

# Allocation of attention during pursuit of large objects is no different than during fixation

Department of Psychology, Wright State University,  
Dayton, OH, USA

**Scott N. J. Watamaniuk**

The Smith-Kettlewell Eye Research Institute,  
San Francisco, CA, USA



**Stephen J. Heinen**

The Smith-Kettlewell Eye Research Institute,  
San Francisco, CA, USA



Attention allocation during pursuit of a spot is usually characterized as asymmetric with more attention placed ahead of the target than behind it. However, attention is symmetrically allocated across larger pursuit stimuli. An unresolved issue is how tightly attention is constrained on large stimuli during pursuit. Although some work shows it is tightly locked to the fovea, other work shows it is allocated flexibly. To investigate this, we had observers perform a character identification task on large pursuit stimuli composed of arrays of five, nine, or 15 characters spaced between  $0.6^\circ$  and  $4.0^\circ$  apart. Initially, the characters were identical, but at a random time, they all changed briefly, rendering one of them unique. Observers identified the unique character. Consistent with previous literature, attention appeared narrow and symmetric around the pursuit target for tightly spaced ( $0.6^\circ$ ) characters. Increasing spacing dramatically expanded the attention scope, presumably by mitigating crowding. However, when we controlled for crowding, performance was limited by set size, suffering more for eccentric targets. Interestingly, the same limitations on attention allocation were observed with stationary and pursued stimuli—evidence that attention operates similarly during fixation and pursuit of a stimulus that extends into the periphery. The results suggest that attention is flexibly allocated during pursuit, but performance is limited by crowding and set size. In addition, performing the identification task did not hurt pursuit performance, further evidence that pursuit of large stimuli is relatively inattentive.

blurring. Given that our information processing capacity is finite, attention is used to focus on specific details in a visual scene, effectively filtering out irrelevant information. During pursuit of a moving object, it could be beneficial not to confine attention to that object, but rather distribute it spatially to other regions. It might also be useful to attend to features on the object so that those features could be discriminated and identified. Although much is known about how attention is allocated away from a pursuit object, little is known about how it is allocated within the object to its features as the few studies investigating this have yielded conflicting results.

Most work on attention allocation during smooth pursuit has been conducted with a small spot pursuit target and has investigated how attention is allocated in space around it. The general approach to these studies is to have observers pursue a small spot and, at a random time, flash a target briefly in its vicinity. Observers typically press a button or make a saccade to the flashed target and are instructed to do so as soon as the target appears (e.g., Khan, Lefèvre, Heinen, & Blohm, 2010; van Donkelaar & Drew, 2002). A short reaction time indicates that attention is preferentially allocated to the area where the target flashed. Typically, the results of such studies show that attention allocation during pursuit is asymmetric, skewed ahead of the pursuit target in its direction of motion. For manual reaction times, this attentional advantage extends up to  $5^\circ$  ahead (Khan et al., 2010).

Lovejoy, Fowler, and Krauzlis (2009) were the first to examine how attention during pursuit was allocated across a large moving object that extended into the peripheral visual field. Their stimulus was a linear array of 15 tightly spaced ( $0.6^\circ$ ) alphanumeric characters that moved together at a constant velocity, and observers

## Introduction

Smooth pursuit eye movements are used to follow moving objects to minimize retinal motion and prevent

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had to pursue a cued element in the array. The characters were all 8s initially, and at a random time, all of the characters except for a target changed to 2s or 5s. The target became an E or a 3, and observers signaled with a key press the target's identity. Changing all of the characters, as opposed to just the target, equalized transients across the stimulus. This ensured that observers could not use transient cues, which are known to attract attention (Deubel & Schneider, 1996), to help locate the target. Using this paradigm, Lovejoy et al. found identification performance fell precipitously and symmetrically for locations  $\sim 1^\circ$  from the pursuit target. They interpreted this to mean that the span of attention during pursuit was symmetric and focused on the pursuit target. They further suggested that crowding may have been responsible for the narrow region of good performance surrounding the pursuit target.

Heinen, Jin, and Watamaniuk (2011) also investigated attention allocation across a pursuit object and obtained a very different outcome. Their stimulus was composed of an array of five widely spaced ( $3^\circ$ ) dots arranged in a plus-sign configuration. The dots moved together, and observers pursued the central one. At a random time, one of the dots dimmed briefly, and observers had to identify with a key press the location of the dimmed dot. In this situation, observers performed the dimming detection task equally well on the central and peripheral dots, indicating that during pursuit attention could be displaced at least  $3^\circ$  from the central fovea, a much wider span than demonstrated by Lovejoy et al. (2009). Attention allocation was also symmetrical in this experiment with no performance advantage observed for dots ahead of the pursuit target.

There are several key differences between Heinen et al. (2011) and Lovejoy et al. (2009) that may explain the studies' differing results. First, the tasks were different with the former authors using a recognition task and the latter a detection task. Second, a transient luminance change specified the target in Heinen et al. (2011), and transients were controlled in Lovejoy et al. (2009). Finally, other key differences were element spacing and set size. In the present study, we adopt the identification task of Lovejoy et al. but manipulate spacing and set size. We find that, consistent with Heinen et al. (2011), attention can extend out at least  $4^\circ$  eccentric of the pursuit target. Furthermore, task performance decreases as a function of the number of characters and increases as character spacing increases. The results suggest that attention allocation during pursuit is broad and symmetric and that performance is spatially constrained by stimulus configuration. Additionally, task performance was no different during pursuit and fixation, and pursuit quality was not compromised during performance of the identification task—evi-

dence that pursuit of larger objects is relatively inattentive.

