The role of eye fixations in concentration and amplification effects during multiple object tracking

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When tracking spatially extended objects in a multiple object tracking task, attention is preferentially directed to the centres of those objects (*attentional concentration*), and this effect becomes more pronounced as object length increases (*attentional amplification*). However, it is unclear whether these effects depend on differences in attentional allocation or differences in eye fixations. We addressed this question by measuring eye fixations in a dual-task paradigm that required participants to track spatially extended objects, while simultaneously detecting probes that appeared at the centres or near the endpoints of objects. Consistent with previous research, we observed concentration and amplification effects: Probes at the centres of objects were detected more readily than those near their endpoints, and this difference increased with object length. Critically, attentional concentration was observed when probes were equated for distance from fixation during free viewing, and concentration and amplification were observed without eye movements during strict fixation. We conclude that these effects reflect the prioritization of covert attention to particular spatial regions within extended objects, and we discuss the role of eye fixations during multiple object tracking.

Theories of visual attention have traditionally assumed that the underlying units of attention are spatial regions: Attention operates in the manner of a spotlight, prioritizing processing for whatever falls within its spatial focus (e.g., Eriksen & Hoffman, 1973; Eriksen & St. James, 1986). In response to such theories, however, a large number of studies in the last two decades have

suggested that selection can also be object based: Attention automatically spreads throughout discrete objects, and/or is constrained by their boundaries (for a review see Scholl, 2001). More recently, theorists have come to see how these views interact: Attention can be both spatially oriented and object based, in different ways and at the same time (e.g., Alvarez & Scholl, 2005; Goldsmith & Yeari, 2003; Soto & Blanco, 2004). These developments can all be illustrated with the paradigm employed in the present studies, multiple object tracking.

MULTIPLE OBJECT TRACKING

In multiple object tracking (MOT; Pylyshyn & Storm, 1988), participants view a display containing a number of identical objects (usually 8–10) moving on independent trajectories. Before they start moving, a randomly chosen subset of the objects is designated as "targets". Participants are instructed to keep track of these targets in order to subsequently identify them once the motion stops. Typically, participants are able to accurately track about four or five objects in this paradigm for at least several seconds (Pylyshyn & Storm, 1988; Scholl & Pylyshyn, 1999; for a review see Scholl, in press).

How do observers segregate tracked objects from distractors? One possibility is that MOT depends on the allocation of spatial attention to target objects. Pylyshyn and Storm, however, argued that a *unitary* spotlight of attention cannot be responsible for MOT, because the targets and distractors are spatially interleaved, and move too fast to allow attention to be switched between individual objects. Alternatively, perhaps spatial attention can be divided into several spotlights, each directed to the moving location occupied by an individual target. Recent variations on the MOT paradigm, however, also render this possibility unlikely. For example, when the tracked entities are presented as substances that appear to "ooze" from one place to another (as a liquid might slide across a surface), tracking is greatly impaired (vanMarle & Scholl, 2003). This suggests that discrete objects are required for successful tracking. Objects have also been directly contrasted with spatial regions or locations via manipulations of objects' structure. In "target merging" manipulations, targets and distractors in MOT are connected in various ways to become parts of the same object (e.g., connecting them via a line segment). In this situation, participants must track only the target *end* of the grouped target/distractor object. However, despite the fact that these endpoints move through exactly the same spatial regions as do the discrete objects in the generic MOT task, tracking is again greatly impaired (Scholl, Pylyshyn, &

Feldman, 2001). This suggests that observers must track *objects*, and find it difficult to keep different parts of the same object separate.

CONCENTRATION AND AMPLIFICATION EFFECTS

The "object-based" MOT demonstrations described earlier are not the whole story, however, since there may also be spatial nonuniformities in the allocation of attention to objects in MOT. Some of these nonuniformities reflect the allocation of attention over large expanses of the visual field. For example, it is easier to attend to a set of objects that span the two hemifields than to a set that spans the top and bottom regions of the same hemifield, suggesting that the two cerebral hemispheres may contain independent tracking mechanisms (Alvarez & Cavanagh, 2005). Here, in contrast, we will focus on nonuniformities in the allocation of attention to *individual objects* during MOT. In particular, two recently reported phenomena (*attentional concentration* and *attentional amplification*) seem to indicate that attention is not uniformly distributed throughout spatially extended objects during MOT (Alvarez & Scholl, 2005).

Alvarez and Scholl (2005) had participants track three of six lines as they moved haphazardly around a display. The lengths of the lines randomly increased and decreased as the objects moved, since each of the lines' endpoints moved independently. To allow for an assessment of the distribution of attention within these objects, participants were required to press a button whenever they detected the appearance of a probe (a small grey circle) during the tracking task. Probes could appear at the centre of an object or near one of its ends. If attention was uniformly distributed over an object during the MOT task (as might be predicted by a simple object-based attention theory), we might expect that probe detection rates would be similar for both centre and end probes. However, this was not the case. Centre probes were detected far more accurately than end probes, suggesting that more attentional resources were concentrated on the centres of the lines than near their ends. This effect was termed "attentional concentration". Furthermore, the attentional concentration effect was modulated by the lengths of the objects being probed: As a line's length increased, centre probes were detected increasingly well and end probes were detected increasingly poorly. In other words, the size of the concentration effect was largest for long lines and smallest for short lines, suggesting that the distribution of attention within an object becomes increasingly concentrated on its centre as its length increases. This effect was termed "attentional amplification", to emphasize that the attentional concentration effect was exaggerated or amplified by increased object length (Alvarez & Scholl, 2005).

THE CURRENT STUDY: A ROLE FOR EYE FIXATIONS?

Although the initial studies of attentional concentration and amplification emphasized the role of covert attentional processes, it is also possible that overt attention mechanisms may be playing a role in these effects. For example, suppose that observers make eye movements between different objects in the display during MOT. Previous work has shown that a saccade to a peripheral target tends to land at the target's centre of gravity, even when this point lies outside the shape (McGowan, Kowler, Sharma, & Chubb, 1998; Vishwanath & Kowler, 2003, 2004). Since the stimuli used in the MOT studies described earlier were lines, their centres of gravity were simply the lines' centre points. In this case, participants may have been more likely to fixate the centres rather than the ends of these objects during tracking—and this sort of differential fixation would favour the detection of centre probes over end probes due to the enhanced acuity in the fovea. Thus, the greater probability of object centres being the targets of fixation might provide an explanation for attentional concentration, and the same mechanism could explain the amplification effect as well if we add the assumption that long lines are fixated more frequently than short lines.[1]

