Some puzzling findings in multiple object tracking (MOT):
II. Inhibition of moving nontargets

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Abstract

We present three studies examining whether multiple-object tracking (MOT) benefits from the active inhibition of nontargets, as proposed in (Pylyshyn, 2004). Using a probe-dot technique, the first study showed poorer probe detection on nontargets than on either the targets being tracked or in the empty space between objects. The second study used a matching nontracking task to control for possible masking of probes, independent of target tracking. The third study examined how localized the inhibition is to individual nontargets. The result of these three studies led to the conclusion that nontargets are subject to a highly localized object-based inhibition. Implications of this finding for the FINST visual index theory are discussed. We suggest that we need to distinguish between the differentiation (or individuation) of enduring token objects and the process of making the objects accessible through indexes, with only the latter being limited to 4 or 5 objects.

Introduction

The idea of attention-related inhibition has been around for some time and has played a role in accounting for a wide range of phenomena, from memory to perceptual selection. The construct of inhibition has played a wide roll in vision science and has been an essential postulate in neuroscience theorizing, especially since the addition of inhibition as one of the basic processes in the formation of neural circuits (Houghton & Tipper, 1996; Milner, 1957). Yet the idea that the visual system might use inhibition to keep irrelevant (distractor) items from interfering with a primary task is not as well-studied. Recently (Watson & Humphreys, 1997) argued that items could be inhibited by a top-down process, called "visual marking," based on the need to keep items with some particular properties out of reach of a primary search task. Many researchers have now replicated this finding and have also confirmed the goal-directed nature of the inhibition (Atchley, Jones, & Hoffman, 2003; Baylis, Tipper, & Houghton, 1997; Braithwaite & Humphreys, 2003) – although there is a question of whether the effect is purely top-down or whether it must be mediated by such visual events as abrupt onsets or offsets (Donk & Theeuwes, 2001).

In (Pylyshyn, 2004) we suggested that inhibition of nontarget items might help us to understand what goes on in the experimental paradigm known as Multiple Object Tracking (MOT). MOT has been used by a number of laboratories to study aspects of visual attention (see the review in Pylyshyn, 2001). In this experimental paradigm, observers track 4 or 5 objects (the "targets") that move randomly among a set of identical, independently-moving objects (the "distractors"). While there are many variants of the MOT task, a typical experiment is illustrated in Figure 1. A number of simple items (typically about 8 circles or squares) are displayed on a screen. About half of these elements are briefly made visibly distinct, often by flashing them on and off a few times. Then all objects move randomly and independently. Sometimes the motion of the objects is constrained so they do not collide, but in recent work they more often travel independently and are allowed to occlude one another. After some period of time the motion stops and observers are required to indicate which objects are the targets. The experiment (and

its many variants) has repeatedly shown that observers can track up to 4 and 5 items in a field containing the same number of identical distractor items over a period of up to 10 seconds with an accuracy of 85% - 95%.
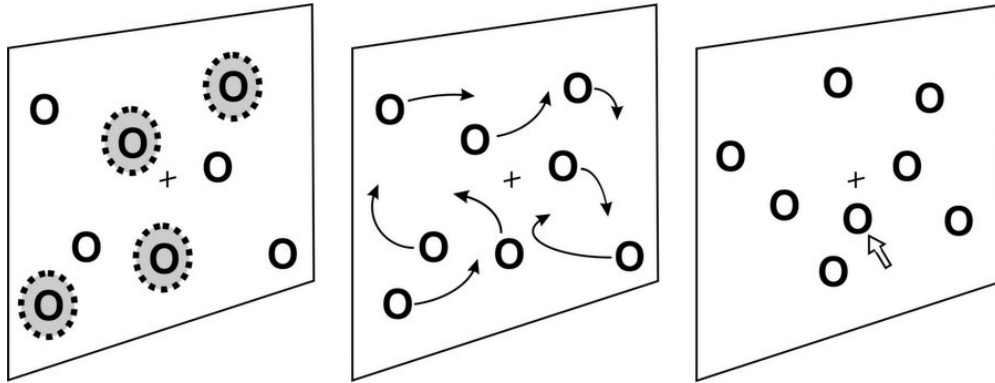
Figure 1. The sequence of events in a typical MOT experiment, in which the observer uses a computer mouse to indicate which items had been flashed at the beginning of the trial (shaded circles indicate items being flashed at the start of the trial).

The reason that we suggested that nontargets may be inhibited in this paradigm is that it would help account for the following puzzling finding. If we provide a unique identifier for each target (e.g., a number appearing inside the circle or a unique starting location such as one of the corners of the screen) observers are poor at recalling which identifier goes with which target, even when they have correctly tracked the targets in question. We showed that this arises because observers confuse (and switch identities between) target-target pairs more often than target-nontarget pairs. If the nontargets were inhibited this result would make sense since nontargets would effectively be taken out of the set of contending stimuli. This, in turn, entails that either everything that is not tracked is inhibited, or else that the individual moving nontargets alone are inhibited. Without some independent baseline measure of enhancement or inhibition, the first option (everything except targets is inhibited) is indistinguishable from the more natural view that tracked objects are attentionally enhanced.

The apparent enhancement of tracked targets relative to nontargets is well established and is implicit in MOT studies that required observers either to judge whether a selected item is a target or to detect/discriminate a feature on an item (Pylyshyn & Storm, 1988; Scholl & Pylyshyn, 1999; Sears & Pylyshyn, 2000). The object-based nature of this apparent enhancement has also been demonstrated in studies that measured either detection (Intriligator & Cavanagh, 1992) or discrimination of events on or off targets (Sears & Pylyshyn, 2000). There is also considerable evidence for the inhibition of nontarget locations in a variety of tasks. This includes evidence from studies of Inhibition-of-Return (in which attention is removed from one focus and switched to another, leaving behind some inhibition at the first locus, see Klein, 2000; Klein, 1988). In addition many investigators have shown that nontarget items in a search task are inhibited (Braithwaite & Humphreys, 2003; Cave & Bichot, 1999; Horowitz, 1996; Koshino, 2001; Mueller & Muehlenen, 2000; Wolfe & Pokorny, 1990). Among the latter are a set of studies that propose a mechanism called "visual marking" for keeping known nontargets clear of the search itself (Donk & Theeuwes, 2001; Olivers, Watson, & Humphreys, 1999; Theeuwes, Kramer, & Atchley, 1998; Watson & Humphreys, 1997; Watson & Humphreys, 2000). The possibility that the inhibition applies to individual nontargets – as opposed to applying to the entire region outside the targets themselves, has been suggested by a number of investigators. For example, there is evidence that moving items can be inhibited if they can be treated as a group, either

because they share a common feature such as color (Braithwaite & Humphreys, 2003; Braithwaite, Humphreys, & Hodsoll, 2003), or because they maintained a rigid configuration (e.g., Kunar, Humphreys, & Smith, 2003; Watson, 2001; Watson & Humphreys, 1998a).

