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How Does Attention Select and Track Spatially Extended Objects? New Effects of Attentional Concentration and Amplification

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Real-world situations involve attending to spatially extended objects, often under conditions of motion and high processing load. The present experiments investigated such processing by requiring observers to attentionally track a number of long, moving lines. Concurrently, observers responded to sporadic probes as a measure of the distribution of attention across the lines. The results revealed that attention is concentrated at the *centers* of lines during tracking, despite their uniformity, and that this center advantage grew as the lines became longer: Not only did observers get worse near the endpoints, but they became better at the lines' centers, as if attention became more concentrated as the objects became more extended. These results begin to show how attention is flexibly allocated in online visual processing to extended dynamic objects.

Keywords: object-based attention, multiple-object tracking

For the last two decades, a major project in the study of visual attention has been the attempt to characterize the underlying units of attention—contrasting spatial areas, individual visual features, and discrete objects. As part of this project, a large literature on *object-based attention* has suggested that attention may often select discrete objects, spreading automatically through them and/or being constrained by their boundaries. The objects used in most object-based attention studies, however, have been limited in several respects. First, these objects have often been relatively compact, whereas many real-world objects are spatially extended. Second, as a result, object-based attention studies have often contrasted high-level categories of entities (e.g., parts and groups) but have rarely explored in detail how attention is allocated *within* spatially extended uniform objects. Third, most object-based attention studies have used paradigms (e.g., spatial cuing) that require only relatively brief bursts of attention, whereas real-world situations often call for sustained attention to objects over time and motion. Fourth, observers in object-based attention studies typically must attend to only two objects with no other competing demands, whereas real-world contexts (e.g., driving) often involve attending to multiple objects and tasks simultaneously. For all these reasons, the experiments reported here investigated a relatively unexplored question: How is attention actively allocated to multiple spatially extended objects over time in complex dynamic displays under conditions of high processing load?

Object-Based Attention

Attention seems to involve a perceptual resource that can both intentionally and automatically select—and be effortfully sustained on—particular stimuli or activities. The core aspects of attention comprise three phenomena (Pashler, 1998): (a) the fact that people can process some incoming stimuli more than others (*selectivity*), (b) an apparent limitation on the ability to carry out simultaneous processing (*capacity limitation*), and (c) the fact that sustained processing of visual stimuli seems to involve a sense of exertion (*effort*). The processes that give rise to these phenomena—which we collectively term *attention*—make visual perception a fundamentally selective process: Because of capacity limitations, and through effort, people often prioritize the processing of certain aspects of the visual world. This selection itself may often be dramatic: Several phenomena such as change blindness and inattentional blindness suggest that in many cases people are only consciously aware of the information to which they attend (e.g., Mack & Rock, 1998; Most, Scholl, Clifford, & Simons, 2005; Rensink, 2002).

To what information can attention be directed? Most traditional theories of attention either assumed or explicitly argued that attention was fundamentally spatial: Attention was characterized as a spotlight or a zoom lens that focused processing resources on whatever visual information fell within the attended spatial region (for a review, see Cave & Bichot, 1999). Such spatial models inherently ignored the structure of the attended information: The process of selection was based on an extrinsic filter, and as a result one could attend to an object, multiple objects, only parts of objects, or even nothing at all—whatever fell within the spotlight. More recent models of attention, in contrast, have stressed the

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Supplementary analyses of these experiments and sample movies are available online at http://www.yale.edu/perception/concentration/.

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complex interplay between attention and the structure of the attended information. For example, many studies of object-based attention have demonstrated that the underlying units of attention are often discrete visual objects: Rather than spreading uniformly through a spatially defined region, attention flows more readily through individual objects and/or is constrained by their boundaries (for a review, see Scholl, 2001).

Evidence for object-based attention has come from many different types of experimental paradigms. For example, spatial cuing studies have suggested that attention will often spread automatically throughout an object even when only a part of it is cued, such that subsequent probes are detected faster and more accurately when they lie at some other noncued part of the object, as compared with spatially equidistant locations in another object (e.g., Atchley & Kramer, 2001; Egly, Driver, & Rafal, 1994; He & Nakayama, 1995; Marino & Scholl, in press; Vecera, 1994). A similar same-object advantage is seen in a class of *divided-attention* paradigms: Across many variations, observers are often able to report and compare two features faster and more accurately when they lie within the same object, compared with when the features are spatially equidistant but span object boundaries (e.g., Barenholtz & Feldman, 2003; Duncan, 1984; Lavie & Driver, 1996; Vecera & Farah, 1994). Such paradigms have often used spatially extended objects such as lines and thin rectangles (e.g., Egly et al., 1994; Lavie & Driver, 1996), but these studies have typically tested only the extreme endpoints of these objects. The object-based nature of visual attention has also been demonstrated using many other paradigms and phenomena (see Scholl, 2001).

Multiple-Object Tracking

In this article we explore the interaction of spatial and object-based attention using the *multiple-object tracking* (MOT) task (Pylyshyn & Storm, 1988). In a typical MOT task, observers initially see eight identical items. Four of these are then blinked to indicate their status as targets, after which all of the (again identical) items begin moving independently and unpredictably about the screen. When their motion stops, observers must indicate which of the eight items are the four original targets. The mere fact that participants are able to perform accurately at this task suggests a type of object-based attention, because the targets as a group are frequently spatially overlapped with the distractors.

MOT contrasts with most other object-based attention paradigms in several ways that make it ideal for our purposes. First, MOT requires continuous sustained attention over time rather than brief attentional shifts as in spatial cuing studies. Second, this task involves attention to multiple objects rather than focal attention to only a single object at a time. Third, MOT is an inherently active task rather than requiring sustained but passive vigilance. Fourth, whereas most object-based attention paradigms must increase the perceptual load by restricting the time available for processing (e.g., via masking or brief displays), MOT allows for more direct control of processing load by varying the number of targets and distractors. As a result, MOT allows for manipulations that unfold over more time than is available in many other paradigms. Finally, MOT yields relatively large and robust effects, making it ideal for studies that need to distinguish several different levels of performance, beyond simply demonstrating that object-based effects do or do not exist. Each of these features of MOT is utilized in the present experiments.

MOT has been used in several ways to explore what can count as an object of object-based attention (e.g., Scholl & Pylyshyn, 1999), including two studies that utilized spatially extended objects similar to those used in the present study. One such experiment used a technique called *target merging* (Scholl, Pylyshyn, & Feldman, 2001). Though observers still attempted to track multiple independently and unpredictably moving items, the nature of these items was altered so that target–distractor pairs were perceived as single objects—with a target at one end and a distractor at the other end. For example, the pair might be drawn as a simple line segment connecting the two points. Crucially, each end of a pair still moved completely independently. Tracking was greatly impaired in such conditions, despite the use of identical sets of trajectories and target selections: Observers could track individual objects but not individual *ends* of uniform objects. This result is compatible with the idea of object-based attention that spreads uniformly throughout the lines, causing observers to lose track of which end was the target.

Another MOT study (vanMarle & Scholl, 2003) also used spatially extended objects that repeatedly moved in a particular type of nonrigid motion: Each object began as a small square, which then extended gradually into a long thin rectangle, before shrinking again from the opposite direction, such that the resulting small square had moved. This type of manipulation also greatly impaired tracking, perhaps because each object's location could no longer be characterized by a single point.

The Present Study

In the present experiments we asked how attention is actively allocated to extended uniform objects over time in complex dynamic displays. To our knowledge, no previous research has directly explored this question.[1] We explored MOT using spatially extended objects, but (a) observers had to attend and track entire lines rather than only specified endpoints, and (b) each endpoint moved independently, yielding lines that periodically changed both their lengths and orientations from both ends rather than simply extending and contracting to and from a single point.

During such tracking, how is attention distributed across the lines? One possibility is that attention truly does spread uniformly without cost through such objects, as is suggested by many discussions of object-based attention. This seems implausible, however: It would be surprising to find that the spatial extent of objects had no effect on attentional capacity, such that one could attend just as effectively to every point along a long line as to a small point. Another possibility is that attention automatically spreads through long extended objects but is somehow diluted in doing so, such that attention to any part of a spatially extended uniform object is always less effective than attention to a relatively com-

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[1] The closest related research of which we are aware has used phenomena such as inhibition of return or spatial cuing to explore asymmetries in the distribution of attention based on intermediate types of object structure, contrasting cases such as the different faces of a three-dimensional cube (Gibson & Egeth, 1994), two regions of an object delineated by a curvature discontinuity (Becker & Egeth, 2000), or corners versus other parts of contours (Cole, Gellatly, & Blurton, 2001).

pact object. This also seems implausible, because it seems to have implications that run counter to everyday experiences: It certainly seems possible to attend to a small region of a long table, say, just as effectively as to a small object. Finally, it is possible that attention is not always distributed uniformly through spatially extended objects. Rather, some regions of the objects may be prioritized over others.

During the motion of the extended overlapping lines in the MOT task used here, observers also had to respond to sporadic probes, and their probe detection performance was used as a measure of the distribution of attention across the lines. In using transient probes for this purpose, we are applying the method developed by Posner and others in the late 1980s (e.g., Downing & Pinker, 1985; Posner, 1980), which has now become an especially popular method for measuring the allocation of attention. By placing the probes at different locations along each line, we were thus able to construct a map of how attention is distributed along lines with various lengths, moving at various speeds, and so forth.