The experiments reported below investigated this possibility by using eye tracking during simultaneous MOT and probe detection tasks similar to those of Alvarez and Scholl (2005). The addition of eye tracking to this paradigm allowed us to compare detection rates for centre and end probes that appeared at similar distances from the locus of eye fixation (in Experiment 1). If the concentration and amplification effects can be explained by differences in eye fixations then we would expect equivalent detection performance for centre and end probes when they appear at similar distances from fixation. In other words, the concentration and amplification effects should be eliminated when differences in the location of fixation are factored out. This possibility can also be investigated by simply forcing observers to fixate centrally while completing both the MOT and probe detection tasks, which is the approach we used in Experiment 2. Together,

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[1] Note that this possibility does not imply that participants *strategically* fixate the objects' centres while tracking spatially extended objects. Rather, our contention is that object centres may be preferentially fixated simply as a result of the normal operation of saccadic eye movements. In fact, Alvarez and Scholl (2005) ruled out potential contributions of higher level strategies in producing concentration and amplification effects by showing robust concentration and amplification under conditions in which such strategies would have favoured the detection of end probes. In one case, the participants' task was to track the endpoints of spatially extended objects; in another case, end probes appeared with a higher probability than centre probes. If attention and/or fixations had been strategically directed to objects' ends in these cases then one would have expected to observe a detection advantage for end probes relative to centre probes— but in fact the concentration and amplification effects were observed in these conditions.

these experiments allow us to test whether attentional concentration and amplification truly reflect new phenomena of covert attention, or whether they might be reducible to previous demonstrations of prioritized saccade target selection at objects' centres of gravity.

EXPERIMENT 1: TRACKING FIXATIONS DURING FREE VIEWING

In this experiment, we attempted to replicate the attentional concentration and amplification effects during free viewing, while monitoring eye fixations.

Method

Participants.   Ten naïve volunteers (ages 19–27 years) were paid \$10/hour for their participation. All participants reported normal or corrected-to-normal acuity and provided informed consent. This experiment was approved by the University of Delaware Human Subjects Review Board.

Apparatus.   Stimuli were generated on a Dell 1.69 GHz computer running custom software written with Blitz3D (Sibly, 2005) and presented on a 17-inch Mitsubishi Diamond Pro CRT (1024) × 768 pixel resolution; 75 Hz frame rate). Testing was conducted in a dimly lit room with a chinrest maintaining a 66 cm viewing distance. Under these conditions, the total viewable area of the screen subtended approximately $27.6° \times 20.7°$.

Eye position was recorded using an ISCAN 60 Hz infrared, camera-based eye-tracker with a spatial resolution of $1°$ (ISCAN, Inc., Burlington, MA) controlled by a Micron 800 MHz computer. A five-point calibration was performed at the beginning of each session and subsequent calibrations were performed as needed.

Stimuli and procedure.   MOT trials consisted of six white objects that moved independently on a black background. The initial positions of these objects were chosen by randomly selecting 12 points to serve as the objects' endpoints and then connecting pairs of endpoints with lines (1 pixel wide). The result was a display that contained six randomly positioned lines of varying orientation and length (see Figure 1).

Motion trajectories for each object were created by independently adjusting the velocities of each object's endpoints. Each of the endpoints was initially assigned random velocities within the range of $+/-2°/s$ separately for horizontal and vertical directions. In order to produce a "wandering" motion pattern, the horizontal and vertical endpoint velocities were modified approximately four times per second by a random amount

Centre Probe   **End Probe**
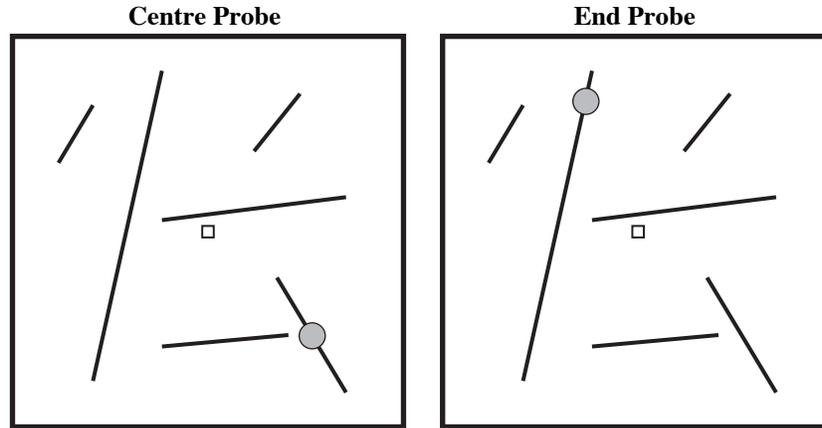
Figure 1. Example stimuli used in these experiments. Participants tracked three (Experiment 1) or two (Experiment 2) lines as they moved around the display. Probes appeared randomly either at the centre (left panel) or near the end (right panel) of an object. Note that the probes are not drawn to scale and the objects were white on a black background.

(range $= +/-0.5°$/s) providing that the horizontal/vertical speeds never exceeded $2°$/s. Note that since the velocity of each endpoint was computed independently, the objects increased/decreased in length and changed orientations haphazardly over the course of each trial. Finally, the endpoint trajectories were also constrained such that all the objects remained visible on the computer screen by reflecting off the edges of the display.

At the beginning of each trial a white fixation box (luminance $= 95.93$ cd/m^2) subtending $0.3° \times 0.3°$ appeared on a black background (luminance $= 0.14$ cd/m^2), but participants were not instructed to maintain central fixation. Participants began each trial by pressing a mouse button to reveal the six objects. A second mouse click caused three target items to blink on and off five times for 133.33 ms each. Once this target cueing was complete, all items moved around the display haphazardly for 20 s. Once the motion phase of each trial ended, the six items remained visible on the screen in their final locations and participants selected each target item with the mouse. Feedback about tracking accuracy was provided immediately by changing the colour of a selected item to green if it was a target and red if it was a distractor.

During the motion phase of each trial probes were presented individually at random intervals such that there was a minimum of 2500 and a maximum of 6000 ms between probe events. Probe presentations were also constrained such that probes were presented at least 2500 ms after the start of the motion

and 1500 ms prior to the end of the motion. This resulted in the presentation of at least two and at most seven probes per trial.

Probes were small grey circles (diameter $= 0.4°$, luminance $= 19.93$ cd/m^2) that appeared for approximately 213 ms and were always located on one of the objects. The particular object on which a probe was presented was selected at random with the constraint that consecutive probes never appeared on the same object. The position of the probe on the object's centre or end was also determined randomly. Probes presented at objects' ends were inset by one probe diameter (as in the right panel of Figure 1). Participants pressed a mouse button as quickly as possible if they detected a probe. Responses that occurred within 1250 ms following probe offsets were scored as hits; responses outside of this time window were scored as false alarms. Feedback about probe detection performance (number of hits, misses, and false alarms) was provided at the end of each trial.