## Methods

### Participants

Data were collected from four healthy observers (two males and two females, 26–49 years of age), three of whom were naïve to the purposes of the experiments, and the fourth was one of the authors. All observers had normal or corrected-to-normal visual acuity. The study was approved by Smith-Kettlewell Eye Research Institute's Institutional Review Board, and all observers gave their informed consent prior to participation in the study.

### Apparatus

Stimulus characters were constructed in a computer drawing program (Intaglio; Purgatory Design, Durango, CO, USA) and saved as jpeg files. Characters were assembled into appropriate configurations and displayed using the PsychToolbox (Brainard, 1997), running under MatLab (Mathworks, Natick, MA, USA). Stimuli were generated with an Apple quad-core i5 laptop computer and displayed on a 17-in., high-resolution Nanao color monitor (1.76 min arc/pixel) at a rate of 60 Hz. Horizontal and vertical eye position were sampled at 1000 Hz by an EyeLink® 1000 video-based eye tracker (SR Research Ltd., Mississauga, Canada). The EyeLink was calibrated and validated using its standard nine-point method. A chin/forehead rest stabilized the observer's head and maintained a constant viewing distance of 48 cm.

### Stimuli

Stimuli were alphanumeric characters arranged in either a linear array of 15 elements (Figure 1A) or a plus sign comprising five or nine elements (Figure 1B). Characters were white ( $55.2 \text{ cd/m}^2$ ),  $0.28^\circ \times 0.5^\circ$  in size, with a stroke width of  $0.05^\circ$  and were presented on a uniformly gray background ( $13.1 \text{ cd/m}^2$ ). Center-to-center spacing of the characters in the plus-sign configuration was either  $0.6^\circ$ ,  $2.0^\circ$ , or  $4.0^\circ$ ; characters in the linear array had  $0.6^\circ$  spacing. The stimulus arrays either remained stationary at the center of the display (with a random horizontal offset of up to  $\pm 6^\circ$ ) or translated either leftward or rightward across the screen at  $8^\circ/\text{s}$ ,  $12^\circ/\text{s}$ , or  $16^\circ/\text{s}$ . Direction and speed were selected randomly in each trial. Note that the stimulus

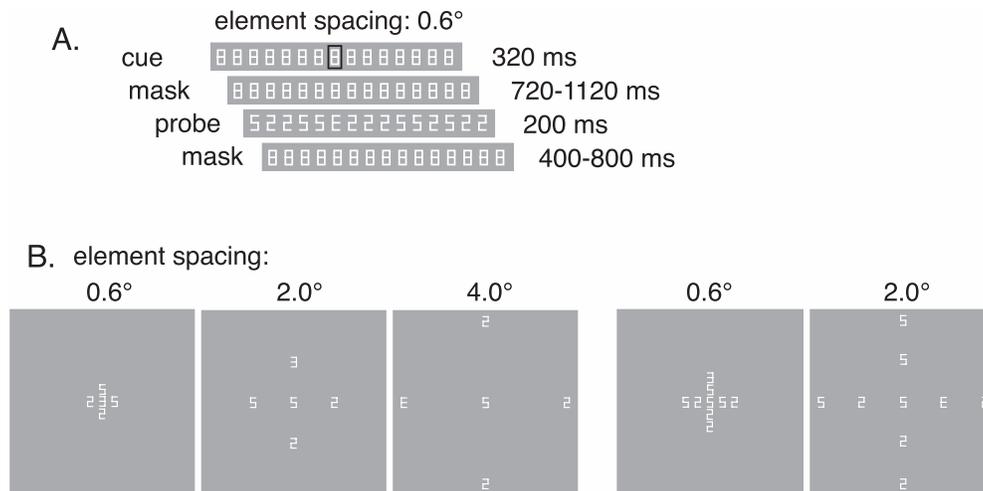


Figure 1. Schematic timeline (sans fixation) for stimuli with 15 characters (A) and examples of stimuli with five and nine characters (B). Probe characters were visible for 200 ms appearing 1040–1440 ms after trial initiation. At the end of a trial, observers identified whether the probe was an E or 3 using a key press. Stimuli and spacing shown to scale.

parameters for the linear array were identical to Lovejoy et al. (2009).

## Procedure

Basic stimulus parameters and procedures mirrored those of Lovejoy et al. (2009) so that our results could be compared directly with theirs. Stimuli appeared stationary for a random fixation duration (500–1000 ms), then either remained stationary or moved for 1640–2440 ms. At a random time after the fixation period (1040–1440 ms), the character array changed from 8s to 2s and 5s except for a single probe character that changed to a 3 or an E. After 200 ms, all characters changed back to 8s. Observers maintained gaze on the central character throughout the stimulus presentation, and at the end of the trial, judged whether the probe had been a 3 or an E. Data for all conditions were collected from every observer (~11,000 trials per observer). An alpha of .01 was used for all statistical tests.

## Eye movement analysis

Two blocks of trials per condition, per observer were randomly selected and the eye movements analyzed. Thus, the analysis included 360 trials per observer for each 15- and five-character configuration and 216 trials per observer for each nine-character configuration.

Horizontal and vertical eye velocity were calculated offline from the recorded position signals by differentiating and filtering (two-pole Butterworth noncausal filter, cutoff = 50 Hz) the raw eye position data.

Saccades were detected with an eye acceleration thresholding algorithm used in previous work (e.g., Badler & Heinen, 2006) and excised from the velocity traces before pursuit detection. Pursuit onset was first detected automatically using 5°/s velocity and variance thresholds, then visually inspected and manually adjusted when necessary. Peak open-loop acceleration was computed with a 20-ms sliding window that moved in steps of 10 ms within a 200-ms region starting at pursuit onset. Acceleration was calculated at each step, and the maximum of these calculated values was taken as the peak. Steady-state gain was assessed 300–800 ms after pursuit onset.