In Experiment 1 we explored probe detection during MOT for extended lines, contrasting probes that appeared at the centers of lines versus near their endpoints. In Experiments 2 and 3 we explored whether some surprising nonuniformities revealed in Experiment 1 reflected automatic visual processing or higher level tracking strategies. In Experiment 4 we unconfounded relative spatial locations (e.g., points near the centers vs. ends of lines) with absolute distances. Finally, we analyzed the role of several other variables, including probe eccentricity, object velocity, display density, and object intersections.

Experiment 1: Attentional Concentration and Amplification

In this first experiment we measured the distribution of attention within uniform, spatially extended objects when those objects were tracked in an MOT task. On each trial six lines were presented, and each end of each line moved on a haphazard, independent, unpredictable path. Thus, the lines continuously changed their positions, lengths, and orientations throughout their motion. Observers were required to track a subset of three target lines, keeping them distinct from three distractor lines throughout each 20-s trial, so that they could indicate the three targets with the mouse cursor at the end of the trial. During the tracking phase of each trial, observers had to simultaneously monitor the display for momentarily presented dim gray circles that served as attentional probes (henceforth *probes*; see Figure 1). The probes appeared at sporadic intervals and were equally likely to appear on a target or a distractor, and on the center or near an endpoint of a line. (Note that endpoint probes were always inset slightly from the ends of the lines so that the local contrast was the same for center and endpoint probes; compare the insets in Figure 1a and 1b.) Sample movies can be viewed online at http://www.yale.edu/perception/concentration/.

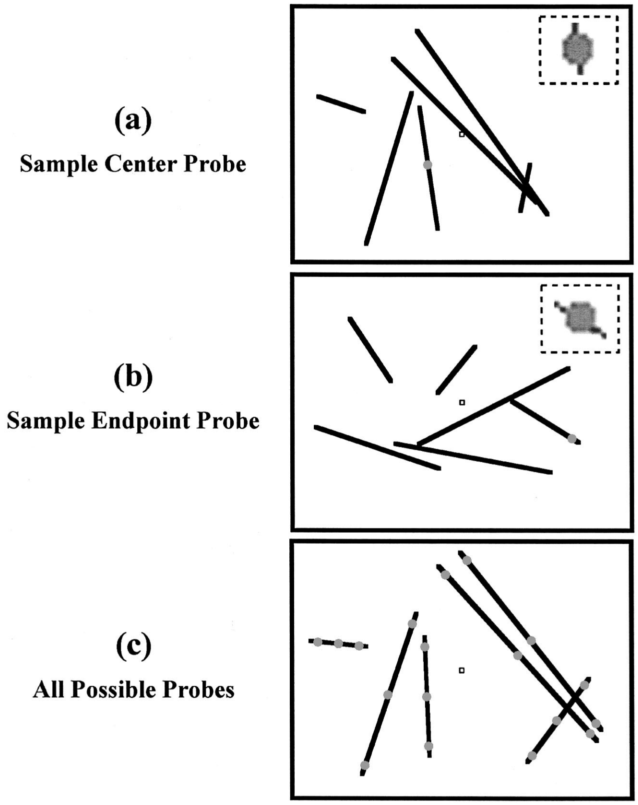

Figure 1. The concurrent multiple-object tracking and probe detection tasks used in each experiment. Observers were required to keep track of three out of six moving lines while concurrently monitoring for the appearance of gray dot probes (not drawn to scale). (The box near the center of the displays is a fixation marker.) a: A center probe trial in which a gray dot appears at the center of a line during the tracking task. The inset shows the local contrast of the center probe. b: An endpoint probe trial in which a gray dot appears near the end of a line during the tracking task. (Note that the local contrast here in the inset is identical to that for center probes). c: A single frame of a trial highlighting all possible probe positions within that frame. (Note that only one probe was presented at a time in the actual experiment).

It has been well established in previous research that shifting attention, even without eye movements, improves the detection of signals at attended locations relative to unattended locations (e.g., Bashinski & Bacharach, 1980; Muller & Findlay, 1987; Posner, Snyder, & Davidson, 1980; Solomon, 2004). Thus, the rate of probe detection is expected to be higher when the probes appeared on targets than when they appeared on distractors, given that MOT intrinsically requires tracking the targets. Critically, this technique also enabled us to determine whether attention was spread evenly throughout the objects. If so, then probe detection should be roughly equal at the centers and near the endpoints. In contrast, any difference in probe detection between these two locations would indicate a nonuniformity in the allocation of attention. Moreover, because we store the state of the display during each probe, we can explore whether the allocation of attention differs as a function of the length of the lines, their speeds, the degree to which they intersect, and several other factors. Note that the probes in this experiment simply had to be *detected*; observers did not have to identify or discriminate them in any way.

Method

Participants

In this and all experiments reported in this article, 10 observers (a different group for each experiment) participated in a 1-hr session to fulfill a course requirement or in exchange for monetary payment. All observers were naive as to the purpose of the experiment and reported having normal or corrected-to-normal acuity.

Materials

The experiment was run on a Macintosh iMac computer. Observers were positioned approximately 40 cm from the monitor without head restraint such that the display subtended approximately 39° × 31° visual angle. Displays were generated using custom software written in C using the Vision Shell Graphics Libraries (Comtois, 2005). All motion appeared smooth and continuous.

Procedure

MOT displays. On each trial, six white lines (122 cd/m^2; line thickness 1 pixel, or approximately 0.05° visual angle) were presented on a black background (0.19 cd/m^2), and a white outlined 2-pixel square frame subtending 0.6° × 0.6° was presented at the center of the display for fixation. Eye movements were not monitored, and no special instructions were given concerning fixation, since different fixation conditions have been found not to affect performance on this task.

At the beginning of each trial, 12 points within the display were chosen randomly and then connected to form six lines. Initially the lines were stationary, and three of the six lines blinked off and on to designate them as targets, disappearing for 128 ms and then reappearing for 128 ms on each of five flashes. Then 20 s of motion started in which each endpoint of each line moved on a haphazard, independent, unpredictable path. Thus the positions, lengths, and orientations of the lines varied haphazardly throughout each trial. The speed of each endpoint was initially set to between $-5°$ and $+ 5°$ per second in both the horizontal and vertical directions (maintaining an overall velocity of between 0° and 7° per second). There was some inertia to the speed of the endpoints with speed changes of ± 1.7° occurring approximately once every 250 ms. Lines were allowed to intersect each other, and the only restriction on the trajectories of the lines was that the endpoints were reflected off of the edges of the display to keep them in view.

Probe presentation. During the 20 s of motion, a variable number of round gray probe disks (approximately 28.4 cd/m^2, subtending 0.4°) were presented on the white lines. Only one probe was presented at a time, each for 215 ms. The onset of the first probe occurred at a randomly chosen moment between 2,500 ms and 6,000 ms from the start of motion. The onset of each subsequent probe occurred randomly between 2,500 ms and 6,000 ms from the onset of the previous probe, and the onset of the final probe occurred at least 1,500 ms prior to the end of motion. Thus, a maximum of seven and a minimum of three probes were presented on every trial. The location of each probe was selected randomly with the restriction that two consecutive probes could not be presented on the same line. Probes were equally likely to appear on a target or distractor, and were equally likely to appear on the center or near the endpoint of a line. Endpoint probes were actually inset from the endpoint toward the center by 0.4° visual angle (one probe diameter). The average interprobe duration was 4.14 s.

Task. Observers were instructed to keep track of the target lines during their motion, keeping them distinct from the distractors, and to monitor for the appearance of probes on targets and distractors. The instructions emphasized that observers should prioritize the tracking task and treat the probe detection task as secondary (i.e., they should not sacrifice accuracy in the tracking task to detect the probes). Observers were instructed to press a key as quickly as possible upon detecting a probe. If a keypress was not recorded within 1,250 ms after the offset of the probe, a timed-out miss was recorded. Responses prior to the appearance of the first probe, or after a response (or timeout) to the previous probe but before the appearance of the next probe, were recorded as false alarms. After the 20 s of motion, all of the lines stopped moving, and the observer used the mouse cursor to sequentially click on the three target lines. As the mouse was moved around the display, the line nearest the mouse was highlighted in green, and lines that were clicked on were marked in red. No feedback was given on tracking accuracy. After the third mouse-click on each trial the display disappeared, and the observer initiated the next trial by pressing any key.

Design. Fifty sets of trajectories were generated and stored offline. Each trajectory specified the target and distractor identities, as well as the position of each endpoint for each frame of a 20-s trial. Note that the time and location of probe appearance were not stored in these files (they were computed randomly online), and thus each individual observer tracked the same target trajectories but was presented with a different set of probes with randomly selected onset times and locations. Observers first completed 10 practice trials of the tracking task in isolation, with trajectories that were computed online, the results of which were not recorded. Then each observer completed 50 experimental trials of the combined tracking and probe detection task using the precomputed item trajectories (run in a different random order for each individual observer). An average of 3.89 probes were presented per tracking trial, yielding 135.5 *probe trials* per observer on average. In the resulting analyses, we treat these probe events as independent of which tracking trial they came from.

Results

Tracking accuracy was high, averaging 88% across all observers, which is similar to the level of performance observed in other MOT experiments (e.g., Pylyshyn & Storm, 1988; Scholl et al., 2001). Because probes were categorized according to whether they occurred on targets or distractors, the analysis of probe detection miss rates included only those trials in which observers correctly identified all three targets, thus excluding an average of 15.22 trials per observer. False alarms in the probe detection task were rare (less than 0.2 false alarms per tracking trial on average—i.e., roughly 1 false alarm every 5 tracking trials) and were not included in the analysis of probe detection miss rates. The analysis of these miss rates shows two novel effects: attentional concentration and attentional amplification.