The original "visual marking" proposal (Watson & Humphreys, 1997) suggested that inhibition operates by targeting particular locations in a display. This idea was subsequently expanded to deal with the inhibition of moving objects by proposing that entire feature maps might be inhibited even if its members were moving (Watson & Humphreys, 1998b). The possibility of purely object-based inhibition of moving items has also been discussed in the literature dealing with Inhibition-of Return (IOR), where it was found that IOR tends to move with the inhibited object (Christ, McCrae, & Abrams, 2002; Tipper, Driver, & Weaver, 1991) rather than remaining fixed at the location initially inhibited. But IOR is not exactly the same as visual marking – it involves the inhibition of formerly attended items and is typically measured in relation to detection performance on the formerly attended item or location (it also differs from other forms of inhibition in terms of its time-course). There has been little evidence of object-based inhibition or visual marking occurring in paradigms such as MOT, where inhibition may function to facilitate performance in a task such as tracking or search. The one exception is a study by (Ogawa, Takeda, & Yagi, 2002), who showed object-based visual marking (which they refer to as "inhibitory tagging") in randomly-moving visual objects. Using a set of moving search items, they confirmed the earlier finding (Klein, 1988) that in difficult (non-popout) search, rejected nontarget items exhibit object-based inhibition, as assessed by a probe detection task. This suggests that individual moving nontargets might be "visually marked" in the Watson & Humphreys sense. Such punctate object-based inhibition might, in turn, explain the relatively low level of target-nontarget identity-switching reported in (Pylyshyn, 2004).

The possibility that nontargets are individually inhibited relative to the entire display (including relative to the background) has ramifications for theories of tracking such as the FINST Visual Index Theory (Pylyshyn, 2001). The FINST theory (as well as theories of MOT based on split attention Scholl, 2001) postulate a limited capacity mechanism that keeps track of target objects *qua individual objects*, despite changes in their properties, including their locations. According to such accounts, however, non-target objects are not tracked and therefore there is no provision for keeping inhibition attached to them in a punctate manner without at the same time inhibiting the entire extra-target region. Thus it is of some theoretical interest whether in tasks such as MOT inhibition occurs on nontargets relative to both targets and empty space. The present experiments were designed to examine this question.

General Method

The experiments reported here were designed to examine whether nontargets in the MOT task are inhibited relative to targets and *also* relative to the background of the display. The measure of inhibition used was the dot-probe detection task, a task used with success by (Watson & Humphreys, 1997) as well as others (Donk & Theeuwes, 2001; Olivers et al., 1999; Theeuwes et al., 1998; Watson & Humphreys, 1998b) to measure inhibition effects on specific visual items. The measure assumes that performance in detecting a small faint dot in a particular location provides an indication of the availability of attentional resources at that location, and therefore that it serves as a measure of either attentional enhancement or inhibition. Because we are interested in distinguishing attentional enhancement from inhibition, we need to compare the measure for at least three distinct locations: for example, on targets, on nontargets and in the empty space between them. If the effect is one of inhibition, then probe detection should not only be worse on nontargets than on targets, but it should also be worse on nontargets than at

other locations. Experiment 1 presents the basic study. Other experiments control for various possible confounds and also explore the spatial distribution of attention or inhibition.

Materials and apparatus

The experiments were programmed using the VisionShell© graphics libraries (Comtois, 2003) and were presented on iMac computers. The circles in the tracking task consisted of white outline rings (with a luminance of 55.8 cd/m^2) with dark interiors and were displayed on a dark background. The interior dark region was drawn as opaque so that when one of the circles passed by another, occlusion cues (T-junctions) showed one of the circles to be in front of the other. The circles were 47 pixels or 2.7 degrees of visual angle with outer rings 2 pixels (approximately 0.12°) thick.

The motion algorithm is the same as that used in other recent MOT experiments. Each circular item was assigned a random initial location and a horizontal and vertical velocity component chosen independently at random from the values -2, -1, 0, +1 and +2 pixels/frame (with frames lasting 17.1 ms). These could be incremented or decremented on each video frame by a single step, with a probability referred to as the "inertia" of the motion. In the present experiments, this probability was set at 0.10, which kept the objects from changing velocity too suddenly. Since the position of each item was determined independently, this results in independent and unpredictable trajectories within the permitted range. In the resulting motion, items could move a maximum of 0.12° vertically or horizontally per frame buffer. Since frame buffers were displayed for 17.1 ms each (corresponding to two screen scans of 8.55 ms for the iMac's 117 Hz monitor), the resulting item velocities were in the range from 0 to 7.02 deg/s, with an average velocity across all items and trials of 2.37 deg/s. When a circle reached the perimeter of the buffer it was reflected from the edge by reversing the perpendicular component of its velocity.

The probe dot used in experiments 1 and 3 was a red square of 6 x 6 pixels (approximately 0.34° x 0.34°) with a luminance of 7.72 cd/m^2 displayed for 128 ms (a slightly different probe was used in Experiment 2 as we were exploring whether a more difficult probe might lead to stronger effects). Probes were present on half the trials and occurred equally often among the locations being tested in each experiment (e.g., in Experiments 1 and 2 they occurred equally often on targets, nontargets or in the space between them; in Experiment 3 they could occur at two additional locations). On trials containing probes, the probes occurred once at a randomly chosen time in the third or fourth second of the 5 second trial.

Procedure

After being instructed on the tracking and probe detection responses required, observers were told that since only trials in which they correctly tracked the targets could be used, they should place special emphasis on the tracking part of the task. Participants pressed a key to start each trial. There were 5 practice trials at the beginning of each experiment. Each trial began with 8 static circles in the screen. Four of these flashed on and off a few times, then all 8 circles began to move. After 5 seconds, all circles stopped moving. Observers then had to select the four circles that had been indicated as targets, using a computer mouse. After making these 4 responses, a screen appeared with the question: "Did a red dot appear anywhere during this trial?" and observers made a forced choice response by selecting one of two labeled buttons on the screen. All responses were recorded automatically and stored on the computer disk. Only after the set of 5 responses were completed was the next trial allowed to proceed. The number of trials and other aspects of the design varied with each experiment and are described separately for each case.

Experiment 1

Participants

Eighteen Rutgers undergraduates participated either as part of their course requirements or for remuneration. Two additional participants were omitted from the analysis because their overall tracking performance or probe detection performance was too low (tracking below 65% or probe detection below 50%).

Method

The method was as described above. In the Empty Space condition a probe location was chosen at random subject to the constraint that it was located at least two diameters (5.4 °) from any other circle or from the edge of the screen. In the Target and Nontarget conditions the probe was always located at the center of the circle. There were 240 trials in all with a break after each 80 trials.