## Results

### Psychophysics: 15-character conditions

The 15-character stimulus was a replication of the Lovejoy et al. (2009) study. Figure 2 shows the percentage correct probe identification (averaged over observers) as a function of probe eccentricity for the moving and stationary stimuli. For moving stimuli, positive and negative eccentricity values refer to locations in the same direction and opposite that of pursuit, respectively. The data are also collapsed over stimulus speed to make them comparable to Lovejoy et al. As can be seen here, our data for both pursuit and fixation are similar to those of Lovejoy et al. (gray curves) as the plots virtually overlap.

To quantify the results, separate repeated-measures ANOVAs were conducted on the percentage correct identification for the fixation and pursuit conditions.

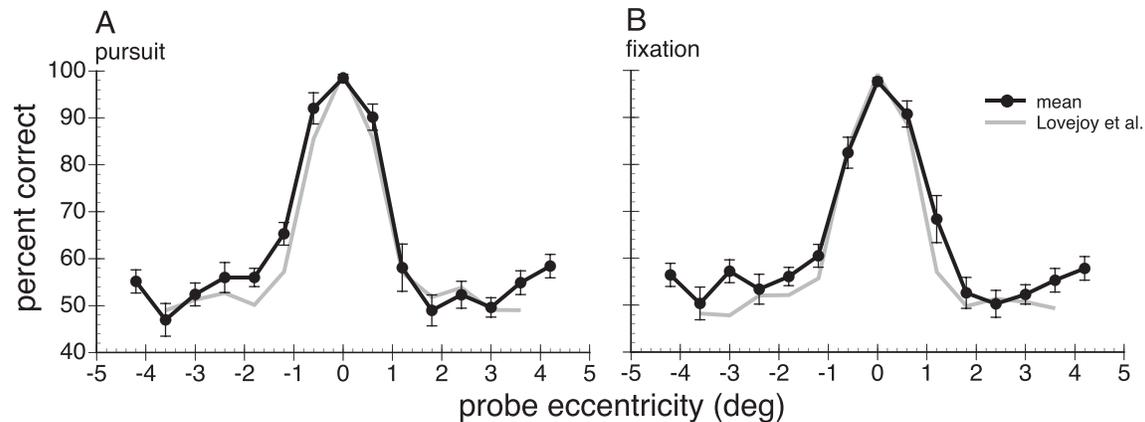


Figure 2. Average percentage correct probe identification as a function of probe eccentricity for the 15-character stimulus during pursuit and fixation. Data have been averaged over the four observers and three stimulus speeds in the pursuit condition. Data for the same respective conditions from Lovejoy et al. (2009) have been plotted for comparison (gray curves). Each datum is the average of 36 trials/observer and error bars represent  $\pm 1$  SEM.

Performance significantly declined with eccentricity: pursuit,  $F(14, 42) = 36.61$ ,  $p = 0.0001$ ; fixation,  $F(14, 42) = 10.9$ ,  $p = 0.0001$ . Furthermore, pursuit direction had no significant effect on identification performance ( $p = 0.48$ ), nor did stimulus speed ( $p = 0.69$ ). A contrast comparing performance for locations ahead of the pursuit target with those behind the pursuit target also revealed no significant difference ( $p = 0.60$ ).

To test whether the decrease in identification performance with eccentricity occurred because of acuity limitations, we performed a control experiment with two observers in which a single probe character (E or 3) was presented alone at each of the 15 possible probe locations for 200 ms during pursuit of a spot target. From trial to trial, character location was random, and without a pre- or postmask. Probe identification in this case was perfect (100% correct) at every probe location, indicating that acuity did not limit performance.

Finally, we compared the pursuit and fixation conditions with a repeated-measures ANOVA with stimulus type (moving or stationary) and eccentricity as variables. For the pursuit condition, data were averaged over pursuit direction and speed. Stimulus type had no significant effect on performance ( $p = 0.76$ ), but eccentricity showed the expected deleterious effect,  $F(14, 42) = 45.5$ ,  $p = 0.0001$ . The interaction between stimulus type and eccentricity was not significant ( $p = 0.90$ ), implying that the effect of eccentricity on probe identification was the same during fixation and pursuit. We suspect, as did Lovejoy et al. (2009), that this pattern of performance was due to the effects of crowding rather than a narrowly focused attentional window. In addition, we hypothesize that set size imposes a further limit on performance.

### Limits of crowding on performance

Identification of closely spaced stimuli can suffer because of a phenomenon known as crowding (e.g., Flom, 1991; Levi, 2008). In crowding, a stimulus that is readily identified when viewed alone becomes obscured when flanked by other stimuli. Lovejoy et al. (2009) suggested that crowding may be responsible for the pattern of performance in their study because of the close spacing of characters in their stimuli ( $0.6^\circ$ ). Here, we test this hypothesis with stimuli composed of nine characters that were either spaced by  $0.6^\circ$  or by  $2.0^\circ$ , taken in separate blocks. Figure 3 shows the percentage correct probe identification as a function of probe eccentricity for the nine-character stimuli during pursuit (A, B) and fixation (D, E). Because repeated measures ANOVAs showed no differences between horizontal and vertical probe positions, pursuit:  $F(1, 3) = 0.962$ ,  $p = 0.40$ ; fixation:  $F(1, 3) = 0.941$ ,  $p = 0.40$ , and no difference as a function of speed for the pursuit-condition data,  $F(2, 6) = 1.326$ ,  $p = 0.33$ , the data are collapsed across these parameters. Data taken during pursuit and fixation are similar and show the same general pattern.