Attentional Concentration

Overall performance was much better for center probes than for endpoint probes. Figure 2 shows probe detection miss rates for probes appearing on target centers, target endpoints, distractor centers, and distractor endpoints. As expected, miss rates were lower (better probe detection) for target probes than for distractor probes. (This main effect illustrates that our two tasks tapped shared attentional resources, because it was only the MOT task that defined some lines as targets and others as distractors.) In addition, center probe miss rates were dramatically lower than endpoint probe miss rates for both targets and distractors. These effects were confirmed by a 2 × 2 repeated measures analysis of variance (ANOVA) with probe object (target vs. distractor) and probe location (center vs. endpoint) as variables. The main effect of object was extremely reliable, $F(1, 9) = 32.72$, $MSE = 102$, $p < .001$, $\eta_p^2 = .78$, as was the main effect of location, $F(1, 9) = 39.52$, $MSE = 144$, $p < .001$, $\eta_p^2 = .81$, but the interaction was not significant, $F(1, 9) < 1$. It is important to emphasize not only the statistical significance of these effects but also the magnitude of the observed differences. For example, the average difference between target centers and target endpoints is over 25% in miss rate, which is substantially larger than the accuracy differences of

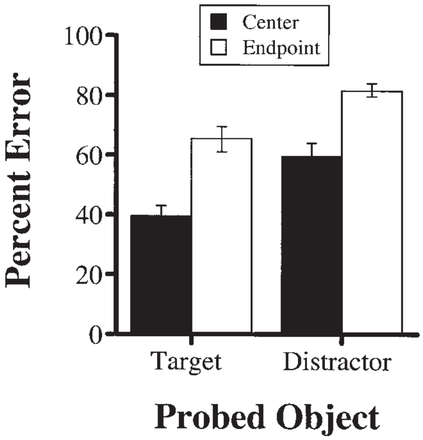

Figure 2. Probe detection performance in Experiment 1. Lower miss rates correspond to better probe detection performance. Error bars represent one standard error of the mean.

approximately 5% that are commonly found in object-based attention experiments (e.g., Duncan, 1984; Marino & Scholl, in press; Vecera, Behrmann, & Filapek, 2001; Vecera & Farah, 1994). This is important because it allows us to distinguish between intermediate levels of performance in the additional analyses reported below.

There are two confounding factors that could potentially affect these results: Center probes tended to be slightly less eccentric in the display than endpoint probes, and line centers tended to move slightly slower on average than line endpoints. Either of these factors could potentially directly affect probe detection performance and could thus provide an alternative explanation for the putative attentional concentration effect just described. In fact, however, when these factors were carefully equated across center and endpoint probes, we still observed a robust attentional concentration effect. Because these comparisons required somewhat long and detailed analyses for each of the experiments presented in this article, we provide them in the supplementary "Auxiliary Analyses" appendix (available online at http://www.yale.edu/perception/concentration/). This supplementary appendix also contains a considerable amount of detail about other aspects of this rich data set, exploring the influence of factors such as (a) the distance between probed locations and other target or distractor lines; (b) the number of target or distractor lines that intersected a probed line at the moment of the probe presentation; and (c) the influence of recent *changes* in the lengths of probed lines, beyond their absolute length at the moment of the probe presentation.

Attentional Amplification

We further explored the extent to which the difference in miss rates for centers and endpoints is related to tracking spatially extended lines by examining the effect of line length on probe detection accuracy (see Figure 3). The trials were binned into four categories of line length: less than 150 pixels (10.7°), between 150 and 300 pixels (10.7° and 21.4°), between 300 and 450 pixels (21.4° and 32.1°), and greater than 450 pixels (32.1°). As line length increased, detection accuracy at the endpoints decreased, as expected. Surprisingly, however, the converse was true for line centers: As line length increased, detection accuracy at line centers *increased.*

These impressions were borne out in a 2 × 2 × 4 repeated measures ANOVA run on miss rates with probe object (target vs. distractor), probe location (center vs. endpoint), and line length (very short, short, long, and very long) as variables. Target miss rates were lower than distractor miss rates, $F(1,\ 8) = 30.60$, $MSE = 305$, $p < .001$, $\eta_p^2 = .79$; center miss rates were lower than endpoint miss rates, $F(1, 8) = 46.49$, $MSE = 623$, $p < .001$, $\eta_p^2 = .85$; and the effect of line length was significant, $F(3, 24) = 4.42$, $MSE = 370$, $p = .013$, $\eta_p^2 = .36$. There was also a significant interaction between location and line length, $F(3, 24) = 11.44$, $MSE = 291$, $p < .001$, $\eta_p^2 = .59$, confirming the observation that miss rates for center probes decreased with line length whereas miss rates for endpoint probes increased with line length. None of the other interactions were significant (all Fs < 1.83, all ps $> .17$).

It is important to emphasize that there were two effects of line length in these data: Averaged over targets and distractors, there was an improvement of about 27% in accuracy at centers as line length increased, $F(3, 27) = 7.3$, $MSE = 173$, $p = .001$, $\eta_p^2 = .45$, and a drop in performance of nearly 18% in accuracy at endpoints as line length increased, $F(3, 27) = 12.2$, $MSE = 111$, $p < .001$, $\eta_p^2 = .58$. Thus it appears that attention is concentrated at the centers of extended lines and that this concentration becomes more amplified at the centers as the lengths of the lines increase. Again, note the magnitude of these effects as the center–endpoint difference increased from less than 6% for short targets to nearly 40% for long targets.

Discussion

The purpose of Experiment 1 was to determine the distribution of attention across spatially extended objects when those objects

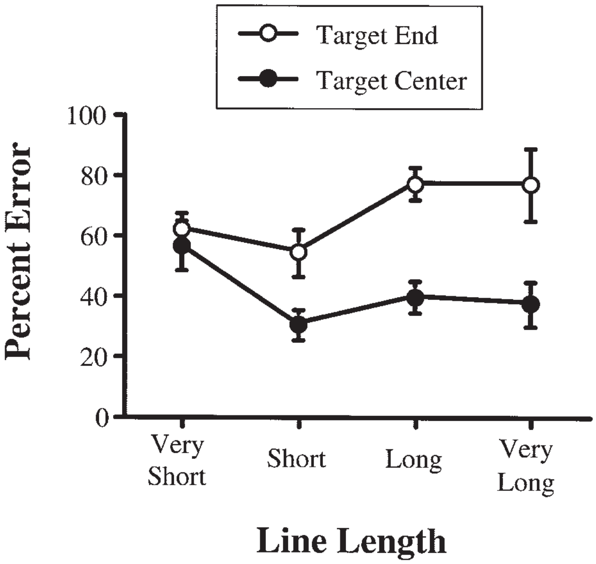

Figure 3. The effect of line length on probe detection performance for target lines in Experiment 1. As line length increased, miss rates decreased for center probes but increased for endpoint probes. Error bars represent one standard error of the mean.

were tracked in an MOT task. The results revealed two novel effects: attentional concentration and attentional amplification. Probe detection performance was better at the centers of objects than at the endpoints, suggesting a concentration of attention near the centers of uniform extended objects. More surprisingly, there was a substantial improvement in performance at the centers of lines as line length increased, suggesting that attention is not only concentrated at the centers of long lines but actually becomes more amplified at the centers as the lines become longer. The magnitudes of the effects were quite large, on the order of 20%–40% error, strongly suggesting that attention does not spread evenly throughout spatially extended objects.

Why did these attentional effects occur for distractors in addition to targets? In most MOT tasks the distractors may be irrelevant, but they still appear to be actively processed, perhaps to realize attentional selection via distractor inhibition in addition to target facilitation (Ogawa & Yagi, 2003; Pylyshyn, in press). This factor alone could explain part of our effects for distractors, because this "inhibitory tracking" could also prioritize probe detection. In addition, however, the distractors in our task were relevant, because observers knew that probes would appear on distractor lines half of the time (whereas in standard MOT tasks the distractors are never task-relevant). It may be that this led participants to monitor distractors as well as targets. The target selection was still quite salient in our data, because we always observed a large main effect of better probe detection for targets than for distractors. In addition, however, the inhibitory tracking of distractors and the probe detection task apparently caused participants to monitor all of the objects to some degree, resulting in effects for all lines. We discuss several implications of these results in the General Discussion, after first clarifying the nature of these effects in three additional experiments.

Experiment 2: Manipulating Probabilities to Rule Out Higher Level Strategies

Do the attentional concentration and amplification effects found in Experiment 1 reflect something fundamental about the nature of visual processing or merely the strategies that observers favor in these circumstances? Either case would be interesting. Finding that observers can strategically concentrate and amplify the distribution of attention within uniform objects would be a novel demonstration of the flexibility and volitional control of object-based attention. However, at least some part of this process would likely be implicitly driven, because we doubt that observers are likely to intuit the presence of an attentional amplification effect (whereas we might expect a completely intentional strategy to be fully reportable).[2] In any case, it would perhaps be even more interesting if the concentration and amplification of attention reflected more automatic aspects of visual processing because it would then remain possible to explore the rules that the visual system uses to distribute attention within objects, beyond the vagaries of individual strategies.

