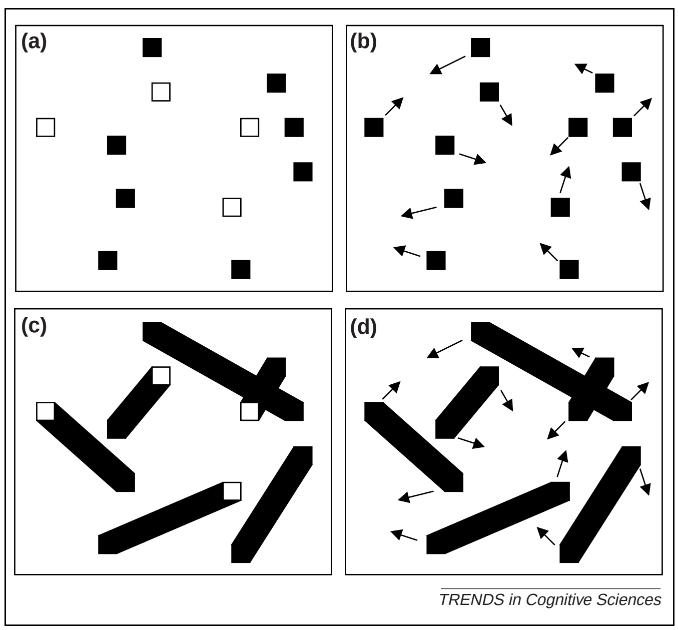

Figure 3. Object merging [33]. **(a)** Targets are briefly marked in a standard multiple-object tracking task and **(b)** followed during a trial. **(c)** In object merging, the experimental conditions have the same target locations and target and distractor trajectories as the standard trials except that items are paired and the link between them is maintained throughout the trial. Each pair has at most one target. **(d)** The tracking task is now much more difficult even though trajectories have not changed. The authors conclude that tracking whole objects is obligatory and parts of objects cannot be tracked in isolation. The joined pairs must then be tracked as a whole and, in addition, the end of the object that is the target also has to be marked.

task was harder for two reasons: (i) Apparently, the subjects could not focus solely on the end points but were obliged to follow the larger bars. The bars had more complex motions (rotations and length changes) than did the bars' end points (translation only); (ii) Subjects also had to keep track of which end of the bar was the target and the bars could occasionally rotate at speeds too fast to track [32]. The authors showed that the increased difficulty of tracking the bar endpoints could only arise if object tracking (whole bar tracking) were obligatory. The importance of object properties for tracking targets was underscored when van Marle and Scholl [34] showed that a target region that appeared to move as a flowing substance was also difficult to track.

Combining a target and a distractor together in one object [33] forced observers to track the connected distractors but Suganuma and Yokosawa [35] have shown that obligatory tracking is not limited to distractors grouped to targets in well defined objects. These authors grouped targets and distractors with common motion, where one often seemed to be 'chasing' the other. Tracking performance was degraded as if subjects were obliged to monitor the motion-linked distractors as well as the intended targets. Despite the name of the task, multiple-object tracking, the definition of a target may be broader than objects, including components that group together, a suggestion first made by Yantis [3].

Hemifield independence

Whatever the capacity for a given tracking task, a recent study shows that this capacity is split between left and right hemifields [13]. Rather than a limit of, say, 4, subjects demonstrated a limit of 2 + 2 (see Figure 4), with 2 each in the left and right hemifields. This unexpected hemifield specificity indicates that an early stage of attentive tracking could be based in the retinotopic cortical areas. Certainly, other attention-limited tasks show little or no hemifield independence in normal subjects (e.g. [36,37]), suggesting that this independence is limited to the initial steps of acquisition or tracking control. This hemifield independence does not appear to be tied to the motions of the targets in the tracking task. An advantage for displays split across hemifields is also seen in a visual memory task [38] but only for memory for spatial locations, and not for target colors. Hemifield specificity is found in the parietal lobes where fMRI studies of activation during multiple-object tracking show that sites in the inferior parietal lobule and the intraparietal sulcus are active when tracking targets [39–41]. Lesions of the parietal lobes affect tracking only on the side contralateral to the lesion [42].

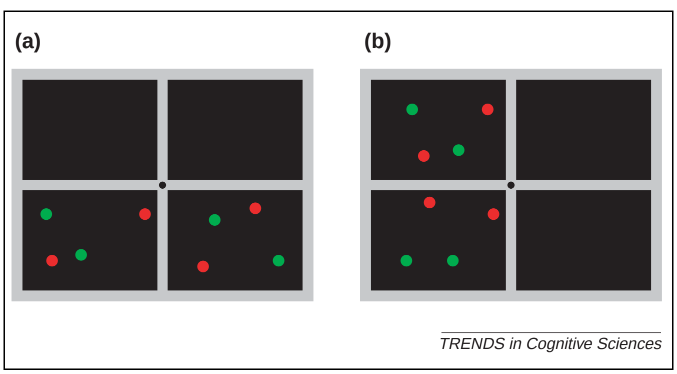

Figure 4. Tracking capacity. Two of the four panels centered at the fixation point have two targets and two distractors each. All items start to move and the red target items, both of which the subject is meant to track, change to green, indistinguishable from the distractors. The items bounce off the walls of their respective regions, never crossing the gray separators. When the two tracking tasks are in separate hemifields **(a)**, tracking is much easier than when the two regions are in the same hemifield **(b)** [13]. Tracking capacity is four items only when there are two in each hemifield.