When characters were spaced by  $0.6^\circ$  (see Figure 3A, D), performance for the central character (pursuit target) was near perfect for all observers. Performance declined away from the central character, and for some observers, the decline was precipitous even for characters adjacent to the central one (e.g., EF & MO). Interestingly, for three of the four observers, performance at the most eccentric position was equal to or better than performance at the neighboring position. This is likely due to the fact that the eccentric characters were only flanked by one character, a situation that reduces crowding (e.g., Bouma, 1970;

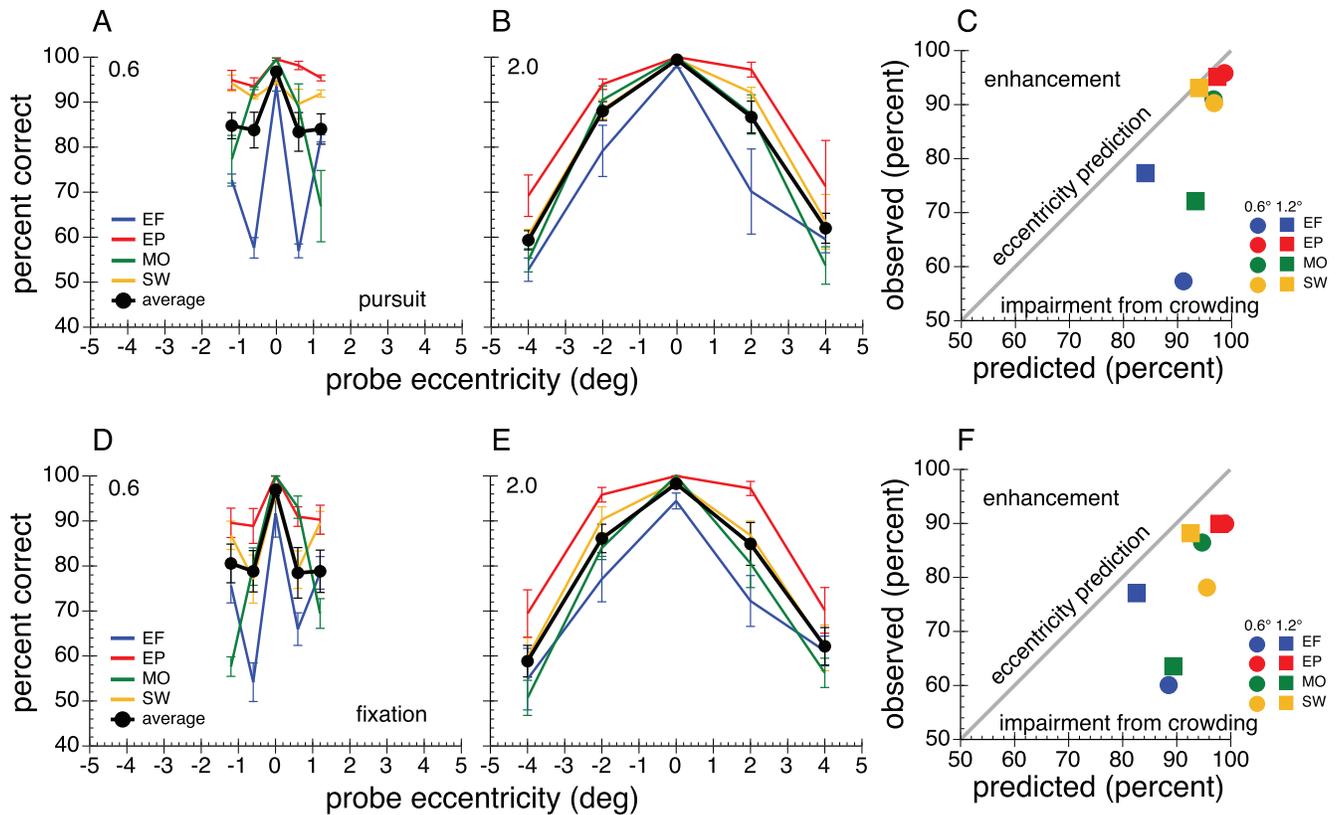


Figure 3. Average percentage correct probe identification as a function of probe eccentricity for the nine-character stimulus during pursuit and fixation. (A & D) Data for the 0.6° character spacing. (B & E) Data for the 2.0° character spacing. Data are shown for the four observers and the average. Pursuit data are averaged over the three stimulus speeds and two directions. Error bars represent  $\pm 1$  SEM. (C & F) Observed probe identification performance for eccentricities of 0.6° and 1.2°, plotted as a function of predicted performance interpolated from the 0° and 2.0° character spacing data in (B & E).

Chanceaux & Grainger, 2012; Chastain, 1983; Krumhansl, 1977; Marzouki & Grainger, 2014; Petrov & Popple, 2007; Petrov, Popple, & McKee, 2007). Although there are considerable individual differences in the magnitude of performance loss due to crowding, the average data (black curve) captures the general features of performance. In contrast to the 0.6° data, when the spacing between characters was 2.0°, performance was similar across observers and declined gradually for all (see Figure 3B, E), approaching chance at 4° eccentricity. Because the extent of crowding has been shown to be greater behind the pursuit target (Harrison, Remington, & Mattingley, 2014), we also compared identification performance for probes appearing behind and ahead of the pursuit target but found no difference (post hoc contrast,  $p = 0.849$ ).