To test whether the distribution of attention within extended lines is under volitional control, we again asked observers to track three of six lines while simultaneously monitoring for the appearance of probes. In this experiment, however, the probability that a probe would occur near an endpoint was set to 80%, and the remaining 20% of the probes occurred on line centers. Given these probabilities, the concentration of attention on even one endpoint would make observers twice as likely to detect the probes than if attention was concentrated at the centers of the lines. Observers were informed of these probabilities and were encouraged to focus on the endpoints of the lines, or a single endpoint of a line if possible, to maximize probe detection. (Scholl et al., 2001, showed that it can be difficult to maintain attention on only a single endpoint of a uniform line over time, but that study used a higher attentional tracking load.) If the tendency to concentrate attention on object centers reflects only a voluntary strategy, then the incentive and instruction to focus on the endpoints of lines should reduce the difference between the detection rates for endpoint and center probes, possibly even reversing the effect. However, if the attentional concentration effect reflects something more fundamental about the nature of visual processing, then the results of this experiment should replicate those of Experiment 1: We should see an advantage for center probes (increasing in magnitude with line length) despite the greater number of endpoint probes.

Method

This experiment was identical to Experiment 1 except as noted here. The probes were still equally likely to appear on a target or distractor, but the probes were four times more likely to appear on an endpoint than on a center (80% endpoint probes vs. 20% center probes). Observers were fully informed of these probabilities and were encouraged to focus on one or both endpoints of the tracked lines.

Results

The results of this experiment replicated those of Experiment 1 in all qualitative aspects, and the magnitudes of the attentional concentration and amplification effects were equal to or larger than those observed in Experiment 1. Overall tracking accuracy was high, averaging 91% across all observers, which is similar to the level of performance observed in Experiment 1. Again, only trials in which observers correctly identified all three targets were included in the analysis of probe detection miss rates, thus excluding an average of 11.8 trials per observer. False alarms in the probe detection task were rare (less than 0.2 false alarms per tracking trial on average—i.e., about 1 false alarm every 5 tracking trials) and were not included in the analysis of probe detection miss rates.

Attentional Concentration

Overall performance was again much better for center probes than for endpoint probes. Figure 4 shows probe detection miss rates for probes appearing on target centers, target endpoints, distractor centers, and distractor endpoints. As expected, miss rates were lower for target probes than for distractor probes. Most important, the large difference between center and endpoint probes was observed for both targets and distractors despite the low

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[2] In fact, the existence of the attentional amplification effect was a great surprise to us. Our original line-length comparisons were an attempt to see if the magnitude of the center–end *difference* scaled, and we were quite surprised by the specific way in which it did (i.e., by the fact that the performance at line centers actually improved). Despite this, we consider the amplification effect to be one of the most robust and theoretically important results of this study.

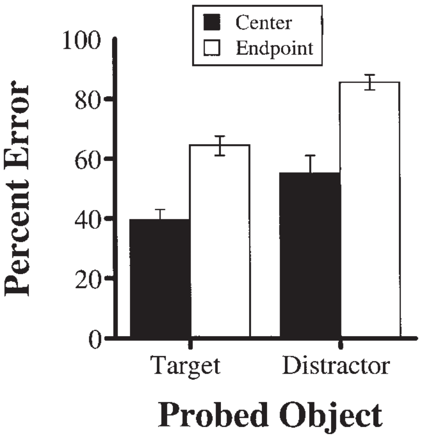

Figure 4. Probe detection performance in Experiment 2. Lower miss rates correspond to better probe detection performance. Error bars represent standard errors of the mean.

probability of probe appearance on the centers. A 2 × 2 ANOVA was run on miss rates with probe object (target vs. distractor) and probe location (center vs. endpoint) as variables. Miss rates for target probes were significantly lower than for distractor probes, $F(1, 9) = 42.54$, $MSE = 78.5$, $p < .001$, $\eta_p^2 = .83$, and miss rates were significantly lower for center probes than for endpoint probes, $F(1, 9) = 104.10$, $MSE = 73.3$, $p < .001$, $\eta_p^2 = .92$, but the interaction was not significant, $F(1, 9) < 1$. As in Experiment 1 these effects were quite large, with an average difference in miss rate of about 25% between target centers and endpoints. The online supplementary Auxiliary Analyses appendix again rules out the possibility that these results could be explained by extrinsic factors such as eccentricity or velocity.

Attentional Amplification

The improvement in center probe detection (and decline in endpoint detection) with increasing line length was just as apparent in the present study as in Experiment 1. Trials were binned into the same four categories of line length. As line length increased, probe detection miss rates for the centers decreased, whereas miss rates for endpoints increased (see Figure 5). A 2 × 2 × 4 ANOVA was run on miss rates with probe object (target vs. distractor), probe location (center vs. endpoint), and line length (very short, short, long, and very long) as variables. Target miss rates were lower than distractor miss rates, $F(1, 6) = 27.42$, $MSE = 464$, $p = .002$, $\eta_p^2 = .82$, and center miss rates were lower than endpoint miss rates, $F(1, 6) = 32.65$, $MSE = 344$, $p = .001$, $\eta_p^2 = .85$. The main effect of line length was marginally significant, $F(3, 18) = 2.75$, $MSE = 390$, $p = .073$, $\eta_p^2 = .31$, and there was a significant interaction between location and line length, $F(3, 18) = 15.87$, $MSE = 274$, $p < .001$, $\eta_p^2 = .73$, confirming the observation that miss rates for centers decrease with line length whereas miss rates for endpoints increase with line length. None of the other interactions were significant (all Fs < 1.1, all ps $> .37$).

As in Experiment 1, it is important to note that there are two effects of line length: Averaged over targets and distractors, there is an improvement of about 36% in accuracy at centers as line length increases, $F(3, 27) = 6.3$, $MSE = 359$, $p = .002$, $\eta_p^2 = .41$, and a drop in performance of nearly 18% in accuracy at endpoints as line length increases, $F(3, 27) = 23.5$, $MSE = 30$, $p < .001$, $\eta_p^2 = .72$. Thus, even with the relatively rare occurrence of center probes, there is a marked amplification of attention at the centers as the length of the lines increases. This amplification effect appears to be even greater than that observed in Experiment 1, despite the incentive to focus attention on the endpoints: The center–endpoint difference increases from −6% for short targets to over 58% for long targets.

Discussion

The results of this experiment suggest that the concentration and amplification of attention at the centers of extended lines reflects an automatic aspect of visual processing rather than only a higher level voluntary strategy. Here the probes were four times more likely to appear on an endpoint than on a center, thus providing observers with an incentive to focus their attention on the endpoints, or at least one endpoint of each line. Although observers were informed of these probabilities and instructed to attempt to focus on endpoints, the concentration of attention near the centers of lines (better probe detection at centers than endpoints) was as strong in the present experiment as in Experiment 1. Moreover, the amplification of attention at the centers of lines (improvement in probe detection at centers with increasing line length) was, if anything, even greater than that observed in Experiment 1.

Experiment 3: Manipulating the Tracking Task to Rule Out Higher Level Strategies

One could argue that despite the greater probability of endpoint probes in Experiment 2, observers may still have strategically chosen to track the centers of the lines as a way of succeeding at

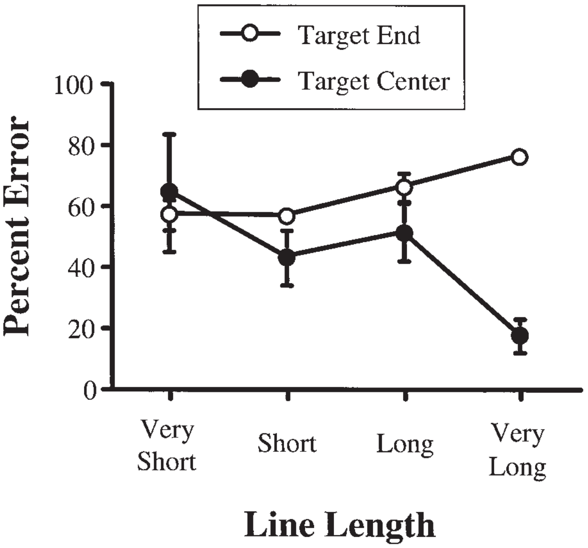

Figure 5. The effect of line length on probe detection performance for target lines in Experiment 2. As line length increased, miss rates decreased for center probes but increased for endpoint probes. Error bars represent one standard error of the mean.

the tracking task (which was identical in Experiments 1 and 2), and that this may have resulted in the maintenance of the attentional concentration effect. The purpose of this experiment was to provide a further test of this "strategic" hypothesis by explicitly requiring observers to track only the endpoints of the lines. This methodological goal immediately raised several problems, however. First, observers clearly could not be asked to track *both* endpoints of each target line, because they could still succeed at such a task simply by attending to the target lines' centers and then clicking on the endpoints of those lines at the end of each trial. Observers thus had to be required to track only a single endpoint of each target line. The problem with this task is simply that it is exceedingly difficult. Indeed, the primary result of the previous MOT study of Scholl et al. (2001) was that tracking ability is destroyed in exactly this situation—a result that they interpreted in terms of attention automatically spreading throughout each entire target line, via object-based attention. (Below we reinterpret this effect.) This difficulty is especially salient here, of course, because we are only able to analyze probe detection performance on those trials in which observers tracked perfectly. We thus had to reduce the tracking load further in this experiment, so that observers had to track only one specified endpoint of each of two target lines.

Observers were required to track one endpoint on each of two separate lines while simultaneously monitoring for the appearance of probes. Given that the task was explicitly to track the endpoints of lines, the optimal strategy in this task would be to concentrate attention on the endpoints of the target lines. Thus, to the extent that the focus of attention is under volitional control, more endpoint probes should be detected than center probes. If, however, the concentration of attention at object centers reflects an automatic aspect of visual processing, attention should remain relatively more focused on the center of objects than on either endpoint, and thus center probes should still be detected at greater rates than endpoint probes despite the explicit necessity of tracking endpoints.