Participants were tested individually, beginning with 10 practice trials of the MOT task followed by 50 experimental trials combining MOT and probe detection. Participants were instructed to prioritize the MOT task over the probe detection task. MOT displays for the practice trials were computed online, but MOT displays for the experimental trials were created offline so that each participant experienced the same tracking trials (albeit in a different random order). The timing and locations of probes were computed online and independently for each participant.

Results

Tracking trials were counted as correct when participants accurately identified all three target objects. As expected, participants were reasonably accurate in the tracking task, achieving an average performance of 86.4% correct. All subsequent analyses of *probe miss rates* utilize data from correct tracking trials only. False alarm rates were very low, averaging only 0.11 false arms per MOT trial, and were not included in any analyses. On average there were 168.4 probe presentations from correct tracking trials per participant; in the analyses here, these probes are considered as a single group, without regard for the specific trials in which they occurred. On average, 28.2% of these probes appeared on target centres, 27.8% appeared on target ends, 23.5% appeared on distractor centres, and 20.5% appeared on distractor ends. Miss rate proportions were arcsine transformed before they were analysed in order to address the non-normality of proportional accuracy data, but the figures depict the more intuitive miss rate percentages.
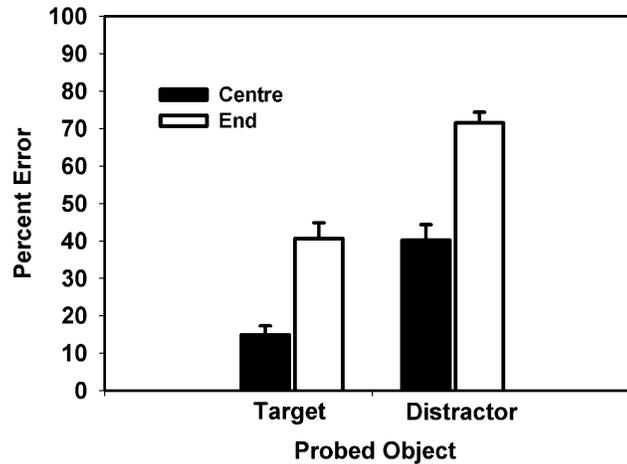
Figure 2. Concentration results for Experiment 1. Probes were detected more readily when they were presented on MOT targets compared to distractors. A concentration effect was observed since centre probes (filled bars) were detected more accurately than end probes (open bars). Error bars represent 1 standard error.

Concentration effect. Figure 2 plots probe miss rates as a function of probe position (centre vs. end of object) and probed object (tracking target vs. distractor). A 2 × 2 (Probed object × Probe position) repeated-measures ANOVA performed on probe miss rates confirmed that we replicated the concentration effect reported by Alvarez and Scholl (2005). There was an overall detection advantage for probes located on tracked targets compared to probes located on distractors, $F(1, 9) = 327.7$, $MSE = 0.003$, $p < .001$, and for probes located at the centres of objects versus their ends, $F(1, 9) = 108.4$, $MSE = 0.009$, $p < .001$. Both of these effects were large, with effect magnitudes in excess of 20% accuracy. The interaction was not reliable, $F(1, 9) < 1$, $MSE = 0.009$.[2]

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[2] One puzzling aspect of these results is that concentration effect (and amplification effect, as reported later) occurred for the distractors as well as the targets, even though observers had no obvious incentive to attend to distractors. This was also true in the studies of Alvarez and Scholl (2005), and it is reminiscent of the finding that probes presented on MOT targets were easier to detect than probes occurring on distractors—which, in turn, were harder to detect than probes presented in empty space (Pylyshyn, 2006; see also Flombaum & Scholl, 2008; Flombaum, Scholl, & Pylyshyn, 2008). Observers are apparently "paying attention" in some way to distractors, if only to suppress them (Pylyshyn, 2006) or to mark some of them as distractors in order to improve guessing performance (Hulleman, 2005). The fact that both targets and distractors show the same nonuniform distribution of attention over the shape of the object suggests that the amplification and concentration aspects of object-based attention may be separable from other processes responsible for determining task relevance.

In order to determine if the concentration effect was related to the distance between the probes and the locus of eye fixation, we created bins based on the distance (in visual angle) between eye fixation and each probe location at the time of its onset. We categorized these distances as very near (less than $4°$), near ($4–8°$), far ($8–12°$), and very far (more than $12°$). Since probes occurred at random intervals, the number of observations within each of these bins varied across participants and bins, but on average there were 10.3 probe presentations per bin for each participant (minimum = 1; maximum = 27). Probe miss rates were then subjected to a 2 (Probed object: Target vs. distractor) × 2 (Probe position: Centre vs. end) × 4 (Probe-fixation distance: Very near, near, far, very far) repeated-measures ANOVA. The results showed a marginal three-way interaction, $F(3, 27) = 2.8$, $MSE = 0.049$, $p = .068$, so we then conducted separate 2 (Probe position) × 4 (Probe-fixation distance) repeated-measures ANOVAs for targets and distractors. The results of these analyses showed that the marginal three-way interaction resulted from a significant two-way interaction between probe position and probe-fixation distance for probes presented on targets, $F(3, 27) = 14.09$, $MSE = 0.031$, $p < .001$, but not distractors, $F(3, 27) < 1$, $MSE = 0.113$.

When probes were presented on targets, the concentration effect was modulated by probe-fixation distance (Figure 3a). More specifically, when probes were presented very near to a fixated location, centre and end probes were detected at similar rates, $t(9) = 0.08$, Bonferroni-corrected, $p > .99$, but centre probes were detected at higher rates than end probes for each of the other three probe-fixation distances: Near, $t(9) = 4.04$, $p < .05$; far, $t(9) = 3.52$, $p < .05$; very far, $t(9) = 4.97$, $p < .001$; Bonferroni corrected ps. In other words, the only case in which concentration effects were not observed was when probes were presented very near to fixation.

When probes were presented on distractors (Figure 3b), centre probes were detected at higher rates than end probes, $F(1, 9) = 24.87$, $MSE = 0.07$, $p < .001$, and probe miss rates increased with probe-fixation distance, $F(3, 27) = 13.67$, $MSE = 0.145$, $p < .001$. In other words, the size of the concentration effect (i.e., the advantage for centre probes) did not vary as a function of distance for distractors even though overall error rates increased as probes appeared further from a fixated location.