To quantify the crowding effect, for each observer, we fit a line between the 0° and 2.0° data points in each of the four directions (left, right, up, and down). At these points, performance should be relatively free of crowding because the 2.0° spacing exceeds the critical crowding spacing (e.g., Bouma, 1970). We then interpolated between these points to predict each

individual's “crowding-free” performance at eccentricities of 0.6° and 1.2° along each meridian. We then compared the predicted performance to the observed performance at those eccentricities. Figure 3C and F show the observed performance at 0.6° and 1.2° as a function of that predicted by the 0° and 2.0° eccentricity data for the pursuit and fixation conditions, respectively. The diagonal line represents where the data should fall if eccentricity was the only parameter determining probe identification performance. Data falling above this line represents enhanced performance, and data falling below the diagonal represents impaired performance. We expected that crowding would impact the 1.2° eccentricity character less because it was flanked on only one side, and the character at 0.6° was flanked on both sides (e.g., Bouma, 1970); three of the four observers showed this pattern. Separate one-tailed paired  $t$  tests were conducted on the 0.6° and 1.2° stationary and moving data to determine if the difference scores (observed - predicted) were significantly different from zero. All  $t$  tests were significant, indicating that crowding significantly reduced probe identification at 0.6°,  $t(15) = -3.56$ ,  $p = 0.0014$  (pursuit);  $t(15) = -5.48$ ,  $p = 0.00003$

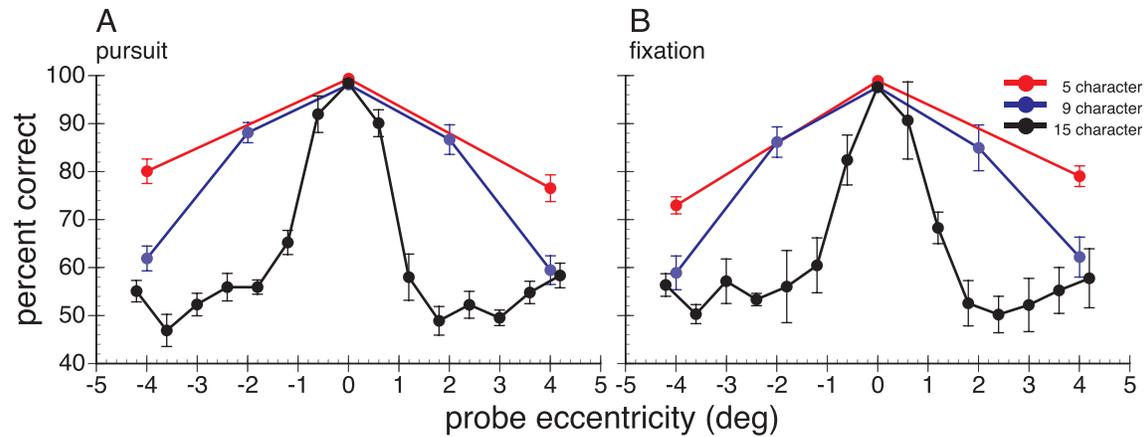


Figure 4. Average percentage correct probe identification as a function of probe eccentricity for five-, nine-, and 15-character stimuli for the (A) pursuit and (B) fixation conditions. Data have been averaged over the four observers, horizontal and vertical meridians, and for the moving stimuli, stimulus speed, and direction. Error bars represent  $\pm 1$  SEM.

(stationary), and at  $1.2^\circ$ ,  $t(15) = -3.01$ ,  $p = 0.0044$  (pursuit);  $t(15) = -3.77$ ,  $p = 0.0009$  (stationary).

### Limits of set size on performance

Another possible reason for the discrepancy between the results of Lovejoy et al. (2009) and Heinen et al. (2011) is the number of elements in the stimuli or set size. Set size is known to limit performance during visual search tasks, a limitation usually linked to attention allocation (e.g., Treisman & Gelade, 1980). In Heinen et al. (2011) the identification task was performed on five potential target elements, and in Lovejoy et al., in which identification performance was poorer, it was performed on 15. To investigate this, we ran an additional condition with five characters and compared performance to the nine- and 15-character conditions. Figure 4 plots data averaged over observers for the five-, nine-, and 15-character conditions. Note that because all set sizes spanned approximately the same eccentricity, the spacing between characters changed systematically with set size ( $4.0^\circ$  for set size = 5,  $2.0^\circ$  for set size = 9,  $0.6^\circ$  for set size = 15). Because repeated-measures ANOVAs on each set size data set showed no significant effects of speed (all  $ps > 0.33$ ), stimulus direction (all  $ps > 0.62$ ), or meridian (horizontal vs. vertical probe positions: five-character,  $p = 0.11$ ; nine-character,  $p = 0.40$ ), the data have been collapsed across these parameters. Performance is clearly better for stimuli with fewer elements and, furthermore, drops off more steeply when elements are spaced more closely.

To isolate the set size effect, we compared performance at the greatest eccentricity ( $\pm 4^\circ$  for the five- and nine-character and  $\pm 4.2^\circ$  for the 15-character conditions). The five- and nine-character conditions should suffer little from crowding as the spacing is wide

enough ( $4^\circ$  and  $2^\circ$ , respectively) to fall at or beyond Bouma's critical spacing limit ( $0.5 \times$  eccentricity). Crowding effects due to narrow spacing in the 15-character stimulus should also be reduced here because these targets are flanked by only one distractor (e.g., Bouma, 1970).