Method

This experiment was identical to Experiment 1 except as noted here. The task was to track one endpoint on each of two separate lines (target lines) and to ignore the four other lines (distractor lines). After the motion phase of each trial, observers clicked on the tracked endpoints; whereas the entire lines were highlighted during this process in Experiments 1 and 2, in this experiment a small cursor was able to select only the endpoints of the lines. Even with fewer targets, tracking accuracy tends to be lower for endpoints than for whole lines. Thus, we also increased the number of trials from 50 to 70 so that the number of trials with perfect tracking would be high enough to analyze probe detection as a function of line length. While tracking the endpoints, observers also monitored for the appearance of probes. There was no target–distractor end on the distractor lines, thus endpoint probes on target lines only occurred near the target end to simplify the comparison with distractor probes (such that probes occurred on the target end, target center, distractor end, or distractor center).

Results

The results of this experiment replicated those of Experiment 1 in all qualitative aspects, again revealing robust attentional concentration and amplification effects. Overall tracking accuracy was lower than in the previous experiments, averaging 66% across all observers, but this was consistent with previous research showing that it is exceedingly difficult to track the endpoints of lines (Scholl et al., 2001). This lower tracking accuracy did not affect the analysis, however, because we intentionally included more trials to compensate for this, and we again only analyzed the probe detection results from trials in which observers correctly identified both of the target endpoints, thus excluding an average of 36 trials per observer. False alarms in the probe detection task were rare (less than 0.2 false alarms per tracking trial on average—i.e., about 1 false alarm every 5 tracking trials) and were not included in the analysis of probe detection miss rates.

Attentional Concentration

Figure 6 depicts probe detection miss rates for probes appearing on target centers, target endpoints, distractor centers, and distractor endpoints. As expected, error rates were lower for target probes than for distractor probes. Surprisingly, there was again a large difference between center and endpoint probes for both targets and distractors despite the requirement to track the endpoints (and the apparent success at this task, given that only trials with successful tracking were included in this analysis). A 2 × 2 ANOVA was run on miss rates with probe object (target vs. distractor) and probe location (center vs. endpoint) as variables. Miss rates for target probes were significantly lower than for distractor probes, $F(1, 9) = 10.8$, $MSE = 120$, $p = .009$, $\eta_p^2 = .55$, and error rates were significantly lower for center probes than for endpoint probes, $F(1, 9) = 30.4$, $MSE = 149$, $p < .001$, $\eta_p^2 = .77$, but the interaction was not significant, $F(1, 9) < 1$. These differences were again quite large, with an average difference in error rate of about 21% between center and endpoint probes. The online supplementary Auxiliary Analyses appendix again rules out the possibility that these results could be explained by extrinsic factors such as eccentricity or velocity.

Attentional Amplification

The improvement in center probe detection with increasing line length was just as apparent in the present study as in Experiments

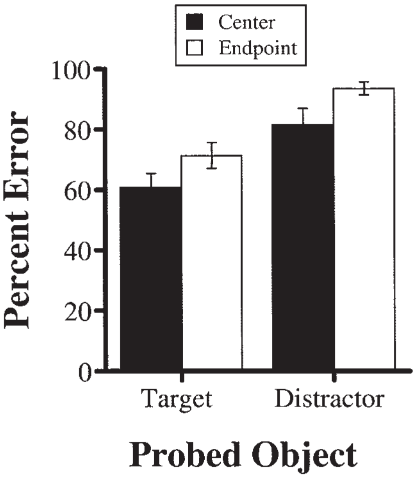

Figure 6. Probe detection performance in Experiment 3. Lower miss rates correspond to better probe detection performance. Error bars represent standard errors of the mean.

1 and 2. Trials were binned into four categories of line length (less than 11.4°, between 11.4° and 21.4°, between 21.4° and 31.4°, and greater than 31.4°) that were similar to those used in Experiments 1 and 2, except they were adjusted slightly to include more trials in the shortest and longest length bins. As line length increased, probe detection miss rates for the centers decreased, whereas miss rates for endpoints were roughly constant (see Figure 7). A 2 × 2 × 4 ANOVA was run on miss rates with probe object (target vs. distractor), probe location (center vs. endpoint), and line length (very short, short, long, and very long) as variables. Target miss rates were lower than distractor miss rates, $F(1, 9) = 7.2$, $MSE = 487$, $p = .025$, $\eta_p^2 = 45$, and center miss rates were lower than endpoint miss rates, $F(1, 9) = 45.36$, $MSE = 459$, $p < .001$, $\eta_p^2 = .83$. The main effect of line length was not significant, $F(3, 27) = 1.68$, $MSE = 480$, $p = .198$, $\eta_p^2 = .16$, but there was a significant interaction between location and line length, $F(3, 27) = 3.90$, $MSE = 247$, $p = .019$, $\eta_p^2 = .30$, confirming the observation that error rates for centers decrease with line length whereas error rates for endpoints are constant. None of the other interactions were significant (all Fs < 2.1, all ps $> .12$).

As in Experiment 1, averaged over targets and distractors, there is an improvement of about 20% in accuracy at centers as line length increases, $F(3, 27) = 2.99$, $MSE = 316$, $p = .049$, $\eta_p^2 = .25$. However, unlike Experiment 1, there was no increase in error rates at endpoints, $F(3, 27) = 1.24$, $MSE = 64$, $p = .313$, $\eta_p^2 = .12$. The lack of effect for endpoints seems likely to be due to a floor effect in this case, but this does not affect the measurement of attentional amplification, which is based on the increasing attentional concentration at line centers with increasing line length.

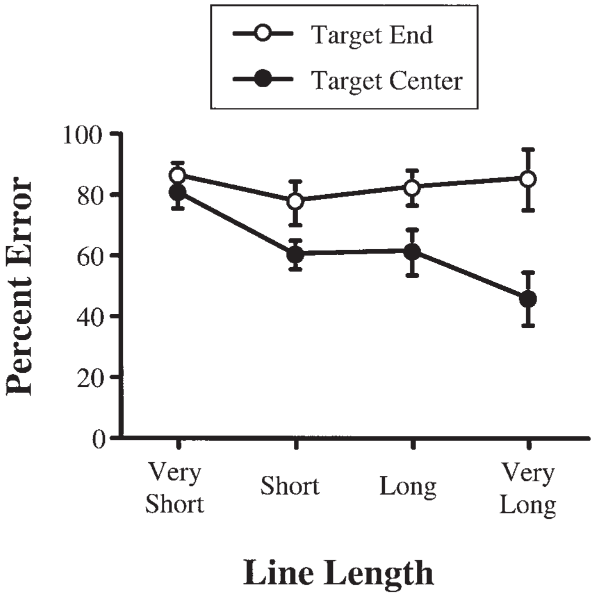

Figure 7. The effect of line length on probe detection performance for target lines in Experiment 3. As line length increased, miss rates decreased for center probes but increased for endpoint probes. Error bars represent one standard error of the mean.

Discussion

The results of this experiment again revealed robust attentional concentration and amplification effects: Attention was apparently concentrated at the centers of lines (increasingly so as line length increased) despite the explicit necessity of tracking endpoints. These results again suggest that the attentional concentration and amplification reflect an automatic aspect of visual processing rather than a higher level voluntary strategy.

Note that these results also suggest a reinterpretation of the previous "target merging" results of Scholl et al. (2001). In this study participants exhibited a marked inability to track single endpoints of lines, and the authors interpreted this effect in terms of the automatic spread of attention throughout the lines. This assumption was fueled by typical object-based attention effects with spatial cuing paradigms that have received similar interpretations, but the results of the present experiments suggest that this assumption is unwarranted. Attention may not have spread uniformly through the lines in this previous study but may rather have been concentrated at the *centers* of those lines, as in this experiment.

Experiment 4: Attentional Amplification at Matched Absolute Distances

The previous experiments yielded two primary results. First, attention appears to be automatically concentrated at the centers of spatially extended lines, regardless of whether observers are attempting to track the lines themselves (Experiments 1 and 2) or only single endpoints (Experiment 3). Second, there is an increasing amplification of attention at the centers of lines with increasing line length. In many ways this amplification effect is the most surprising and counterintuitive finding of these experiments, taken as a whole. For example, one may have predicted that attention has a fixed spatial extent over which it can spread and that as a line extends progressively further beyond this limit the detection of endpoint probes would decrease, but the detection of center probes would remain constant. In contrast, while the detection of endpoint probes did decrease with increasing line length (at least in Experiments 1 and 2), the detection of center probes *increased* as line length increased, and this effect was especially strong under higher attentional loads when observers had to track the lines as wholes (in Experiments 1 and 2). This implies that there is a default increase in attentional concentration, or an amplification of attention, at the centers of lines with increasing length.

What is the nature of this effect? Attentional amplification may be a categorical effect, such that probe detection accuracy is determined not by the absolute distance of the probe from the line's center, but rather by its object-relative position (i.e., whether it is at the center or near the end). This view implies that a probe at the very same distance from the line's center should be detected more easily when the line continues far beyond that point (such that the probe occurs near but not at the center, as in Figure 8a), compared with when the line ends just beyond that point (such that the probe occurs near the end of the line, as in Figure 8b). The previous experiments could not test this hypothesis, because the center versus endpoint distinction was always necessarily confounded with absolute distance from the center on any given line.