Amplification effect.   In order to assess the effect of line length on probe miss rates, line lengths (defined as the length of the probed line at probe onset) were binned into four object length categories. These were classified as very short (less than $6.75°$), short ($6.75–13.5°$), long ($13.5–20.25°$), and very long (more than $20.25°$). Probe miss rates were subjected to a 2 (Probed object: Target vs. distractor) × 2 (Probe position: Centre vs. end) × 4 (Object length) repeated-measures ANOVA. As shown in Figure 4, probes on
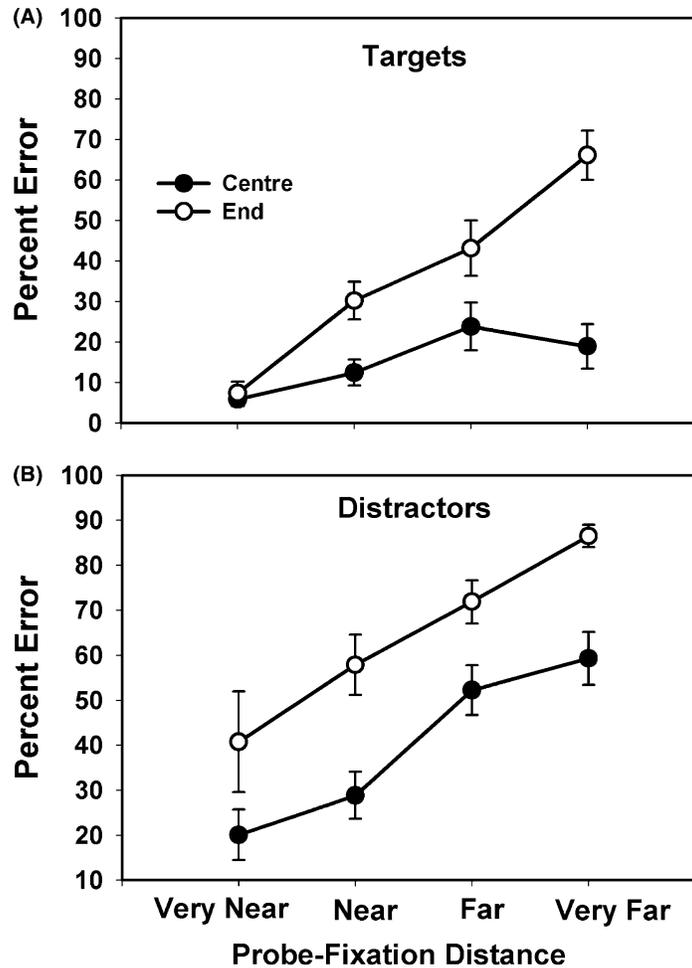
Figure 3. Concentration results as a function of probe-fixation distance for Experiment 1. (A) When MOT targets were probed, centre (filled symbols) and end probes (open symbols) were detected equally often when they appeared very near fixation, but centre probes were detected more accurately (i.e., a concentration effect) for the other three distances. (B) When MOT distractors were probed, centre probes were detected more often than end probes regardless of probe-fixation distance. Error bars represent +/–1 standard error.

tracked targets were detected more often than those on distractors, $F(1, 9) = 151.3$, $MSE = 0.032$, $p < .001$. A significant main effect of probe position was also observed, $F(1, 9) = 44.2$, $MSE = 0.132$, $p < .001$, but this effect was modulated by a Probe position × Object length interaction, $F(3, 27) = 12.02$, $MSE = 0.078$, $p < .001$. Miss rates for centre probes decreased with increased
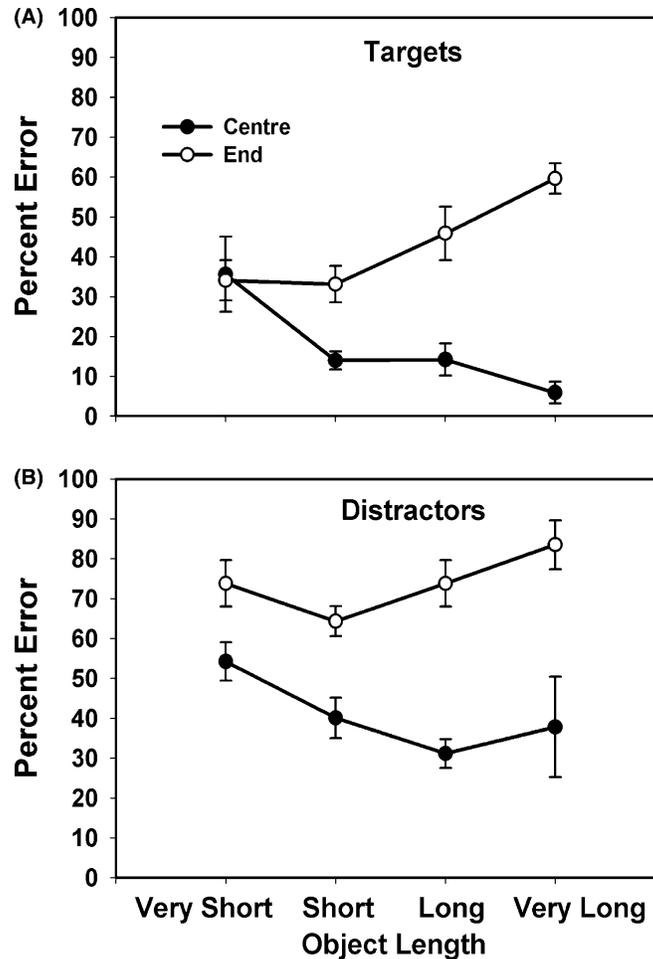
Figure 4. Amplification results for Experiment 1. Miss rates for end probes (open symbols) increased and miss rates for centre probes (filled symbols) decreased with increases in line length for MOT targets (A) and distractors (B). Error bars represent +/–1 standard error.

object length, $F(3, 27) = 6.2$, $MSE = 0.053$, $p < .05$, and miss rates for end probes increased, $F(3, 27) = 7.1$, $MSE = 0.033$, $p < .01$, indicating that the size of the concentration effect increased with object length. In other words, we observed a significant amplification effect that replicated Alvarez and Scholl (2005).

In order to determine if this amplification effect was related to fixation location, a 2 (Probed object: Target vs. distractor) × 2 (Probe position:

Centre vs. end) $\times$ 2 (Object length) $\times$ 2 (Probe-fixation distance) repeated-measures ANOVA was performed. We used object length bins that were short (less than $13.5°$) or long (greater than $13.5°$) and probe-fixation distance bins that were near (less than $8°$) or far (greater than $8°$). It was necessary to use larger bins in this analysis in order to keep cell counts from becoming too small. For this analysis there were, on average, 10.3 probes per condition per participant (minimum $= 1$; maximum $= 23$).