Figure 5 shows the comparison of performance at the greatest eccentricity for each set-size condition and observer in the pursuit and fixation conditions. Performance is best for the five-character set, falls for the nine-character set, and appears to saturate as performance changes little for the 15-character set. Separate one-way repeated-measures ANOVAs on these reduced data sets showed that performance declined significantly as set size increased: pursuit,  $F(2, 6) = 52.48$ ,  $p = 0.0002$ ; fixation,  $F(2, 6) = 20.131$ ,  $p = 0.0022$ . Post hoc comparisons showed that performance was significantly better for five than for nine (moving:  $p = 0.0002$ ; stationary:  $p = 0.003$ ) or 15 characters (pursuit:  $p = 0.0001$ ; stationary:  $p = 0.006$ ); however, performance was not different between the nine- and 15-character conditions (pursuit:  $p = 0.134$ ; stationary:  $p = 0.272$ ). This suggests that for the brief 200-ms presentation used, set size has reached its maximum effect by approximately nine characters. Note that performance on the 15-character stimulus was likely affected adversely by crowding, but given performance on it and the nine-character stimulus was no different, crowding likely does not confound our interpretation of the set-size results.

### Eye movements

In general, smooth pursuit was little affected by stimulus configuration and resembled typical pursuit. One-way repeated-measures ANOVAs on steady-state gain and the horizontal saccade frequency with

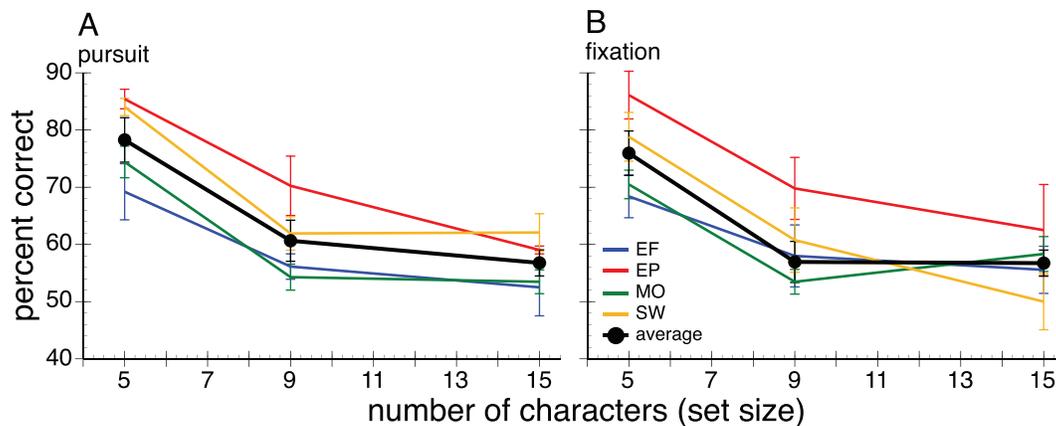


Figure 5. Percentage correct probe identification for the pursuit and fixation conditions at the largest eccentricity tested as a function of set size for the four observers. The thick black lines indicate average performance. Error bars represent  $\pm 1$  SEM.

condition as the variable (conditions: five-character with  $0.6^\circ$  spacing, five-character with  $2.0^\circ$  spacing, five-character with  $4.0^\circ$  spacing, nine-character with  $0.6^\circ$  spacing, nine-character with  $2.0^\circ$  spacing, 15-character with  $0.6^\circ$  spacing) showed no differences between the different stimulus configurations (average steady-state gain = 1.023,  $p = 0.213$ ; average horizontal saccade frequency = 2.19,  $p = 0.437$ ). However, the repeated-measures ANOVA on peak open-loop acceleration revealed a significant effect of condition,  $F(5, 15) = 12.51$ ,  $p = 0.0001$ . Inspection of the peak open-loop acceleration data (Figure 6) shows that it was higher for the 15-character stimulus than all other conditions, and paired contrasts confirmed this (all  $ps = 0.0001$ ). This is consistent with previous results that showed open-loop acceleration increases with the number of moving elements in a stimulus (Heinen & Watamaniuk, 1998). The repeated-measures ANOVA on vertical saccade frequency also revealed a significant effect of condition,  $F(5, 15) = 3.49$ ,  $p = 0.0272$ . Not surprisingly, vertical

saccade frequency increased systematically as the vertical extent of the stimulus increased, going from an average of 0.09 vertical saccades per trial for the 15-character stimulus (characters arranged horizontally) to a maximum average of 0.36 for the five-character stimulus with a  $4.0^\circ$  spacing and the nine-character stimulus with a  $2.0^\circ$  spacing (both of these stimuli extended out to vertical eccentricities of  $4.0^\circ$ ).

That task performance was identical between pursuit and fixation is consistent with the interpretation that pursuit of the character arrays did not require attentional resources beyond those required to fixate. Furthermore, the finding that increasing attentional demands on the identification task (task difficulty) had no effect on pursuit performance suggests that pursuit of the character arrays is relatively inattentive. Additionally, pursuit was not degraded when the task was performed, further evidence that pursuit of the character arrays is inattentive (see Table 1). We used the five-character stimulus with  $4.0^\circ$  spacing, and the nine-character stimulus with  $2.0^\circ$  spacing to assess pursuit performance without the task as these stimuli spanned the same eccentricity but yielded a drop in identification performance when going from five to nine characters. Steady-state gain and catch-up saccade frequency (horizontal saccades) were measured for both the task and no-task conditions (Figure 7).

Surprisingly, performing the identification task actually improved pursuit, yielding higher steady-state gain and fewer catch-up saccades than in the no-task condition. Two-tailed  $t$  tests on each individual's data showed that these differences in pursuit were significant (see Table 1). These results are consistent with the findings of Jin, Watamaniuk, Khan, Potapchuk, and Heinen (2014), who also showed that pursuit quality improved when observers performed a simultaneous multiple-object attentional tracking task on the pursuit stimulus.