In this experiment we tested whether attentional amplification is object-relative by testing probe positions located between the

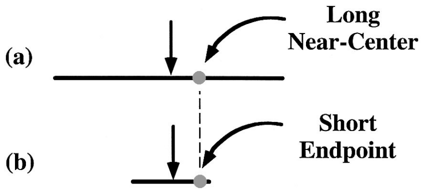

Figure 8. Matched short endpoint and long near-center probes in Experiment 4. The vertical arrows point to the center of a short line and a long line. The probe can then appear near (but not at) the center of a long line (a) or near the endpoint of a short line (b). Note that the absolute distance from the center of each line to the probe is exactly matched in these cases.

centers and endpoints—in particular, by holding absolute distance from the center of the line constant for probes appearing on lines of different lengths. If the amplification effect is driven solely by the absolute distance between the centers and probes, then there should be no difference in probe detection for endpoint probes on short lines versus probes presented near (but not at) the center of long lines, as in Figure 8. In contrast, if attentional amplification is a categorical object-relative effect, then attention should be more concentrated near the centers of long lines than short lines, resulting in better performance for matched-distance probes on long lines compared with short lines.

Method

This experiment was identical to Experiment 1 except as noted here. The presentation of the probes was identical to Experiment 1 except that probes occasionally appeared on the near-center of longer lines (somewhere between the center and an endpoint). In particular, the absolute center-to-probe distance was always perfectly matched for probes appearing on the endpoints of short lines and on the near-centers of longer lines. To achieve this, we separated probed lines by length into three categories: short (less than 14°), medium (between 14° and 17.4°), and long (greater than 17.4°). The probes could appear on the center or near an endpoint of short and medium lines, or on the center, near-center, or endpoint of long lines. As in the previous experiments, each probe was equally likely to appear on a target as on a distractor for each line length. The probes were also equally likely to appear on the center or an endpoint of short and medium lines.

For long lines, however, 50% of the probes appeared on an endpoint, 25% on a near-center, and 25% on a center. Critically, the absolute probe-center distances were matched for short endpoints and long near-centers as follows. Each time a probe appeared near the endpoint of a short line, the center-probe distance was stored in a queue (with separate queues kept for target and distractor probes). When a probe was later selected to appear at the near-center of a long line, its position was shifted away from the center based on the next distance stored in the queue (which was then removed). (If the probe was to appear on a long near-center but there was no distance currently stored in the list, then the probe appeared on the center.) Because the analysis of probe detection miss rates excluded trials in which there was a tracking error, each such error caused the queues to be restored to the state they were in at the end of the previous trial. (This is equivalent to simply ignoring trials in which there was a tracking error.) This procedure produced an average of about 20 perfectly matched short endpoint and long near-center probes per observer (about 10 target probes and 10 distractor probes, located an average of 4.2° from the center of the line).

Results

The results of this experiment replicated the previous experiments in all qualitative aspects, showing both an attentional concentration effect and direct evidence that there is *object-relative* amplification of attention near the centers of extended lines. Overall tracking accuracy was high, averaging 92% across all observers. Only trials in which observers correctly identified all three targets were included in the analysis of probe detection miss rates, thus excluding an average of 10.4 trials per observer. False alarms in the probe detection task were rare (less than 0.1 false alarms per tracking trial on average—i.e., about 1 in every 10 tracking trials) and were not included in the analysis of probe detection miss rates.

Short Endpoints Versus Long Near-Centers: A Direct Test of Attentional Amplification

Figure 9 illustrates that miss rates for probes appearing on the near-centers of long lines were lower than miss rates for probes appearing on the endpoints of short lines, even though the absolute probe-center distance was identical. These impressions were borne out in a 2 × 2 ANOVA run on miss rate with probe object (target vs. distractor) and probe location (short endpoint vs. long near-center) as variables. Miss rates for target probes were significantly lower than for distractor probes, $F(1, 9) = 43.44$, $MSE = 96.4$, $p < .001$, $\eta_p^2 = .83$, and miss rates were significantly lower for long near-centers than short endpoints, $F(1, 9) = 33.15$, $MSE = 191.3$, $p < .001$, $\eta_p^2 = .79$, but the interaction was not significant, $F(1, 9) < 1$. Note that the magnitude of the difference between long near-center and short endpoint probes is also quite large, with a 27% difference on target probes.

Attentional Concentration at Centers

As in the previous experiments, miss rates at centers were substantially lower than at the endpoints, replicating the finding

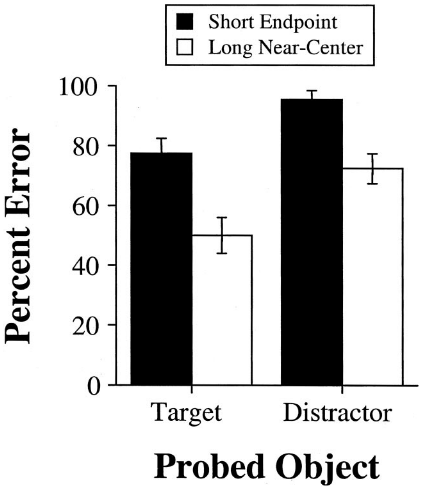

Figure 9. Probe detection performance for matched-distance probes in Experiment 4. Miss rates were lower for targets than for distractors (for both the short endpoints and the long near-centers). Most important, miss rates were *lower* (performance was better) for long near-center probes than for short endpoint probes (for both targets and distractors), despite the matched absolute distances. Thus, the observed difference in probe detection performance was driven not by the absolute probe-center distance but rather by the categorical probe position within the object (center vs. endpoint). Error bars represent one standard error of the mean.

that attention concentrates near the center of these objects. A 2 × 3 ANOVA was run on miss rate with probe object (target vs. distractor) and probe location (center vs. near-center vs. endpoint) as variables. Miss rates for target probes were significantly lower than for distractor probes, $F(1, 9) = 64.29$, $MSE = 121$, $p < .001$, $\eta_p^2 = .88$, and there was a main effect of probe location, $F(2, 18) = 19.67$, $MSE = 203$, $p < .001$, $\eta_p^2 = .69$, but the interaction was not significant, $F(2, 18) = 3.10$, $MSE = 112$, $p = .070$, $\eta_p^2 = .26$. There was no difference in probe miss rates for centers and near-centers: targets, $t(9) < 1$; distractors, $t(9) = 2.14$, $SEM = 4.7$, $p = .061$, $r^2 = .34$, whereas miss rates for centers were significantly lower than for endpoints: targets, $t(9) = 4.92$, $SEM = 6.0$, $p < .001$, $r^2 = .73$; distractors, $t(9) = 4.83$, $SEM = 2.7$, $p < .001$, $r^2 = .72$; and miss rates for near-centers were significantly lower than for endpoints: targets, $t(9) = 4.92$, $SEM = 6.3$, $p < .001$, $r^2 = .73$; distractors, $t(9) = 4.70$, $SEM = 4.8$, $p = .001$, $r^2 = .71$. The difference in miss rates was quite large, particularly for targets, with an average difference of 30% between center and endpoint probes as well as between near-center and endpoint probes.

Attentional Amplification

There was also an improvement in performance at target centers and a decline in performance for target endpoints as line length increased, replicating the effects observed in each of the previous experiments. The trials were binned into four categories of line length: less than 7.8° (center miss rate = 57.5% vs. endpoint miss rate = 83.4%), between 7.8° and 15.7° (52.9% vs. 70.4%), between 15.7° and 23.6° (50.7% vs. 80.8%), and greater than 23.6° (40.3% vs. 88.7%). Because near-center probes were only presented on long lines, they are not included in this analysis. As line length increased, probe detection miss rates for target centers decreased, whereas miss rates for target endpoints increased (see Figure 10). Unlike the previous experiments, however, the difference between distractor centers and distractor endpoints was roughly constant with line length. A 2 × 2 × 4 ANOVA was run on miss rates with probe object (target vs. distractor), probe location (center vs. endpoint), and line length (very short, short, long, and very long) as variables. Target miss rates were lower than distractor miss rates, $F(1, 8) = 39.3$, $MSE = 419$, $p < .001$, $\eta_p^2 = .83$, and center miss rates were lower than endpoint miss rates, $F(1, 8) = 24.0$, $MSE = 643$, $p = .001$, $\eta_p^2 = .75$. The main effect of line length was not significant, $F(3, 24) = 1.61$, $MSE = 250$, $p = .214$, $\eta_p^2 = .17$, but the interaction between location and line length was marginal, $F(3, 24) = 2.47$, $MSE = 235$, $p = .087$, $\eta_p^2 = .24$, suggesting that there is a trend for miss rates at centers to decrease with line length, whereas miss rates for endpoints tend to increase with line length.

Unlike the previous experiments, this effect seemed to hold mainly for targets and not distractors: The Object × Location × Length interaction was marginal, $F(3, 24) = 2.92$, $MSE = 138$, $p = .055$, $\eta_p^2 = .27$. Although simple effects of line length were not significant for target centers, $F(3, 24) = 1.35$, $MSE = 331$, $p = .281$, $\eta_p^2 = .14$, or target ends, $F(3, 27) = 2.74$, $MSE = 215$, $p = .063$, $\eta_p^2 = .23$, the center–end difference did increase with line length (from 26% for the shortest lines to 44% for the longest lines). This observation was supported by a more focused 2 × 4 ANOVA on target miss rates with location (center vs. endpoint) and line length as variables. There was a significant effect of location, $F(1, 8) = 16.60$, $MSE = 819$, $p = .004$, $\eta_p^2 = .67$, and the interaction between location and line length was significant, $F(3, 24) = 3.40$, $MSE = 228$, $p = .034$, $\eta_p^2 = .30$. Thus, as line length increased, attention became increasingly focused at the centers of target lines, resulting in improved performance for center relative to endpoint probes.