Figure 5 shows probe miss rates for each combination of probed object, probe position, object length, and probe-fixation distance. Recall that amplification refers to the finding that the size of the concentration effect (i.e., the detection advantage for centre probes) is larger for long objects than short objects. The data appear to follow this trend but the effect was not reliable; Probe position $\times$ Object length interaction: $F(1, 9) < 1$, $MSE = 0.066$, $p = .38$. There was, however, a Probed object $\times$ Probe position $\times$ Probe-fixation distance interaction, $F(1, 9) = 6.7$, $MSE = 0.048$, $p < .05$: When tracked targets were probed, centre probes were detected at higher rates than end probes, but this disparity was larger when probes were presented far from fixation, $F(1, 9) = 7.9$, $MSE = 0.022$, $p < .01$. In other words, the size of the concentration effect increased with increased distance from fixation. For distractors, centre probes were detected at higher rates than end probes, $F(1, 9) = 23.5$, $MSE = 0.049$, $p < .01$, and near probes were detected more often than far probes, $F(1, 9) = 16.3$, $MSE = 0.058$, $p < .01$, but the difference between centre and end probes remained constant across probe-fixation distance, $F(1, 9) < 1$, $MSE = 0.021$. In other words, for distractors, the size of the concentration effect remained constant regardless of how far probes were presented from fixation.

Eye fixations.   In order to determine where participants were looking during MOT with free viewing, we computed the distance between eye location and several points of interest (POIs) during each video frame for correct MOT trials. (Sample animations of our displays including traces of observers' patterns of eye fixations can be found online at http://hoffman.psych.udel.edu/MOT/index.html) The amount of time that participants spent fixating a given POI was then computed by simply counting the number of video frames when eye location was nearest, and within one degree of visual angle of, a given POI. We employed the following four POIs. The target centre of gravity was defined as the geometric average of the centre points of each target object. Centre and end POIs were defined as the end or centre point of a given object, for both targets and distractors. Finally, we included a category that consisted of fixations on a given object (target or distractor) that did not satisfy the centre or end conditions. In other words, we also assessed the amount of time spent
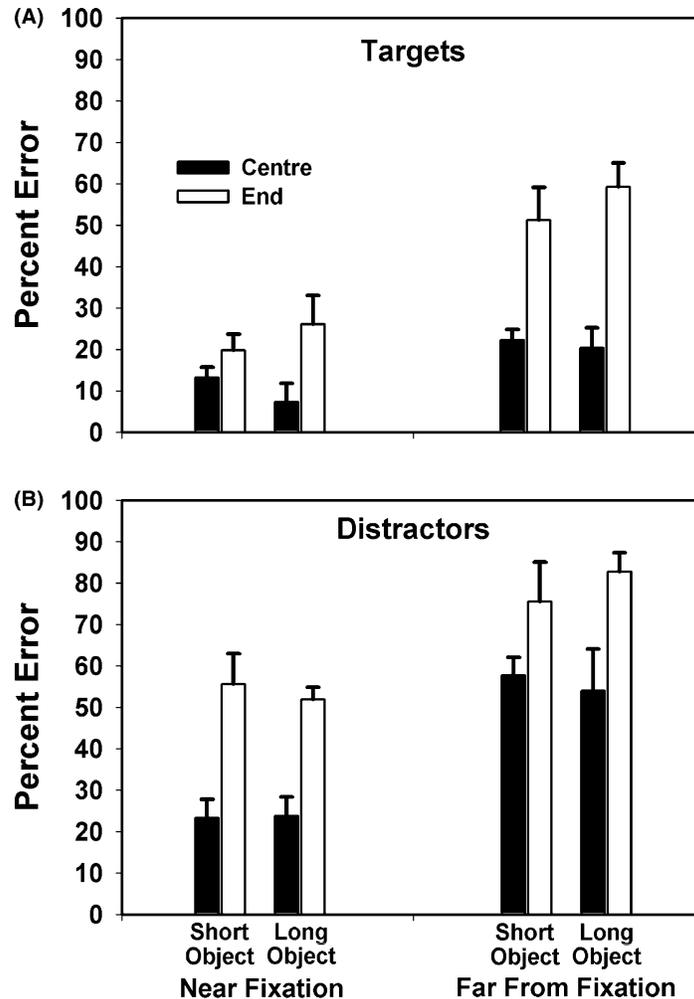
Figure 5. Amplification results for Experiment 1 as a function of probe-fixation distance. When MOT targets were probed (A), overall miss rates were lower than when MOT distractors were probed (B). Increases in line length did not increase miss rates for end probes (open bars) or decrease miss rates for centre probes (filled bars). Error bars represent 1 standard error.

fixating parts of targets or distractors that were neither the centre nor the end.

Figure 6 plots the percentage of time that participants fixated each POI. A one-way repeated-measures ANOVA with POI as the factor showed a significant effect of POI, $F(6, 54) = 158.4$, $MSE = 14.5$, $p < .001$. Planned
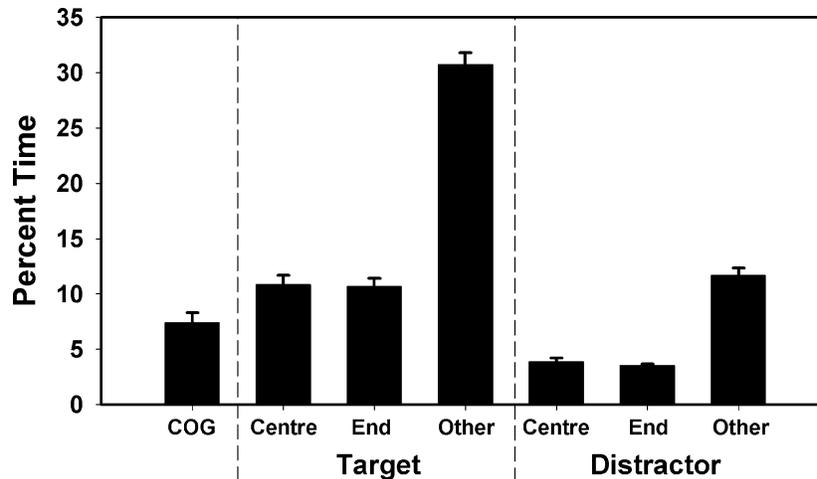
Figure 6. Percentage of time spent fixating various points of interest in Experiment 1. Centre and end probes were fixated for similar durations of time during MOT and target items were fixated more than distractors. Participants spent some time fixating the target centre of gravity (COG) but spent more time fixating items in the display.

contrasts showed that participants spent more time fixating targets than distractors, $F(1, 9) = 114.8$, $MSE = 95.7$, $p < .001$. However, the patterns of eye movements that were observed in this experiment were not consistent with the hypothesis that eye movements were responsible for concentration and amplification effects. As was highlighted previously, one way that eye movements could produce concentration and amplification effects would be if participants preferentially fixated objects' centres rather than their ends. In this case we would expect that participants would spend a larger portion of time fixating the centres of objects compared to their ends. In contrast, there was no difference in the percentage of time spent fixating the centres versus the ends of objects: Target centre vs. end, $F(1, 9) < 1$, $MSE = 4.7$, $p = .79$; distractor centre vs. end, $F(1, 9) < 1$, $MSE = 1.4$, $p = .4$.