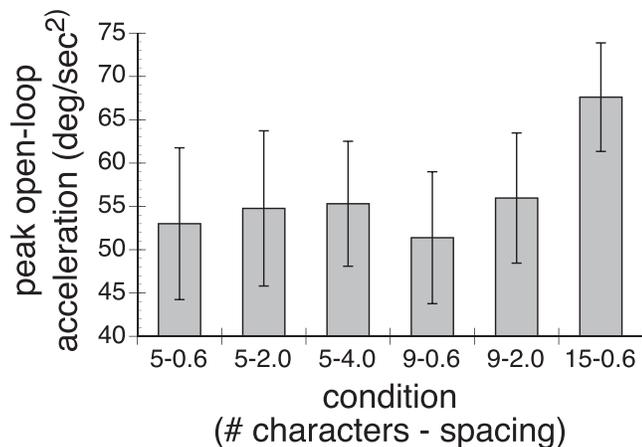


Figure 6. Average peak open-loop acceleration as a function of stimulus condition identified by the number of elements and interelement spacing.

Observer	Stimulus	SS gain ID task	SS gain no ID task	<i>t</i> test <i>p</i> value	Horizontal saccades ID task	Horizontal saccades no ID task	<i>t</i> test <i>p</i> value
EP	Five characters	1.04 ± 0.007	0.95 ± 0.021	<0.00001	2.258 ± 0.077	4.206 ± 0.141	<0.00001
	Nine characters	1.08 ± 0.006	0.95 ± 0.016	<0.00001	2.456 ± 0.066	3.903 ± 0.125	<0.00001
SW	Five characters	1.04 ± 0.010	0.97 ± 0.018	0.0003	2.536 ± 0.102	3.861 ± 0.127	<0.00001
	Nine characters	1.03 ± 0.009	0.96 ± 0.012	<0.00001	2.546 ± 0.096	3.005 ± 0.101	0.0016

Table 1. Steady-state gain and horizontal saccade frequency for pursuit trials with and without performing the character identification task.

Although observers made fewer saccades when they performed the character identification task (see Figure 7B), it may be that they employed saccades to search for the probe. Because target characters were presented for a limited duration, and executing saccades takes time, a saccade search strategy could increase the time required to find a target character, causing performance to drop with increasing set size. To assess this possibility, we analyzed saccade frequency during pursuit of the different stimulus configurations. Although catch-up saccade frequency was constant across the conditions, averaging  $2.19 \pm 0.09$  saccades/trial, vertical saccades, on the other hand, increased in frequency as the vertical extent of the stimulus increased, consistent with a saccadic search strategy: linear contrast,  $F(1, 5) = 15.09$ ,  $p = 0.0015$ . However, even stimuli with the greatest vertical expanse induced

an average of approximately one vertical saccade every three trials (0.36 per trial), making it unlikely that saccades were systematically used to search for the probe.

To verify that saccades were not being used to search for the probe, we excluded all trials in which a saccade occurred during or within 100 ms prior to the period during which the probe was presented. We then computed identification performance for the remaining trials and compared it to performance in the full data set. Repeated-measures ANOVAs were run on each of the three set-size conditions with eccentricity and saccade presence as variables. With saccade trials removed, performance differed significantly as a function of eccentricity for all set sizes: five characters,  $F(6, 18) = 11.315$ ,  $p = 0.0001$ ; nine characters,  $F(8, 24) = 7.416$ ,  $p = 0.0001$ ; 15 characters,  $F(14, 42) = 16.864$ ,  $p = 0.0001$ , a result that was no different compared to that obtained with the full data set (five characters:  $p = 0.706$ ; nine characters:  $p = 0.292$ ; 15 characters:  $p = 0.834$ ). There were no interactions between saccade presence and eccentricity (five characters:  $p = 0.819$ ; nine characters:  $p = 0.737$ ; 15 characters:  $p = 0.953$ ). Therefore, it appears that a saccade search strategy was not used for the task.

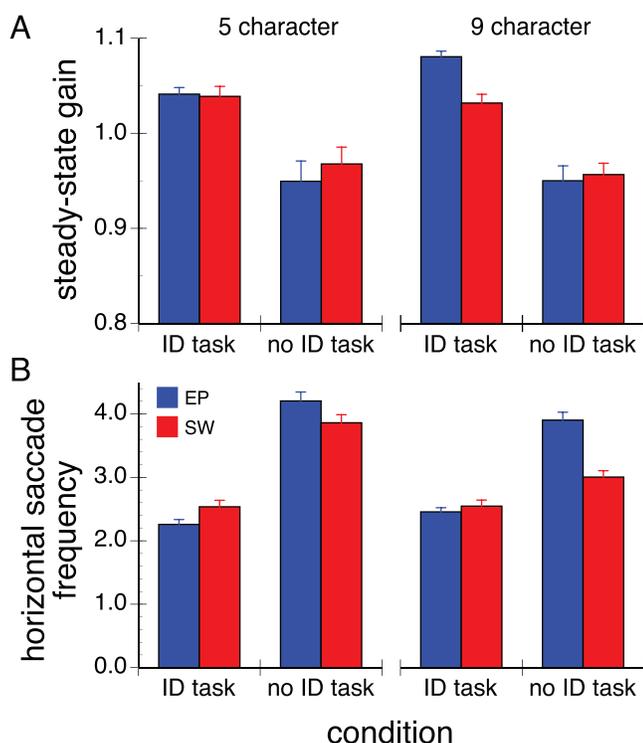


Figure 7. Steady-state gain (A) and horizontal saccade frequency (B) as a function of task condition for two observers (EP: blue bars, SW: red bars).