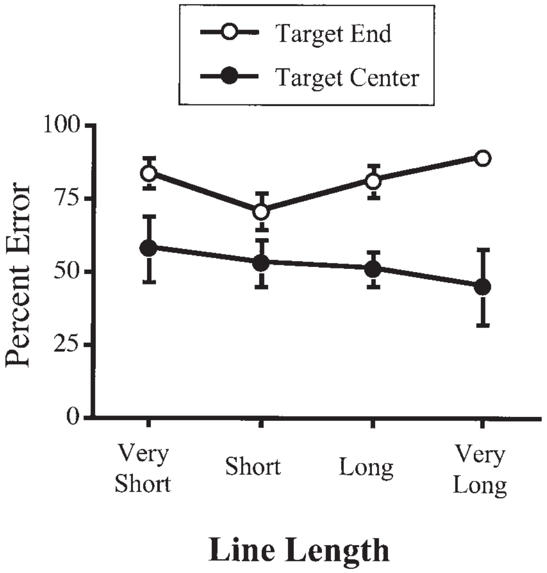

Figure 10. The effect of line length on probe detection performance for target lines in Experiment 4. Overall, miss rates decreased for center probes but increased for endpoint probes. Error bars represent one standard error of the mean.

Discussion

The most important result of this experiment was that probe detection miss rates did not depend on the absolute distance between the probe and the center of the line but rather seemed to be driven by the probe's categorical location near the endpoint versus near the center. Miss rates were higher for probes that appeared on short endpoints, compared with those that appeared on long near-centers, even though the probe-center distances were perfectly matched in these cases. This result is consistent with the hypothesis that the distribution of attention within uniform objects is flexible and that there is an amplification of attention at the centers of lines as line length increases. Thus, the amplification of attention is an object-relative effect: At a given absolute distance from the center of the line, the allocation of attention will depend on the categorical position of that point within the object.

General Discussion

The goal of this study was to discover how attention selects and tracks uniform spatially extended objects. We were particularly interested in how such selection operates under conditions that are characteristic of many real-world situations (such as driving), which call for sustained attention to multiple objects in changing scenes under conditions of high processing load. Observers in our experiments were required to track multiple spatially extended target lines, keeping them distinct from distractor lines, while concurrently monitoring for the appearance of probes that could appear at the centers or near the endpoints of any line.

This study had two primary results. First, we observed an *attentional concentration* effect: Attention was not distributed uniformly throughout the uniform lines but rather was concentrated near the center of extended lines. This effect was demonstrated in four separate experiments by showing that detection of probes was better at the centers of lines than at the endpoints. This concentration effect was found even when observers knew that probes were much more likely to appear on endpoints and were instructed to attend to the endpoints as much as possible (Experiment 2). Moreover, we observed a robust concentration effect even when the primary tracking task required observers to track only a single endpoint of each line (Experiment 3). This suggests that the concentration of attention at the centers of lines reflects an automatic aspect of visual processing rather than a higher level voluntary tracking strategy. Moreover, detailed analyses presented in the supplementary appendix ruled out any explanation for these results based on differences in eccentricity or velocity.

The second primary result observed in our experiments was an effect we call *attentional amplification*: When observers tracked uniform lines, the attentional concentration effect was generally amplified in longer lines compared with shorter lines. This effect was demonstrated robustly in all four experiments by showing that detection of probes not only worsened at target endpoints in longer lines but *improved* at the centers of longer lines, compared with shorter lines. This suggests that attention actually becomes more amplified at the centers of objects as their spatial extent increases. Furthermore, this amplification of attention is an object-relative effect: Probe detection performance was driven not by the absolute distance of the probe from the center of a line but rather by its relation to a line's *endpoint*—that is, whether it was near the center of a long line or near the end of a short line (Experiment 4). In the remainder of this article, we discuss several theoretical implications of the attentional concentration and amplification effects.

Nonuniform Attentional Distributions Within Uniform Objects

The attentional concentration effect can be considered as a case study of nonuniformity in the distribution of attention within uniform objects. In the present studies, observers were required to select and track homogeneous lines of various lengths. There were no texture or surface features within these objects, and they did not consist of multiple parts. Despite this uniformity, attention did not spread evenly throughout them. Instead, there was a marked concentration of attention near the centers of the objects.

Whereas nonuniform processing in uniform objects has not been the norm in studies of attention, such results are evocative of other areas of vision science. Some such studies have used randomly structured displays and found counterintuitive spatial effects. For example, when a given region is attended in a complex change-detection task, changes are more reliably detected in both that region and in the corresponding region of the opposite hemifield (Tse, 2004; Tse, Sheinberg, & Logothetis, 2003). Thus even when participants attempt to attend only to a single region, other unrelated discrete regions may also be selected.

This unintentional prioritization of certain regions of uniform objects may also arise in some situations because those objects are mentally represented in nonuniform terms. In studies of shape representation, for example, many investigators have suggested that objects may be efficiently represented via their salient axes and via individual points along those axes. This is true, for example, in medial-axis representations (e.g., Blum, 1973), medial-point representations (e.g., Kovacs, Fehér, & Julesz, 1998), core representations (e.g., Burbeck & Pizer, 1994), and shock graphs (e.g., Siddiqi, Shokoufandeh, Dickinson, & Zucker, 1999). Although these models differ in their details, they each propose that the boundaries of an object are essential for extracting a description of shape that includes certain key points within the object boundary, and experimental evidence suggests that observers have greater sensitivity to such points (e.g., Kovacs et al., 1998; Psotka, 1978). Consistent with this, the present experiments suggest that there can be attentional nonuniformities even within simple uniform lines. Indeed, beyond measuring simple sensitivity, the present results suggest that attentional probes in complex dynamic displays involving such shapes might also be a powerful method for exploring the psychological reality of such representational schemes (many of which were initially constructed in applied computer-vision contexts).

Attention and Stability

Our studies of spatially extended lines revealed a particular type of nonuniformity: a concentration of attention at the lines' centers. Why did this occur, and how might it generalize to other types of objects? We can speculate about several reasons for attention to concentrate at the center of a line. First, it could be that the center of gravity is particularly important in the localization of objects. Consider, for example, how you might point to and track various types of objects with your finger. With a locally compact object, you could simply continuously point at the object as it moved through a scene. But how would you use your finger to track a long slithering snake? Would you point at its head? Its tail? Or, perhaps, at its middle? This difficulty in determining and representing *where* a spatially extended object is (see vanMarle & Scholl, 2003) may lead to a summary representation of sorts, and the center of gravity may be a particularly useful candidate for such a point. In support of this idea, previous research has shown that saccadic landing locations, preferred fixation locations, and perceived locations all appear to be near the center of gravity of an object, even when that point is outside of the object boundary (Vishwanath & Kowler, 2003). An intriguing possibility is that even these effects reflect attentional concentration, given the tight coupling of attention and eye movements, and the fact that attentional shifts typically precede saccades (e.g., Hoffman & Subramanian, 1995; Kowler, Anderson, Dosher, & Blaser, 1995).

The centers of objects, in particular, may also be important because they prove to be the most *stable* points across various types of motion. To track a person, for example, you would do well to track a point along their torso rather than their hands or feet (which may undergo many spurious local motions), especially because a person's foot may often be moving locally in the *opposite* direction that the person herself is moving (e.g., while walking, measured in a local reference frame relative to the trunk). This increased stability at the centers of objects also holds for the lines used in the present experiments. Because each endpoint always moved independently, the center was consistently the most stable point of the objects, with a slower average speed and fewer average changes in direction than any other point along the line. Thus, under conditions of high load, such as in the tracking task, attention might have a tendency to concentrate near the most stable point within an object. (This idea may help to explain why the attentional concentration effect exists, but recall that it cannot explain away the effect, because it persists even when comparing probes at endpoints and centers that are matched for velocity, as demonstrated at length in the supplementary appendix.) All of these possibilities will be relatively easy to evaluate in future research with this paradigm, by using (a) differently shaped objects whose centers of gravity lie at various other positions, and (b) lines whose endpoints move in various ways such that certain endpoints may be more stable over time than the lines' centers.

The Nature and Importance of Attentional Amplification

Throughout our experiments we also observed that the attentional concentration effect scaled in interesting ways with the length of the probed lines. What do traditional object-based attention models predict in such circumstances? No previous models to our knowledge have explicitly addressed such issues. Traditional work in object-based attention, for example, has simply suggested that attention automatically spreads throughout an object when one region of it attended, or alternatively that attention is simply constrained by object boundaries. (The one exception to this rule is that most investigators find especially good performance for the validly cued within-object locations; of course, this likely reflects something special about cuing rather than object-based attention per se.) Such theories have not often studied how object-based attention interacts with spatial constraints (though cf. Vecera, 1994; Vecera & Farah, 1994), but we can derive two plausible models based on earlier research on spatial attention.