Results

Probe-dot detection performance was analyzed using a within-subject ANOVA.   The effect of location was significant, $F(2,34) = 21.3$, $MSE = 35.97$, p<000. A post-hoc paired comparison of the performance at 3 locations revealed that probe detection at the nontarget location was significantly worse (p <.001) than at either the Target location or the Empty Space location. There was no statistically reliable difference between the Target location and the Empty Space location (p>.32) (using the Bonferroni correction for multiple comparisons). These results are shown in Figure 2.

The tracking performance was also analyzed and showed that performance did not differ significantly when probes occurred in different locations, $F(2,34) = 2.88$, $MSE = .001$, p>0.07. Tracking was 88.6%, 90.5%, and 91.2% for the probe on Nontargets, Empty Space and Targets, respectively. When there was no probe, tracking performance was 89.6%, which is just about at the median.
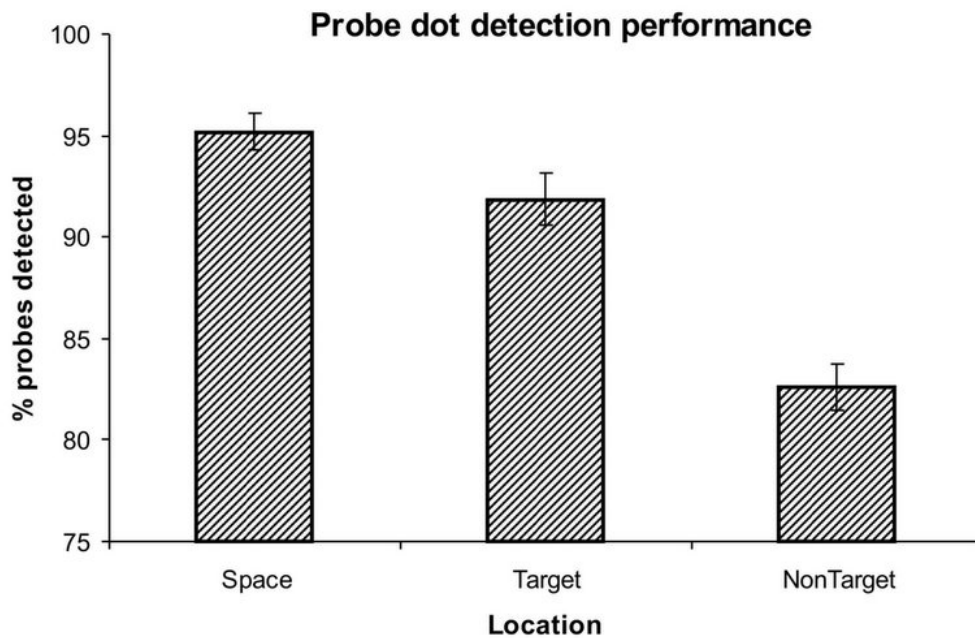
Figure 2. Performance in detecting a probe dot at three types of locations during a multiple object tracking task (in this and all other graphs, error bars represent standard errors).

Discussion

These results provided support for the hypothesis that in MOT the Nontarget items are inhibited relative to the target items and also relative to the empty space between items. Probe detection on targets and on empty space did not differ significantly.

Although the inside of the circular objects was the same color and brightness as the background, it is possible that a probe occurring far from a moving object might be more easily detected than one occurring on an object, independent of any effect of the tracking itself. A probe that occurs at the center of a 2.7 ° diameter circle is more likely to be subject to masking than one that is surrounded by empty dark space. This would not affect the difference between probe detection on targets and nontargets, since these are physically identical, but it could effect the detection of probes in the empty space condition. Thus it might be that the effect we found, in which detection in empty space was more like that on targets, was the result of the superiority of empty space detection, superimposed on the enhanced detection on targets. In other words it might be that the empty space is actually inhibited as much as the nontargets, but that the greater visibility in the empty region raised probe detection performance. If that were the case we would not be entitled to conclude that inhibition was specific to nontargets, as opposed to being a general inhibition of everything in the scene, and thus it might be that what we were observing was the effect of the relative enhancement of targets.

The problem of controlling for masking effects is ubiquitous in studies of probe detection where the difference between detection of probes on objects and in empty space is of interest. Several designs have been proposed to control for baseline differences between probes on objects and probes in empty space. One method, used by (Cepeda, Cave, Bichot, & Kim, 1998;

Humphreys, Stalmann, & Olivers, 2004) is to populate the background with elements that are physically the same as the target and nontarget objects themselves and therefore might be expected to provide the same baseline masking effect. Since in our experiments the objects are constantly moving, this technique is not appropriate because these background elements would either have to be static, and therefore unlike the relevant objects in a critical respect, or moving, which would correspond to an increase in the number of nontargets which we know results in poorer tracking performance (Sears & Pylyshyn, 2000). Consequently we adopted a different control method better suited our particular purpose.

Since our concern in the present studies is with the effect of tracking on probe detection, the control we adopted in the next two experiments was to obtain a baseline probe detection measure by repeating the experiment without the tracking task – i.e., we measured performance in detecting probes at the same sites as in the experiment proper but under conditions where observers were not engaged in tacking but were passively watching the 8 objects moving on the screen. Any differences between performance in detecting probes in this baseline condition and in the tracking condition would presumably be due to one of two factors, either masking or dual-task interference, with only the first of these having a differential effect on probe detection in empty space and on circles. (Notice that in the baseline condition there is no distinction between "targets" and "nontargets" since none of the objects was singled out by flashing at the start of the trial). This baseline control condition was described to the participants simply as the task of detecting probes in the presence of moving distracting circles. In order to discourage observers from spontaneously tracking some of objects, the control task was presented first before the tracking condition – and before any mention of object-tracking.

Experiment 2

Participants

Twenty-four volunteers from the undergraduate subject pool participated to fulfill course requirements.

Method

The method is the same as in Experiment 1, with the addition of a block of control trials that were identical to the experimental trials except that they involved no tracking. In this experiment we explored the effect of decreasing the visibility of the probe by reducing it to 4x4 pixels, displayed for 76 ms. The control trials preceded the tracking trials and involved only a single two-alternative forced choice response at the end of each trial. There were 60 control (no tracking) trials and 120 experimental (tracking) trials, in half of which there was no probe.   In the experimental (tracking) trials observers were asked to first pick out the targets by clicking on them using a computer mouse and then to make a forced choice response to the question whether a probe had appeared in that trial, as described in the general method section above.