It is interesting to note that participants occasionally fixated the centre of gravity of the target items. In fact, they spent more time fixating the target centre of gravity than the centres of distractor objects, $F(1, 9) = 13.9$, $MSE = 9.1$, $p < .01$, but less time fixating the target centre of gravity than the centres of target items, $F(1, 9) = 8.6$, $MSE = 13.6$, $p < .05$. So, while it may be useful to sometimes track the target centre of gravity, participants spent far more time fixating individual targets during MOT (cf. Zelinsky & Neider, in press; Zelinsky, Neider, & Todor, 2007).

Discussion

The results of this study clearly show that the concentration effect is not due to participants preferentially fixating the centres of spatially extended objects during MOT. If this were the case, the concentration effect (i.e., the detection advantage for centre probes) would have been eliminated when centre and end probes were presented at similar distances from eye fixation. However, we observed robust concentration effects even when these distances were equated in the analyses. One notable exception was the case in which probes were presented on tracked targets very near to fixation, where we found equivalent detection rate for probes presented at centres and ends. In this case, probes likely benefited both from relatively good visual acuity and the allocation of attention to target items such that probes were easily detected at high rates regardless of where they appeared on the target object. In other words, the lack of a concentration effect in this particular condition is likely the result of a ceiling effect: By definition, these were probes that just happened to appear literally right in front of the observers' eyes.

The amplification results were somewhat less clear. On one hand, we replicated the amplification effect (i.e., larger concentration effects for longer objects) reported by Alvarez and Scholl (2005), and in fact this effect was large—with the magnitude of concentration more than doubling for targets when comparing short versus very long lines. On the other hand, we failed to find significant amplification when probes were presented at similar distances from eye fixation. We might be tempted to conclude from this that the amplification effect is due to differential patterns of fixation for long versus short objects, but this conclusion should remain tentative for at least two reasons. First, though the amplification effect was not significant when probes were equated for distance from fixation, the effect was in the right direction, and so the resulting null effect may have reflected inadequate statistical power. Second, we may have minimized our chances of finding amplification effects because we were forced to use only two levels of line length in our analysis (in order to avoid overly small cell samples). For example, suppose that the smallest concentration effects would be observed for extremely short lines and that the largest concentration effects would be observed for extremely long lines. A comparison of concentration effects for these two cases would then maximize our chances of observing differences in the size of the concentration effects (i.e., of observing the amplification effect) because the mean difference between these conditions would be as large as possible. However, in our analysis extremely short and extremely long lines were each binned together with lines of more moderate length, which may have caused us to underestimate the size of the concentration effect for

long lines and to overestimate the size of the concentration effect for short lines.

EXPERIMENT 2: TRACKING WITHOUT EYE MOVEMENTS

In Experiment 1, observers were free to move their eyes while performing the MOT task and we evaluated the role of eye fixations in producing concentration and amplification effects by equating centre and end probes "after the fact"—i.e., during the analyses—by measuring each probe's distance from fixation. In this experiment, we controlled eye fixation by requiring observers to maintain fixation on the centre of the display while performing the same MOT and probe detection tasks as in the first experiment. If concentration and amplification effects do not depend on the particular pattern of eye fixations produced during free viewing, we should be able to observe them when participants maintain central fixation.[3]

Method

This experiment was identical to Experiment 1, except as reported here. Fifteen naïve volunteers (ages 18–29 years) were paid $10/hour for their participation. The key difference between this and the previous experiment was that observers were instructed to maintain central fixation during the motion phase of the tracking task. Eye tracking was used to monitor fixation and trials in which the eye deviated more than $1.6°$ from fixation were excluded from the analyses.

Pilot data suggested that adding the requirement to maintain fixation during MOT and probe detection tasks made the tasks too difficult when using display parameters identical to those of Experiment 1. (Note that in some ways this is a "triple-task", since maintaining fixation for extended periods of time while viewing these displays can be a difficult task on its own.) Since the primary dependent variable in this study was probe detection performance for *correct tracking trials without eye movements*, the following changes were made in order to minimize the number of tracking trials that would have been excluded from the analyses as a result of incorrect tracking or eye movements: Participants tracked two out of six objects (rather than three out of six as in Experiment 1); the speed of the

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[3] Observers in Alvarez and Scholl (2005) were not required to maintain fixation, but in the Supplementary Appendix to that paper, these authors nevertheless showed that the concentration and amplification effects persisted when probes at objects' centres versus ends were equated for their distance from the centre of the display.

objects was reduced by half from Experiment 1; changes in velocity occurred half as frequently as in Experiment 1; and the object locations were restricted to the central $22.2° \times 15.3°$ of the display. In order to keep probe detection performance below ceiling, the probes were a slightly darker grey (i.e., with a lower contrast relative to the display background) than in the previous experiment (luminance $= 12.13$ cd/m^2). As in the previous experiment, participants were instructed to prioritize MOT accuracy over probe detection.

A set of 75 MOT trajectories were computed offline for the experimental trials. Initially a random subset of 50 of these MOT trials was allocated to each participant. However, in order to obtain enough probe presentations per cell, trials that contained eye movements were replaced using the remaining precomputed trajectories. The experimental trials ended either when a participant completed a total of 50 trials that did not contain eye movements, or when a participant had completed all 75 precomputed trial trajectories. During the experiment, eye blinks were occasionally counted as eye movements, but this problem was subsequently corrected offline. As a result, the number of trials without eye movements varied slightly across participants. On average there were 51.7 such trials per participant.

Results

A tracking trial was scored as correct when participants accurately identified both target objects at the end of the motion phase, which they did on 84.6% of trials. Only probe detection data from correct trials were used in subsequent analyses. On average there were 166.5 valid probe presentations for each participant. On average 29.6% of these probes appeared on target centres, 28.3% appeared on target ends, 20.5% appeared on distractor centres, and 21.6% appeared on distractor ends. False alarm rates were very low, averaging only 0.05 false alarms per MOT trial, and so were not included in any analyses. As in Experiment 1, our analyses considered all probes as a single set (without regard for the specific trials in which they occurred) and miss proportions were arcsine transformed for the analyses (but not in the figures).