First, as illustrated in Figure 11a, object-based attention may simply be subject to overarching spatial limitations. Lines of three different lengths are shown, and the distribution of attention (and the likelihood of probe detection) is illustrated by the color of the line at each point, with darker areas indicating more attention and whiter areas indicating less attention. In this type of spotlight view (see Eriksen & Hoffman, 1972; Posner et al., 1980), attention would still be constrained within object boundaries but could only span a limited spatial extent (delimited by a maximum width of the spotlight) within the object itself. This would result in a fixed uniform extent of attention, which could fully encompass shorter lines (and most of the objects used in previous object-based attention research) but would fail to encompass the endpoints of longer lines. A second intuitive model might correspond to an object-based analogue of spatial zoom-lens models of attention (e.g., Eriksen & St. James, 1986), as depicted in Figure 11b. Perhaps attention always does spread uniformly through entire objects but is subject to a fixed capacity limit such that every point along a short line is attended to a relatively large degree, whereas attention is more diffused throughout longer lines such that every point is attended to a relatively smaller degree.

Our results showed that probe detection scaled with line length in neither of these ways when observers attempted to track uniform lines. Rather, we observed an attentional amplification effect, wherein probe detection at the centers of lines was dramatically *better* with longer lines than with shorter lines. (As noted above, we had some reason to predict the existence of attentional concentration, but the enormous and statistically robust amplification effect completely surprised us.) Figure 11c depicts the attentional amplification effect and a schematic representation of the observed results: As line length increases, attention becomes more concentrated on the center of the line relative to the endpoints. The gradient of attentional allocation depicted in this figure is reminiscent of other spatial gradient effects involving attention (e.g., LaBerge & Brown, 1989) but with two changes corresponding to our main effects: (a) The gradient appears to be automatically centered on the centers of lines during attentional tracking (i.e., attentional concentration), and (b) the extent and precise distribution of the gradient appear to automatically and flexibly adjust on the basis of the length of the line (i.e., attentional amplification).

Why might this amplification of attention occur in our stimuli? One possibility is that the relative stability of various points on lines of various lengths may explain both attentional concentration and amplification. As discussed earlier, the center of a spatially extended object is likely to be more stable over time and motion than an endpoint both in our stimuli and in many real-world contexts. For especially compact objects (e.g., especially short lines), however, such stability differences are likely to be extremely small. We might thus expect that the center advantage in terms of stability would be greater with longer than with shorter lines. This view would directly predict the existence of attentional amplification, because the concentration on object centers would become increasingly useful—and thus perhaps extreme—as line length grew. Because of the possibility that both concentration and amplification could be explained in such a unified framework, it will be a particularly important goal for future research to directly manipulate various forms of stability. In any case, these results illustrate a new way in which object-based attention is realized and demonstrates how such research can move beyond categorical conclusions about *whether* objects and attention interact to more focused studies of precisely *how* attention is flexibly allocated in spatially extended objects.

Temporal Dynamics of Object-Based Attention

Though we have emphasized the property of spatial extent throughout this article, it remains possible that the distribution of attention is even more affected by *changes* in spatial extent. One of the auxiliary analyses in the supplementary appendix revealed that a change in line length over a relatively brief period prior to the probe appearance has a dramatic effect on probe detection accuracy. In particular, a fast increase in line length prior to the probe resulted in a marked concentration and amplification of attention, increasing the difference in probe detection accuracy for centers and endpoints by nearly 60%. These results suggest the operation of an online process in which the allocation of attention can be flexibly scaled as objects change, and also suggest that such rescaling can occur extremely quickly. Though initially surprising, such results do seem natural when considered in the context of real-world events, given that many objects are constantly changing their shape either physically (e.g., as a bird flaps its wings) or perceptually due to viewpoint changes. Though most research on object-based attention has involved static scenes, it seems that any

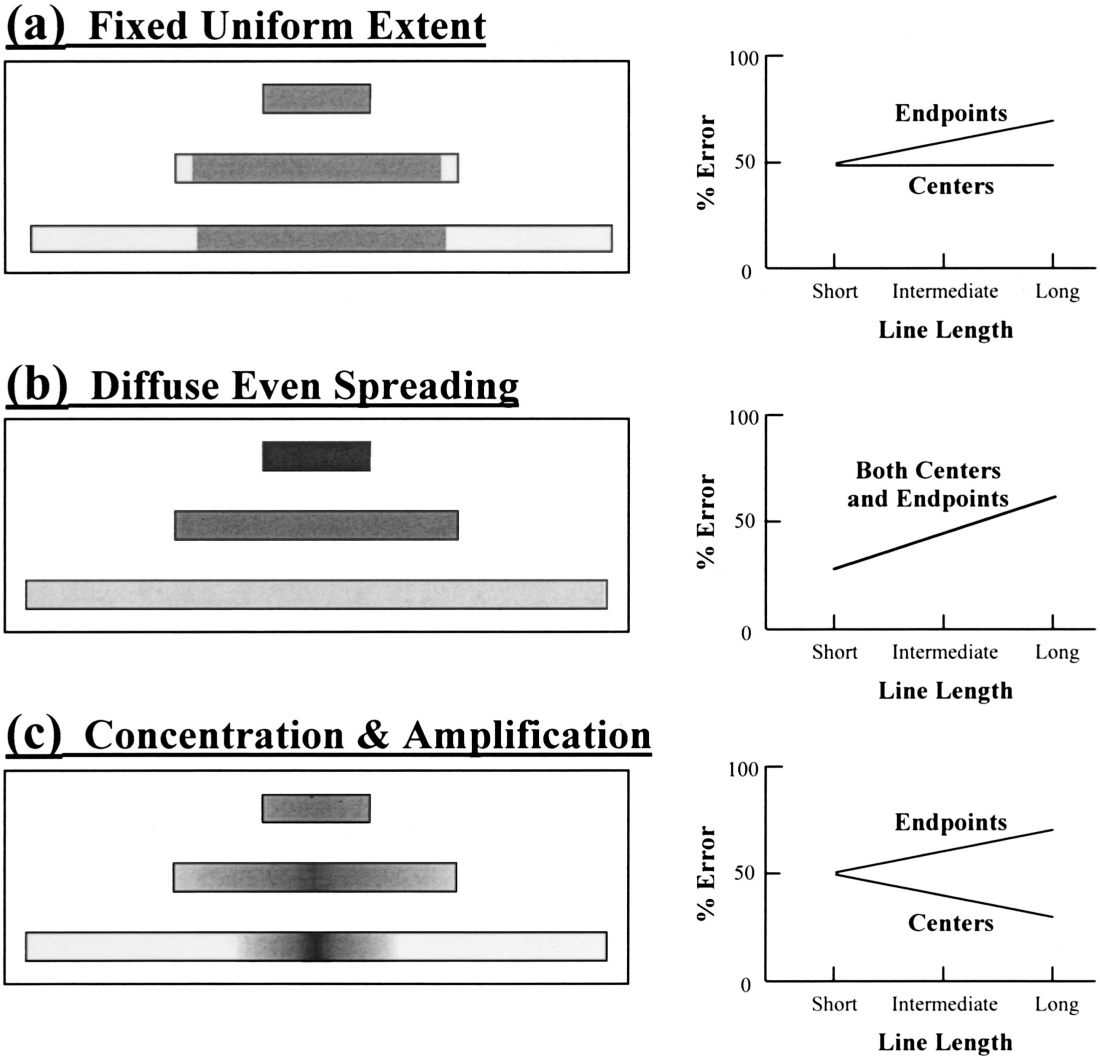

Figure 11. Three possible patterns of attentional distribution. Here we depict three possible patterns of attention across the centers and endpoints of both long and short lines. In each case, the color of the line at each point represents the amount of attention (and the likelihood of probe detection), with darker areas indicating more attention and whiter areas indicating less attention. a: The performance predicted by a model in which attention spreads uniformly through as much of a line as is allowed by available capacity. In short lines this yields uniform attention over the whole object, whereas in long lines this yields uniform attention over only a central portion, with little or no attention at the endpoints. b: The performance predicted by a model in which attention always spreads uniformly through entire objects but becomes more diffuse with increasing spatial extent. c: A schematic depiction of our actual results, illustrating both concentration and amplification: Attention is concentrated at centers compared with endpoints, with centers receiving relatively more attention as line length increases and endpoints receiving relatively less attention as line length increases.

type of attention that could not scale flexibly in real time would be unable to cope with many dynamic real-world situations (e.g., tracking an animal, merging onto a highway).

Further studies will be required to work out several details of this process: Just which types of cues can trigger a shift in the distribution of attention? Just how fast does attention adapt, and what are the rate-limiting factors? How flexible is the adaptation process—for example, can attention adapt in two directions at once for multiple objects, perhaps spreading throughout one object while concentrating on another? All of these questions can be readily addressed using the combination of MOT and probe detection introduced here, and these topics form the core of our current research using this method.

Conclusions

The attentional concentration and amplification effects reported here temper current theories of object-based attention, which often describe object-based effects in terms of the automatic spread of attention through an object or the constraints imposed by structural boundaries across objects. Our results suggest that such effects may be limited in several ways. In particular, uniform attentional spread may not always occur in scenes and tasks (a) with more than two objects, (b) that require sustained attention over time rather than brief bursts of attention, (c) that are constantly changing rather than static, and (d) that involve a high processing load. All of these features were true of the MOT task used here, whereas few of these features hold in other paradigms.

We suggest that all of these features are highly relevant to the project of determining how attention operates in real-world situations, from sports, to driving, to trying to cross a busy intersection. In all of these cases, the visual system must cope with demanding processing constraints so as to sustain attention on multiple moving objects that change in real time. As such, the method introduced here—and the resulting effects of attentional concentration and amplification—may be representative of the allocation of attention under several real-world constraints.

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