Results

As expected, the overall probe detection in Experiment 2 was somewhat lower than in Experiment 1, due to the use of a slightly smaller and briefer probe. An analysis of the average non-tracking control trials for each subject revealed that performance on the probe detection task was indeed better when the probe appeared in the empty space than on the circles (t=4.5; df=23; p<.000), thus raising the possibility that the failure to find a difference between probe detection on targets and in empty space, found in Experiment 1, might be due to a combination of target enhancement and superior probe detection in empty space. Thus we proceeded to examine the quantitative relation among the probe detection performance at different locations in order to

ascertain whether it is compatible with this interpretation. To do this we analyzed the control and experimental conditions together using a within-subjects analysis of variance.[1]

The analysis of variance revealed a significant difference between control and experimental conditions $F(1,23) = 8.38$, p<0.01, and between the three different probe locations, $F(2,46) = 28.27$, $MSE = .022$, p<.000, as well as a significant interaction between these two factors, $F(2,46) = 6.10$, $MSE = .019$, p<.01. A planned comparison t-test revealed that the locations were significantly different from one another, but the difference between control and experimental condition was only significant when the probe occurred on nontargets (t=4.7; df=23, p<0.000). In other words, only probe detection on nontargets was affected by the presence of the tracking task, over and above the matching control condition. This result supports the conclusion that tracking causes the inhibition of probe detection on nontargets, as opposed to enhancing the detection on targets (or inhibiting everything but targets). These results are shown in Figure 3.

The difference between the average probe detection performance in the control (nontracking) condition and the experimental (tracking) condition was confounded by the fact that the tasks were performed in separate blocks in a fixed order (nontracking first) in order to discourage tacit tracking. Moreover, since the experimental condition requires carrying out two tasks it might be expected to produce the standard dual-task performance decrement and perhaps even have a differential effect where probes were particularly easy to detect. Because of this we adopted a second way of exhibiting the results which takes into account not only the baseline (nontracking) probe detection performance but also the statistical correlations between control and experimental conditions at each of the three locations. To do this we performed an analysis of covariance with the nontracking control measures as covariants, using the method described in (Green, Salkind, & Aken, 2000, Lesson 26). The result is essentially a multiple regression prediction of the performance that would have been observed had the control detection performance been the same at all probe locations. These "adjusted" detection scores are shown in Figure 3, along with the unadjusted scores. They confirm the pattern found in the uncorrected detection means and show, perhaps even more graphically, that only the nontarget performance was impaired relative to both target and empty space performance.

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[1] There is no distinction between Targets and Nontargets in the control (nontracking) condition. However, to meet the analysis of variance requirement that scores in different conditions be independent we divided these probe detection scores at random for purposes of the analysis (in fact since the algorithm for generating the displays for the control condition is the same as that for the tracking condition, except that the "target" subset did not flash, the algorithm itself designated half of the circles as "targets" and the other half as "nontargets"). This division of circles into a notional set of "targets" and "nontargets" was not applied to the graphs so that adventitious differences are not distracting. The graphs simply showed the means for all circles under both "target" and "nontarget" bars for the control condition.
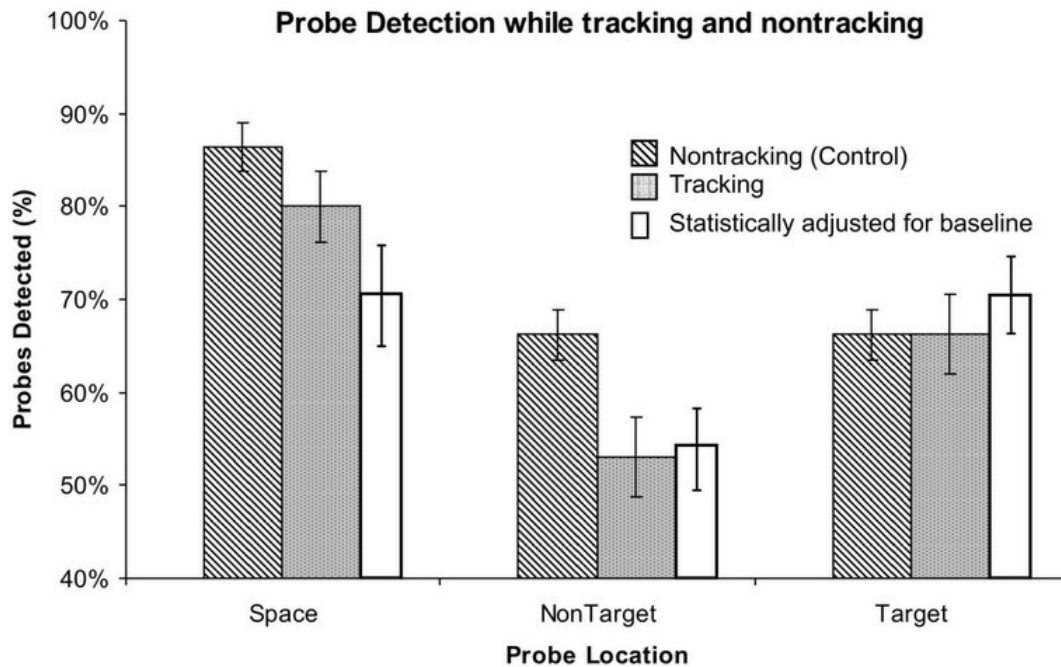
Figure 3. Performance in detecting a probe dot during tracking and also in the same probe detection task when there was no tracking. The thinner bars, marked "statistically adjusted for baseline" are statistical predictions of what the detection score would have been had the baseline been equal for the three probe locations (based on a covariance analysis as described in Green et al., 2000). (Because there is no distinction between targets and nontargets in the nontracking control condition, the values are shown as the same – see Note 1)

Finally, we also examined the tracking performance to check on the possibility that subjects shifted priority from tracking to probe detection in different probe conditions. We found no evidence of a significant difference in tracking performance across probe location, $F(2,46) = 1.50$, $MSE = .0031$, p>.10. (Tracking performance with probes located at empty space, nontarget, and target locations was 88.7%, 88.1% and 86.0% respectively).

Discussion

The results of experiments 1 and 2 support the hypothesis that nontargets are inhibited and that the inhibition is object-based. They do not, however, cast any light on how local or punctate the inhibition is and how quickly it drops off with distance from the nontargets. The question of the locality of inhibition is important to theories of attention and inhibition since it is generally believed that attention drops off slowly as one goes away from the attentional focus (Cheal, Lyon, & Gottlob, 1994) and thus one might expect that inhibition does as well. The probe detection method has been used successfully to plot the gradient of attention in other tasks, including ones in which moving objects are involved (Kerzel, 2003), so we continued to use that measure to assess the gradient of inhibition.