In terms of tracking mechanisms, hemifield independence places strict constraints on strategies of attention control. The multifocal model is least affected because it already assumes independent channels of selection; the hemifield limit simply places a limit on the number of channels deployed per hemifield rather than the number for the entire visual field. The grouping model is most affected. Subjects in Yantis's experiments often reported spontaneous grouping that formed a single polygon with the targets at the vertexes, but not two polygons, one for the targets of each hemifield. Perceptual grouping is therefore ruled out as the mechanism of selection and may be, instead, a consequence of the selection of the targets by earlier, hemifield limited processes.

In the switching and FINST models, the hemifield independence result requires two separate indexing managers for target locations, one per hemifield. These models could retain a single focus of attention that is deployed to remembered (switching) or indexed (FINSTs) locations in either field as required. Note that to preserve the single focus of attention for the switching model, the capacity limit must be set by memory limitations not by speed of switching. As mentioned in the earlier section on mechanisms, the number of items that can be tracked can be limited by the speed of cycling through the remembered target locations to update them; however, the speed of switching of a single focus of attention is a truly global factor that cannot support any hemifield independence. The alternative is that tracking in an attention switching model with very rapid switching could be limited not by the speed of switching but by the memory capacity for the target locations. The tracking limit could then show hemifield independence if the location memory has separate capacities for each hemifield. Delvenne [38] has provided some evidence for this memory independence. The requirement for rapid switching is, however, at odds with the finding that attention switching over stationary targets is extremely slow (300 ms per item) [43], so a very different mechanism for switching would be required.

Advantages of studying attention with tracking tasks

In a typical attention task (e.g. [9]), subjects are given a cue indicating a region of interest and a target is then briefly presented at that location (or not, on some small proportion of trials). By contrast, in a tracking task, there are no brief events; items typically remain constant in every respect but their location and the task is to monitor that changing location, making it more akin to the real-world allocation of attention. Multiple-object tracking is also an inherently active task like many real-world activities, as opposed to the sustained but fundamentally passive vigilance required in many monitoring tasks, characteristics that more resemble the demands of tasks like police stake-outs. Tracking also allows for a disciplined control of load by varying the number of targets whereas most classic attention paradigms vary load by restricting the time available for processing (e.g. via masking or brief displays). Compared with standard attention tasks, tracking tells us how attention connects to a target and how that connection is maintained as the target changes location and in some tasks, identity. We discover not the benefits of attention but the logistics.

Tracking and visual memory

Tracking and visual memory are tightly linked and not only in the switching model which relies directly on visual memory for tracking. With attention serving as the gateway to episodic memory, attention can be described as visual memory at time zero. The attention and memory systems do show similar capacity limits and fMRI results for tracking and for visual short term memory show strong parallels. For example, there is a linear increase in the activation of the posterior parietal area as the number of items increases in visual short term memory [44]. Similarly, in a tracking task [40,41], there is a linear increase in activation of the same region (among other areas) as a function of number of targets being tracked.

Conclusion and future directions

Multiple-object tracking addresses the central question of how attention can be divided. Recent research reveals how many attention 'spotlights' or channels can be deployed, whether concurrently or sequentially, and in some tasks, the nature of the target information that can be read out from each while performing the tracking. The trade-off between capacity and feature encoding [25,26,12] suggests that attention has a fixed total bandwidth for selection and the bandwidth can be shared across several input channels or targets, depending on the model, each with little capacity for encoding, or allocated completely to a single channel or target with maximum capacity for encoding. The finding of hemifield independence identifies an early stage in selection and demonstrates the existence of at least two independent control systems underlying tracking in the two hemifields. This result rules out explanations of multiple-object tracking that rely solely on grouping of all targets into one amorphous object and places strict constraints on the FINST and switching models.

If multifocal attention holds up as the most plausible model for tracking, the implications for the architecture of attention are substantial. Compared with a single focus of attention, the control processes to deploy and position multiple channels must be significantly more complex. Moreover, post selection analyses must then integrate the information arriving on the multiple selection streams. Studies using tracking tasks promise insights into these questions (among others; Box 2) of logistics and functions of multifocal attention [45].

Box 2. Questions for future research

- Is tracking maintained by a single, switching focus of attention or by multifocal attention? Reaction time to brief probes on targets in a multiple-object tracking task should be able to make this distinction. The two alternatives predict very different distributions of reaction times as a function of the number of targets.
- A unit of attention capacity should be established for a standard task using a specific display and target sizes, and speeds. This would put the results of dual task measures of attentional load on comparable scales. The multiple-object task is a good candidate to establish this standard unit of attention.
- Tracking and visual memory are intimately connected. More studies are required to sort out the shared from the independent mechanisms of these two systems.
- The hemifield independence of attention control suggests problems for targets that cross from one hemifield into the other. The costs of the hand off of a target from one field to the other could be evaluated with performance for targets that cross the vertical meridian compared with performance for targets that cross the horizontal meridian.

Acknowledgements

We thank Steve Franconeri for helpful comments. This work was supported in part by NEI grant EY09258 to P.C. and by NRSA grant F31-MH069095–01to G.A.

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