Concentration effect. Figure 7 plots probe miss rates as a function of probe position (centre vs. end) and probed object (target vs. distractor). A 2×2 (Probe position $\times$ Probed object) repeated-measures ANOVA performed on probe miss rates indicated that probe detection accuracy was higher for targets than distractors, $F(1, 14) = 6.45$, $MSE = 0.008$, $p < .05$. We also observed a concentration effect in which centre probes were detected
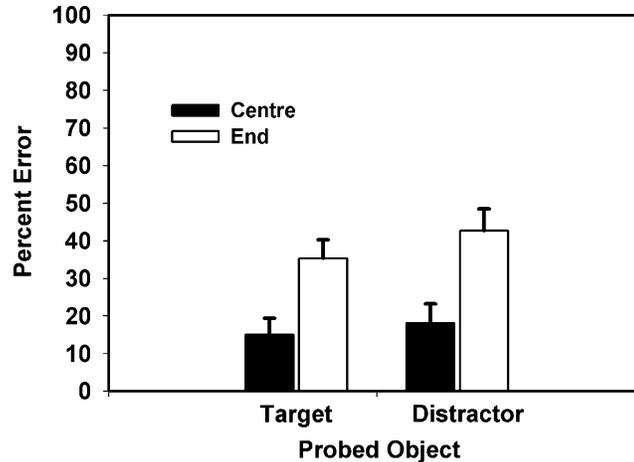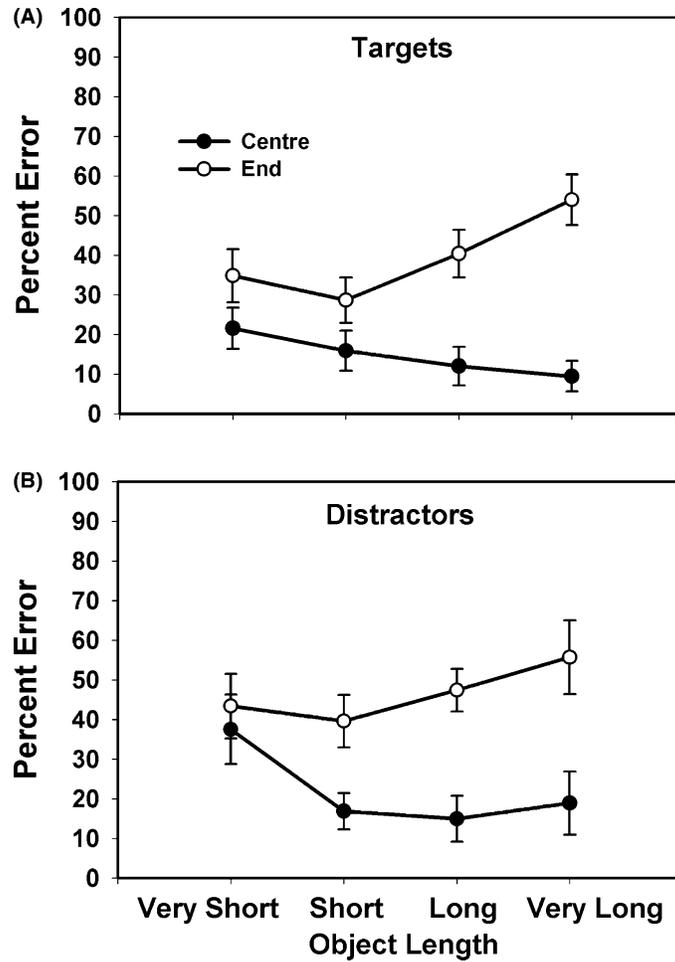
Figure 7. Concentration results for Experiment 2. Probes presented on MOT targets were detected at higher rates than probes on MOT distractors. Centre probes (filled bars) were detected at higher rates than end probes (open bars). Error bars represent 1 standard error.

more often than end probes, $F(1, 14) = 126.2$, $MSE = 0.011$, $p < .001$. The interaction between probe position and probed objects was not reliable, $F(1, 14) < 1$, $MSE = 0.009$.[4]

Amplification effect.   In order to assess the effect of line length on probe miss rates, line lengths at the moment of probe onset were binned into four object length categories. These were classified as very short (less than 5.4°), short (5.4–10.8°), long (10.8–16.2°), and very long (more than 16.2°). Probe miss rates were subjected to a 2 (Probed object: Target vs. distractor) × 2 (Probe position: Centre vs. end) × 4 (Object length) repeated-measures ANOVA. As shown in Figure 8, probes on targets were detected more often than those on distractors, $F(1, 14) = 6.04$, $MSE = 0.077$, $p < .05$. A significant main effect of probe position was also observed, $F(1, 14) =$

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[4] In order to ensure that the observed concentration effect was not produced by inadvertent differences in probe eccentricity produced by random probe presentations, we performed a binned analysis similar to that of Experiment 1. A 2 (Probed object: Target vs. distractor) × 2 (Probe position) × 4 (Probe-fixation distance) repeated-measures ANOVA revealed a significant interaction between probe position and probe-fixation distance, $F(3, 42) = 4.44$, $MSE = 0.074$, $p < .05$. As was the case for target probes in Experiment 1, significant concentration was not observed for probes presented very near to fixation, $t(14) = 0.81$, Bonferroni-corrected $p > .99$, but significant concentration was observed for each of the other three probe-fixation distances: Near, $t(14) = 3.56$, $p < .05$; far, $t(14) = 7.51$, $p < .001$; very far, $t(14) = 5.43$, $p < .001$; Bonferroni corrected ps.

Figure 8. Amplification results for Experiment 2. Miss rates for end probes (open symbols) increased and miss rates for centre probes (filled symbols) decreased with increases in line length for MOT targets (A) and distractors (B). Error bars represent $+/-1$ standard error.

83.7, $MSE = 0.092$, $p < .001$, but this effect was modulated by a Probe position $\times$ Object length interaction, $F(3, 42) = 19.9$, $MSE = 0.045$, $p < .001$. Miss rates for centre probes decreased with increasing object length, $F(3, 42) = 13.3$, $MSE = 0.023$, $p < .001$, while miss rates for end probes increased, $F(3, 42) = 7.2$, $MSE = 0.036$, $p < .01$, indicating that the size of the

concentration effect increased with object length. In other words, we observed a significant amplification effect in the absence of eye movements.[5]

Discussion

The results of this experiment demonstrated that concentration and amplification effects can be observed when participants maintain central fixation during the MOT task. This is important because it shows that eye movements are not necessary to observe concentration and amplification. This suggests that these effects may be due to differential allocation of covert attention to the centres of objects during MOT and that this concentration of covert attention becomes amplified with increased spatial extent.

GENERAL DISCUSSION

The displays used in the experiments reported here required observers to devote sustained attention to moving, spatially extended objects. Two new phenomena—attentional concentration and amplification—have recently been suggested to operate under such conditions (Alvarez & Scholl, 2005), and the goal of the present study was to evaluate whether these phenomena reflect newly discovered effects of covert attentional selection, or whether they could be explained by appeal to the previously discovered phenomena of prioritized eye fixations on objects' centres of gravity.