Experiment 3

In order to determine how localized the attention and inhibition was during tracking, Experiment 3 was designed to test additional locations near to targets and nontargets. In this study we tested five different locations with the probe-dot detection task. These included the three used in experiment 2 as well two other locations, one being one-radius (1.35°) away from a target and the other one-radius from a nontarget. In other words we presented a probe at the same distance from the circular contour as a probe that was on a target or on a nontarget, except it was on the outside of the circle. These additional locations are referred to as the Near Target and Near Nontarget conditions. Placing probes the same distance from a contour as those directly "on" an object has been treated as a control for masking insofar as proximity to a contour is one of the major determiners of masking (e.g., this was the basis for the "empty space" condition in the study by Ogawa et al., 2002). In addition, we used the same nontracking baseline control condition as in Experiment 2. In order to see whether there was any generalized dual-task decrement due to the tracking task, over and above what might be described as an effect of poorer visibility, crowding, or masking in the case of the probes closer to (or inside) the moving objects, we included an additional control condition similar to the one used in Experiment 2, but in which none of the circles moved (referred to as the "static control" condition). Both static and moving control conditions provide a baseline measure of probe detection unaffected by the distinction between targets and nontargets (since in neither case was the difference between targets and nontargets visually indicated). The static control condition, however, was also free of any motion, and therefore provided a more direct test of the visibility/masking hypothesis.

Participants

The data for the experiment was provided by sixteen naïve volunteers who responded to a recruiting poster and participated for a small remuneration. Data from two additional participants were not used on the grounds that their probe detection scores in the moving control condition was at chance. In addition we recruited 4 volunteers who had considerable experience with MOT. These were added to the pool to make a total of 20 participants, although the experienced volunteers were also analyzed and reported separately.

Method

The method is the same as in Experiment 2 except that two additional probe locations were used and half of the control trials (randomly chosen) were ones in which the objects did not move. For the control trials, participants were told that the task was to see how well they could detect small red dots that occurred among static or moving circles. The control trials preceded the tracking trials and involved a single two-alternative forced choice response per trial. The experiment began with a control block consisting of 100 nontracking trials, randomly ordered so that half were static and the other half were moving. This was followed by 100 experimental trials. As before, half of the experimental trials had no probes while the other half had probes distributed equally among the 5 locations as described above (referred to as empty space, target, nontarget, near target and near nontarget).

Results

Examination of the static control condition revealed that the difference in probe detection accuracy was not due to visibility or crowding or lateral masking, caused by the presence of static circles in the region of the probe dots. Despite having been collected at the very start of the experimental session, scores in the static control condition were essentially at ceiling,

ranging from 96.1% (for Near Targets) to 99.3% (for Near Nontargets) and the difference among them did not approach significance, $F(4,76) = .64$, $MSE = .005$, p>0.64. Therefore only the moving control condition was analyzed further.

A within-subjects analysis of variance showed that probe detection in the tracking condition was significantly lower than in the (moving) control condition, $F(1,19) = 12.2$, $MSE = .011$, p<.02, the detection rate was significantly different among the 5 locations, $F(4,76) = 15.6$, $MSE = .016$, p<.000, and the interaction of these two factors was also significant, $F(4,76) = 2.6$, $MSE = .008$, p<.05. (Since no target subset was identified in the control condition, neither the Target/NonTarget nor the Near-Target/Near-Nontarget distinction applies. Consequently, the probe detection scores were divided randomly so that all conditions are statistically independent for purposes of the analysis of variance, though these were combined for purposes of plotting the graphs – see Note 1). Figure 4 shows the probe detection scores for the control condition and for the tracking condition at each of the 5 locations. Planned comparison t-tests revealed that, as in Experiment 2, the only difference between the control and experimental condition that was statistically reliable (using the Bonferroni correction for multiple tests) was on the nontarget, t=4.5, df=19, p<.000. (The comparison of the means on the next largest pair, the empty space condition, resulted in a t=2.4, df=19, which gave a Bonferroni adjusted p > .05).

As in Experiment 2, another revealing presentation of these results uses a covariance analysis technique, with the control measures serving as covariants, to adjust the probe detection rate based on the correlations between the control and tracking performance at the five locations. This gives the predicted probe detection rate had the probe detection in the control condition been the same at all locations. The covariance analysis revealed a significant effect of probe location after adjusting for the control data, $F(4,94) = 2.58$, $MSE = .017$, p<.05, and also showed that the only pairs of locations that were significant (using the Bonferroni correction) were those between the nontarget position and each of the other positions. The result of this analysis is also included in Figure 4 and shows that after the statistical adjustment all locations are equal in the probe detection performance except for the significant depression at the nontarget location, again confirming that only the nontargets appear to be inhibited.

Another interesting finding has ramifications for the question of the proper way to control for the masking effects of nearby moving contours upon probe detection scores. When we compare the probe detection scores in the baseline (nontracking) condition for probes inside circles with those outside the circles (the "near target" and "near nontarget" scores) we find that the difference is not statistically reliable, t=1.26, df=19; p>0.22. This result confirms that probes located close to a circle do not suffer any more masking that those within the circles. Consequently placing the "outside" probes the same distance from the circular contours as the they are in the target and nontarget conditions, as was done by (Ogawa et al., 2002), apparently results in their being subject to the same degree of masking. Thus the graphs for the 4 locations in Figure 4 (not including the "empty space" location) in the tracking condition alone yields results uncontaminated by masking, and confirm that only the probe detection rate on nontargets is depressed relative both to targets and to off-target locations.
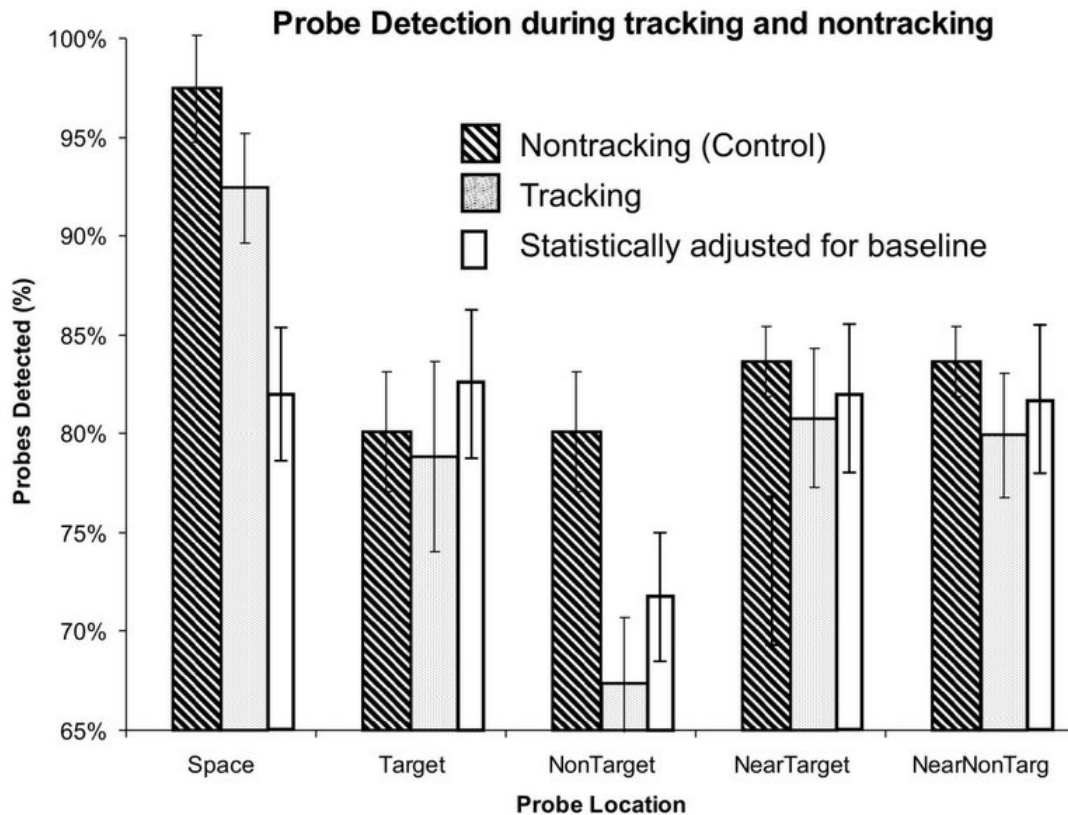
Figure 4. Probe Detection performance as a function of the location of the probes (in the nontracking controls there is no distinction between target-nontargets and neartarget-nearnontargets so these are shown with identical values – see Note 1). Only the performance at the nontarget was significantly different from baseline (error bars are standard errors).

Once again we analyzed tracking performance to see if there was any evidence of tradeoff between tracking and probe detection. A within-subjects ANOVA revealed no reliable difference in the tracking performance as a function of the location of probes, $F(4,76) = 1.56$, $MSE = .0026$, p>0.19. The tracking performance ranged from 84.1% in the Empty Space condition to 87.4% in the Near Nontarget condition. The tracking performance on those trials on which there was no probe was in the middle of this range, at 86.3%. Thus there is no reason to think that the different probe location conditions had their effect through changes in tracking performance, for example through differential effort devoted to tracking when the probe occurred at the different locations.

As mentioned earlier, four of the participants had considerable experience with the MOT task, having participated in previous experiments. These were also highly motivated and were willing to provide 600 trials in 3 one-hour sessions. Consequently we examined the results for these expert subjects separately. The findings are shown in Figure 5, using the same scale as used to show the results for the other subjects in the previous figure. Even with only 4 subjects (over three blocks of trials), the results are statistically significant: there was a significant control vs tracking difference, $F(1,3)=17.6$, SSE = .0023, p<.05, a significant probe location effect, $F(4,12) = 8.4$, SSE = .007, p<.002, and a control-tracking by location interaction, $F(4,12) = 3.5$, SSE = .008, p< .05. The difference among the three blocks of trials was not significant $F(2,6) = .081$, SSE = .006, p>.9) nor were any of the interactions with blocks. It is apparent from the

figure that these subjects (a) performed better at detecting probes, especially on the targets, and (b) showed the same inhibition of nontargets as observed with the naïve participants.

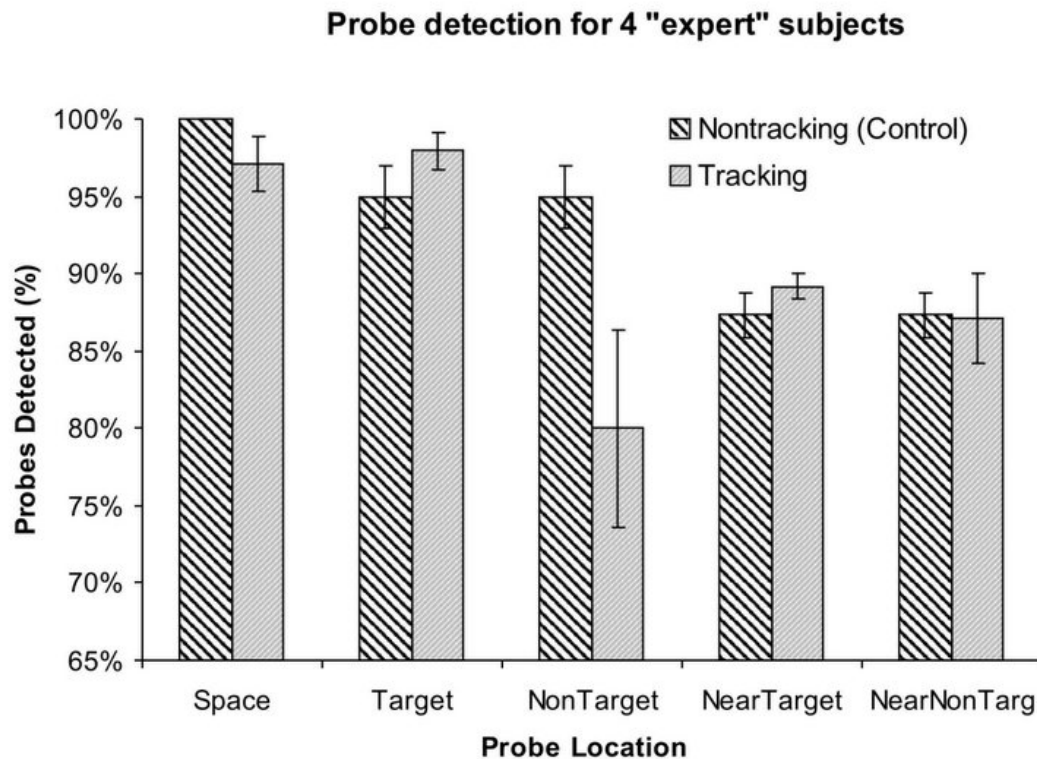**Probe detection for 4 "expert" subjects**

Figure 5. Graph of probe detection performance by four volunteers who had a great deal of experience with MOT and were willing to provide several hours of data. Although they performed better that the other participants, they show the same decrement for probe detection on the nontargets.