Eye movements during tracking of multiple spatially extended objects

Before discussing the concentration and amplification effects themselves, it is perhaps worth noting that the pattern of eye fixations during the free-viewing conditions of Experiment 1 was in some ways unexpected. In particular, the participants in this experiment spent far more time fixating individual targets during MOT then they did fixating at or near the targets' collective centre of gravity. This is a different pattern of fixations than that which seems to emerge when tracking local punctate objects. For example,

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[5] In order to ensure that the observed amplification effect was not produced by inadvertent differences in probe eccentricity produced by random probe presentations, we performed a binned analysis similar to that of Experiment 1. A 2 (Probed object) $\times 2$ (Probe position) $\times 2$ (Object length) $\times 2$ (Probe-fixation distance) repeated-measures ANOVA revealed a significant interaction between probe position and probe-fixation distance, $F(3, 42) = 4.44$, $MSE = 0.074$, $p < .05$, indicating that the size of the concentration effect increased with object length. In other words, reliable amplification was observed.

one recent study conducted in parallel to ours (Fehd & Seiffert, 2008) reported that when tracking three out of eight dots, observers spent more time fixating the targets' centre of gravity than they did fixating the individual dots. (Another study, though, found that such effects held only for smaller tracking loads, in displays with 3-D cues; Zelinsky & Neider, in press.) The direct contrast between these results and those of Experiment 1 suggest that we should be cautious in generalizing any such patterns to "MOT" in general. It may be not be true in all circumstances, e.g., that "observers tend to look toward the centre of multiple targets" (Fehd & Seiffert, 2008). Instead, patterns of eye fixations may depend on the details of such displays (cf. Fazl & Mingolla, 2007).

One possibility is that centre-of-gravity patterns may apply to punctate objects, but that different patterns may prevail in more challenging displays in which the objects are spatially extended and frequently overlapping. Why might this be the case? As suggested in some earlier studies, tracking relatively punctate objects may in many ways be a much easier task, despite the lower overall amount of display "real estate" they involve, since there is always a single unambiguous point for attention to select (vanMarle & Scholl, 2003). In contrast, the long lines used here may not initially have a single locus for attention to select, and so it may be more natural for observers to frequently view individual items during the tracking. In addition, the frequent overlap among the extended lines and their close proximity, especially when adjacent lines are parallel, may require good acuity to maintain the distinction between targets and nearby distractors. Future work will clearly have to study the oculomotor dynamics of MOT during different tasks and styles of motion to determine which patterns of fixation dominate in which conditions.

Another possibility is that the probe-detection task that participants performed in our experiments may have biased observers' gaze toward individual objects. In particular, observers may have looked away from the centre of gravity of the targets in an attempt to detect probes that could occur on the individual objects—even though they were instructed to prioritize the MOT task. This possibility is also highly relevant to the oculomotor behaviour that occurs while tracking multiple objects in the real world. There are many such situations—including driving, sports, air-traffic control, or even simply keeping track of children on a playground. Some such situations may lend themselves to "pure" spatiotemporal tracking (as in most MOT tasks), since there is no need to simultaneously detect or discriminate any of the objects' features. (If you're trying to cross a busy highway, for example, the locations and trajectories of the vehicles matter, but their colours and shapes may not.) Most such situations, however, require you to simultaneously track the objects while processing their features in some way. (In air traffic control, controllers must simultaneously keep track of multiple

aircraft in 2-D displays while also processing the proximate labels that indicate aircraft altitudes. On a basketball court, you must not only track players but notice what they're doing with the ball. And on a playground, you care not only where the children are, but what they are doing.) In this way, the dual-task MOT-plus-probe-detection experiments used here and in other recent studies (Alvarez & Scholl, 2005; Flombaum & Scholl, 2008; Flombaum et al., 2008; Pylyshyn, 2006) may in fact be more characteristic of real-world tracking—and so the oculomotor behaviour during such tasks as reported here may be more indicative of that during real-world tracking than are the eye-movement patterns during "plain" MOT.

Concentration and amplification: Effects of covert attention

The primary purpose of this study was not to evaluate eye movements during MOT per se, but rather to evaluate their influence on concentration and amplification effects. Attentional concentration has been defined as prioritized attentional selection at the centres of uniform spatially extended objects. We replicated this effect in the present experiments: Probes presented at the centres of lines were detected more readily than probes presented near their ends. Attentional amplification has been defined as increased concentration of attention at the centres of objects as those objects grow longer. We also replicated this effect in the present experiments: The superiority of detection for centre relative to end probes was enhanced on longer objects.

Although these results were originally interpreted in terms of the distribution of *covert attention* within uniform objects during MOT, a viable alternative hypothesis was that these effects could be caused by a tendency to *fixate* on the centres of objects. This would be consistent with the finding that saccades to peripheral objects tend to land on objects' centres of gravity (e.g., Vishwanath & Kowler, 2003, 2004), and would explain the data without appeal to any new phenomena of covert attention: Fixated probes would simply enjoy an acuity advantage over probes appearing in more peripheral retinal locations, and this effect could increase for longer lines under the assumption that longer lines are more likely to be fixated at any given time (e.g., because they take up more space on the display).

The results of the current experiments did not support this alternate explanation. If such effects were due to preferential fixation on the centres of objects rather than their ends, then the effects should have disappeared when fixation locations were equated. Instead, we observed a robust concentration effect when analyses were conducted over probes matched for their distances from the locus of eye fixation (in Experiment 1), and both the concentration and amplification effects were obtained when eye movements were eliminated altogether (in Experiment 2).

These observations strengthen the claim that concentration and ampli-
fication effects reflect a nonuniform distribution of covert attention within
objects during MOT, as described by Alvarez and Scholl (2005). Under this
interpretation, the concentration effect indicates that more attentional
resources are allocated to the centres of objects than to their ends during
MOT. In this case, centre probes would be easier to detect because there
would be a greater degree of attention in those intraobject locations, and
apparently attention concentrates to an ever greater degree in this way as
objects become more spatially extended. These effects may reflect the
difficulty of tracking spatially extended objects in the first place: Because
there is no single, explicit location for attention to select, a prioritized
location may have to be effectively "constructed" via an uneven attentional
allocation. Moreover, the need for such an approach may directly reflect the
degree to which there fails to be a single salient point location for such
objects, such that the prevalence of this effect (i.e., attentional amplification)
would increase as the lines grow longer. Further work is necessary to explore
such possibilities, but the present results confirm that these effects are indeed
novel phenomena of covert attention, rather than reflections of more
traditional phenomena of overt fixation patterns.

More generally, given that current conceptions of object-based attention
might predict that attention would be uniformly distributed throughout an
object, the phenomena of attentional concentration and amplification are
somewhat surprising. At this point, however, it is not clear whether these
phenomena are specific to visual tracking, or whether they would occur
during object-based attention more generally. It may be that attention must
be concentrated at the centre of elongated objects in order to *track* them over
time and space. Alternatively, it may be necessary to concentrate attention
on object centres in order to *select* them even in cases that do not require
tracking. Of course further research would be needed to explore these
possibilities, but along with the concentration and amplification phenomena
themselves, they indicate how the processing of space and objects may
interact richly during covert attentional selection.

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