The difference between the pattern of probe detection performance in the control condition and in the tracking condition is an indication of the degree of inhibition observed at each location. The results of Figure 4 are replotted in Figure 6 in terms of control minus experimental detection and confirm that inhibition is highly local at the nontargets. As noted earlier, the absolute values depicted in this chart cannot be univocally interpreted since the control block always preceded the experimental block. Since the suppression effect at the empty space location is likely due to some combination of an order effect and a general dual-task effect, rather than an inhibition effect, we might take the value at empty space as a neutral baseline. If we show the origin at that value (as in the dotted line in Figure 6) we see that there is some basis for conjecturing that there may actually be some attentional enhancement at the target which even spread slightly to the nearby location. Although the evidence for this in the present study is highly tentative it is consistent with the "dual attentional set" hypothesis of (Braithwaite & Humphreys, 2003).
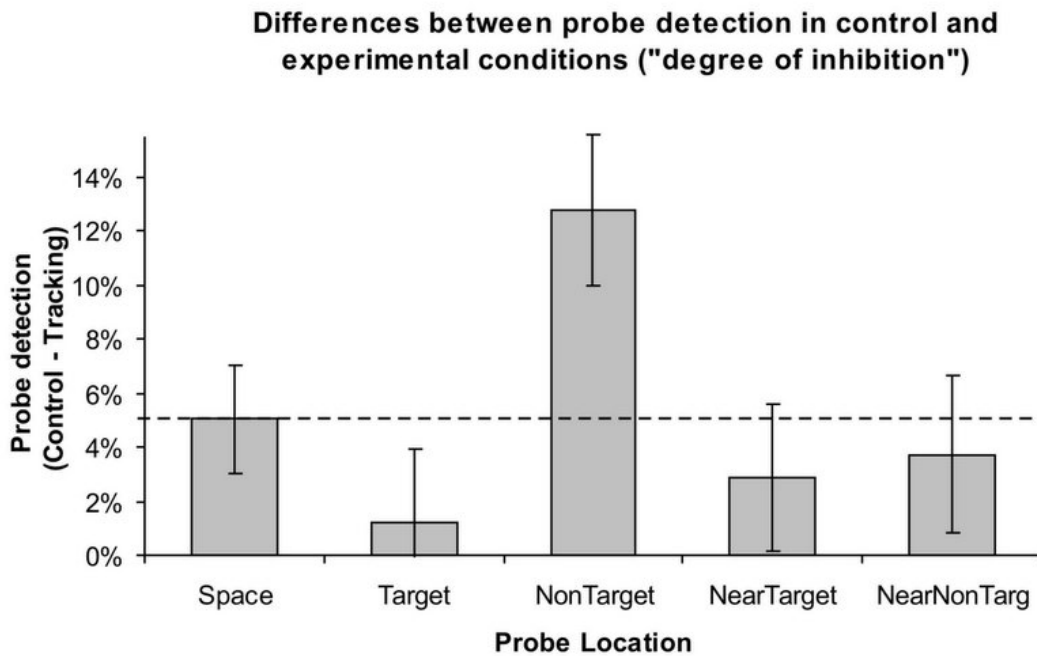
Figure 6. This figure shows the degree of inhibition at each probe location. The dotted line represents a possible baseline for measuring the degree of inhibition, based on the assumption that the inhibition in empty space is due solely to the effect of a secondary task or of the order in which the control and experimental conditions were carried out. One could interpret this figure as suggesting some degree of attentional enhancement at the targets (i.e., the 4% dip below this baseline at the target location might be viewed as an enhancement), as well as a strong inhibition at the nontargets.

Finally we performed an additional precautionary analysis of the records of trajectories and of probe locations used in this study. Although circles were located a random and moved in a random manner (subject only to speed and acceleration constraints described earlier), probe locations were subject to additional constraints. Probes on targets and nontargets were located at the center of the circles. Near Target and Near NonTarget probes were located at random subject to the constraint that they be one radius (1.35 °) from the relevant circle and more than one radius from any other circle and from the edge of the display. Empty space probes met the most stringent criterion as they had to be at least 2 diameters (5.4 °) from any circle. It is thus possible that in order to meet all these constraints, the probes in some conditions (e.g., the empty space condition) might have ended up more or less eccentric than in other conditions. Since eccentricity could be a major factor in their visibility, this possibility needed to be excluded. Fortunately we had a record of the trajectories of the objects used in these studies, as well as the coordinates of probes, we were able to examine a sample of probes in each of the 5 conditions to compare their eccentricities. On a sample of 264 probes at each of the 5 locations we found no significant differences in their eccentricities, $F(4,1052) = 0.732$, SSE = 5037.16, p>0.57. The empty space probes were not even nominally at the extremes of this distribution but somewhere between the targets/nontargets and the neartarget/nearnontarget eccentricities whose means lay in

the range from 178 and 186 pixels, so that the mean eccentricities were within 0.5 ° of each other.[2]

Discussion

Results of experiment 3 are consistent with the hypothesis that nontarget items are inhibited in MOT, possibly along with some attentional enhancement of targets, and they further show that this effect appears to be confined to the immediate region of the moving nontargets. This raises questions about the mechanism that may be responsible for this effect, which is discussed in the next section.

General Discussion

This study began with the hypothesis that in MOT, nontargets are segregated from targets at least in part by an inhibitory process that specifically affects the individual nontarget objects (of course this does not speak to the possibility that both enhancement of targets and inhibition of nontargets is involved, as discussed in connection with Experiment 3, and as suggested by Braithwaite & Humphreys, 2003; Olivers & Humphreys, 2003). The evidence presented here suggests that nontargets are inhibited over and beyond any enhancement of targets and as distinct from the general inhibition of everything that is not being tracked. It also suggests that the inhibition is highly local to nontargets. This finding is consistent with the work on preview search benefit (recently reviewed in Humphreys et al., 2004; Watson, Humphreys, & Olivers, 2004) and with our earlier hypothesis (Pylyshyn, 2004) that the reason that in MOT targets are more often confused with (i.e., identities are switched with) other targets than with nontargets, is that nontargets are suppressed. But the finding raises a further theoretical question: How can moving objects alone be inhibited without the inhibition affecting the space through which they travel? There are at least two possibilities.

(1) One possibility is that inhibition does not actually move, but rather is directed in a more global manner that nonetheless excludes empty space. So, for example, inhibition might encompass all unattended objects sharing some property, such as color or shape or movement. There is evidence for the inhibition of groups of items sharing a common property such as color or shape (Braithwaite & Humphreys, 2003; Braithwaite et al., 2003; Kunar, Humphreys, & Smith, 2003; Kunar, Humphreys, Smith, & Hulleman, 2003), configuration (Kunar, Humphreys, Smith et al., 2003), order of presentation (Humphreys et al., 2004; Watson & Humphreys, 1997), or time of onset (Watson, Humphreys, & Olivers, 2003) and that this selective inhibition may depend on the goals of the task (Watson & Humphreys, 2000).   However, it is not clear what sort of mechanism could realize feature-based inhibition while sparing the region through which the inhibited items move. A number of models of feature-based selection have been proposed which do an excellent job of explaining selection and inhibition in static displays, e.g., the

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[2] Of course if observers made systematic eye movements in tracking targets these eccentricity results would not apply. Although they were asked to keep looking at the fixation cross, many volunteers indicated in the debriefing questionnaire that they had moved their eyes during tracking. If fixations followed targets, or groups of targets, then it remains possible that the superior probe detection performance on targets might be attributed to a residual eccentricity effect due to superior detection in the region of fixation. However this would not account for the pattern of probe detection performance observed in these studies, particularly for the similarity of inhibition of nontargets relative to empty space and for the steep increase in probe detection performance between nontarget and "near nontarget" locations found in Experiment 3.

feature-map hypotheses of (Watson & Humphreys, 1998a) or the FeatureGate model of (Cave, 1999), but in their current form these cannot handle selection and inhibition of moving items.[3]

(2) A second possibility is that individual token nontargets are inhibited and that this inhibition travels with the nontargets as they move (i.e., that inhibition is object-based, in the sense in which this term has been used in the attention literature). This possibility is consistent with the evidence on object-based inhibition of return (IOR) cited earlier. But the only way that inhibition could move with a moving object is if the object in question is being tracked in some way; if it is somehow identified as the same token-object over time. In order to keep inhibition attached to the *same object* the token-identity or same-objecthood of the object must be tracked (which means that the correspondence problem must be continuously solved).   Visual Index (FINST) Theory postulates just a such a mechanism. However it only provides the capacity for tracking about 5 objects in this way. Thus option (2) present a challenge to this sort of theory. If nontargets as well as targets are being tracked in MOT then at least 8 items would have to be tracked. This problem was noted by (Ogawa et al., 2002) who also found that up to 8 moving items could be inhibited in a search paradigm, leading them to suggest that "inhibitory tagging" involved a tracking mechanism other than FINSTs.

Perhaps we need to refine out concept of tracking.   There are independent reasons for thinking that some form of "tracking" must be possible for more items than the limit of 5 generally found in MOT. For example, in order to carry out a search on a large number of moving items (as in the experiment of Ogawa, et al, 2002, as well as many other studies – e.g., Alvarez, Horowitz, & Wolfe, 2000; Cohen & Pylyshyn, 2002), vision must maintain the integrity of the candidate objects as they move, otherwise no two time slices would be perceived as containing the same set of objects, and thus only a repetitive exhaustive scanning of all locations in the display could lead to a successful match in such moving-search experiments. In addition, solving the ubiquitous "correspondence problem" appears to require the preattentive identification of large numbers of visual objects. The correspondence problem is a problem that is solved whenever two initially distinct visual tokens are put into correspondence and thereby treated by the visual system as arising from one and the same distal object. This problem is routinely solved in apparent motion and stereo, and moreover it appears to be solved over some prior segregation of visual tokens. For example, (Ullman, 1979) showed that apparent motion is computed over distinct tokens, as opposed to over a continuous intensity map. Since apparent motion can involve large numbers of token elements (as in the "kinetic depth effect" – Wallach & O'Connell, 1953), the correspondence problem must be solved over many tokens which, in turn, means that many such tokens must be distinguished in early vision and assigned the same persisting identity – far more than the capacity of the FINST mechanism. The same is true of stereo vision, where tokens on each retina must be placed in correspondence in order to compute the disparity of the corresponding distal element. These phenomena all call for distinguishing a large number of token elements at the same time and keeping track of their persisting identity as they move. Since stereo can be computed over a moving field of dots (as in dynamic random-dot stereograms, Julesz, 1971), the stereo correspondence problem has to be solved even when the tokens are in motion which, in turn, means that the temporal correspondence must be solved

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[3] The FeatureGate model (Cave, 1999) bears a certain similarity to the FINST model, especially with respect to speculations about possible neural implementations (Pylyshyn, 2003, p 270-279). However there is a basic difference between the two approaches in that the FINST mechanism assumes a limited number of direct (non-location-mediated) pointers, which helps to account for the data of MOT and other evidence discussed in (Pylyshyn, 2001, 2003).

first. Thus we have independent reason to believe that segregation of moving elements takes place and is not subject to the same sorts of numerical limits as postulated by FINST theory, or as found in MOT.

This suggests that MOT, and other phenomena for which visual indexing has been invoked, involves at least two stages. Before visual objects can be indexed, a scene must first be parsed (or individuated) into tokens and the tokens merged over time so they refer to individual candidate objects or proto-objects.[4] This can be carried out by a process operating in parallel across the scene. Processes that identify tokens by clustering image features were among the first studied in computational vision (Marr, 1982). Processes that merge tokens over time (which solve the correspondence problem) are also well-known in the study of early vision, and various models for their implementation have been proposed (see, Dawson & Pylyshyn, 1988; Koch & Ullman, 1985; Ullman, 1976). Only after a scene has been parsed into such persisting visual objects can pointers be attached to a subset of these objects. This idea is in fact explicit in the original FINST theory, where it is recognized that indexes are only assigned to a subset of the possible objects in a scene. What the present findings (as well as those of Ogawa et al., 2002, and the studies of object-based IOR cited above) suggest is that inhibition is applied to these persisting visual objects before they are indexed, and therefore at a stage prior to when they can be accessed. Such access is required for purposes such as responding correctly in MOT (by picking out the targets using a computer mouse), making judgments about them (as in computing "visual routines", Ullman, 1984), enumerating or subitizing them, and so on (for more on this notion of access see Pylyshyn, 2003, chapter 5).

Given that both targets and nontargets are tagged in a display, it remains a puzzle why such tags do not serve as the basis for target tracking, thereby allowing more than 4 or 5 targets to be tracked. Perhaps the reason is that, according to the view we have adopted here (and elsewhere Pylyshyn, 2001), having inhibitory tags on certain moving items does not provide a direct way to address these items individually. If all we had were inhibitory tags, then in order to identify a particular item as a target, that item would first have to be found and selected, likely by searching the display for items without tags. Evidence from other studies – e.g., the subset search of (Burkell & Pylyshyn, 1997) or the subitizing studies of (Trick & Pylyshyn, 1994) – suggest that when items have been indexed, they can be accessed without search. Thus a prediction of the present theory is that, unlike indexed targets, nontargets cannot be rapidly enumerated or subitized, nor can patterns such as collinearity be recognized over them. Nonetheless, the view that a large number of objects are segregated/individuated leaves open the question why inhibition, as opposed to activation, attaches to these individuated objects. We have no answer to this question except to take it as a further evidence that inhibition has a

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[4] There is a terminological issue here concerning how to refer to the clusters that are perceptually distinguished and tracked. In the preceding I have referred to these as "tokens" on the grounds that it is a neutral term, but the term "individual" (and the process of "individuating") is somewhat more appropriate since it implies that each token is not only distinct from other tokens, but has an enduring existence. Because distinct tokens are merged through a correspondence operation they reflect enduring entities in the world. But this terminological policy is in conflict with the usage of these terms in philosophy (Strawson, 1963) where individuating requires appeal to conceptual properties in order to distinguish one from another. In the present view, by contrast, individuation precedes the encoding of properties. Perhaps the most common way to refer to such individuals in vision science is to refer to them as "visual objects" or even "proto-objects" without implying that properties of these individuals are encoded (the term "individuate" as well as "object" is also used in this way in cognitive development, see Leslie, Xu, Tremolet, & Scholl, 1998).

special status in the analysis of a scene; it appears to be numerically less limited than attention, but has a more constrained function. Further research is needed to clarify the factors that affect when and how inhibition and activation are brought to bear in attentive selection in vision.

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