## Discussion

Our data reveal that element spacing and set size can significantly impact the identification of a target during pursuit. Consistent with Lovejoy et al. (2009), we found that probe identification performance on a large horizontal array of tightly spaced characters was restricted to a small ( $\pm 1^\circ$ ), symmetrical region surrounding the pursuit target. However, increasing the spacing between the characters increased the identification range substantially, indicating that attention by default is not confined around the fovea and that crowding can limit its apparent scope. Independent of crowding, performance was limited by the number of possible target characters and fell off more steeply with eccentricity as set size increased. All of these limitations were identical during pursuit and fixation.

We found performance to be symmetric about the pursuit target, consistent with earlier work (Heinen et al., 2011; Lovejoy et al., 2009), suggesting that attention was allocated symmetrically, centered on the pursuit target. Symmetric attention allocation during pursuit contradicts many earlier studies in which attention was found to be displaced ahead of the pursuit target (e.g., Blohm, Missal, & Lefèvre, 2005a, 2005b; Khan et al., 2010; Tanaka, Yoshida & Fukushima, 1998; van Donkelaar, 1999; van Donkelaar & Drew, 2002). Lovejoy et al. (2009) suggested that the asymmetry reported in these studies was due to luminance transients in the stimuli, which are known to attract attention (e.g., Theeuwes, 1994; Yantis & Jonides, 1984, 1990). However, Heinen et al. (2011) showed that performance on a dimming dot identification task was symmetric about the pursuit target, suggesting that the mere presence of luminance transients does not account for asymmetric attention allocation.

We propose two other possible explanations for attention allocation ahead of pursuit. First, in studies showing this asymmetry, a single target appeared suddenly in a randomly selected location, and in studies reporting symmetric attention allocation, all possible target locations were continuously visible throughout the trial. It may be that keeping the array of potential target locations visible allows the observer to distribute attention over all possible locations prior to target specification. Second, studies reporting attention asymmetry used a single, small spot as a pursuit target, and those reporting symmetric attention allocation used multiple targets that extended into the periphery. Pursuit of larger stimuli is qualitatively different from pursuit of a small spot in that it generates fewer foveating saccades and higher initial accelerations (e.g., Heinen et al., 2011; Heinen & Watamaniuk, 1998; Jin et al., 2014). Therefore, it might be helpful to allocate attention ahead during pursuit of small stimuli in order to predict the target's trajectory in order to compensate for reduced initial acceleration and optimize foveation. Interestingly, Harrison et al. (2014) found asymmetric crowding effects during pursuit, i.e., greater crowding behind the pursuit target than in front of it, under conditions similar to those in studies that found asymmetries in attention during pursuit (e.g., Khan et al., 2010). Because attention can reduce crowding (Chakravarthi & Cavanagh, 2009; Dakin, Bex, Cass, & Watt, 2009; Freeman & Pelli, 2007; Strasburger, 2005; Yeshurun & Rashal, 2010), asymmetric crowding during pursuit may reflect asymmetric attention allocation.

Previously, identification performance during pursuit was shown to be good either in a narrow region surrounding the fovea (Lovejoy et al., 2009) or over a broader region centered on the fovea (Heinen et al.,

2011). The results of the current study show that crowding, a phenomenon in which peripheral targets flanked closely by distractors are less identifiable than targets viewed in isolation, partially explains this disparity. In Lovejoy et al. (2009), the  $0.6^\circ$  character spacing was well within the range of spacing required for crowding to occur (e.g., Bouma, 1970) at all character locations save those nearest the pursuit target. It is thus not surprising that identification performance on their task dropped to near chance only  $1^\circ$  from the pursuit target. In some conditions in the present study, characters were spaced by  $2.0^\circ$  and  $4.0^\circ$ , outside the critical spacing required for crowding. Consistent with a reduction in crowding, identification performance was dramatically better. Other work using transient stimuli has also shown that crowding occurs during smooth pursuit (Harrison et al., 2014).

Another limitation on performance in the present study was the number of potential identification targets or set size. As the number of targets increased, identification performance for the most eccentric targets decreased. In simple “pop out” visual search tasks on static stimuli, performance generally increases or does not change as set size increases. It is thought that a parallel search strategy is used in these situations. However, in more complex search tasks (such as conjunction searches), performance decreases with set size (e.g., Treisman, 1991; Wolfe & DiMase, 2003). In these situations, it is thought that a serial search strategy is used (e.g., Carrasco & Yeshurun, 1998; Jerde, Ikkai, & Curtis, 2011; Wolfe & Horowitz, 2004). In the present task, because the probe characters (E or 3) and distractors (2s and 5s) were similar, it is likely that a serial search strategy was used to identify the probes. Our data show a distinct peak at zero and a decline in performance with eccentricity. It is therefore likely that the serial search in our study begins with the central element and moves from the center outward, resulting in a general drop in performance with eccentricity.

In the present study, character identification performance was the same for moving and stationary stimuli as was previously reported (Lovejoy et al., 2009). The results suggest that pursuit of the character-array stimuli did not require attention resources beyond those needed for fixation. This is consistent with prior work showing that pursuit interferes with performance on secondary tasks (e.g., Khurana & Kowler, 1987) or that secondary tasks interfere with pursuit (e.g., Kerzel, Souto, & Ziegler, 2008; Souto & Kerzel, 2008) when the attended nonpursuit stimuli moved with a different velocity than did the pursuit target. In the current study, the pursuit object and task characters moved as a whole in the same direction; thus, neither pursuit nor identification task performance was compromised. In addition, it may be that the large stimuli used in this

and the previous study (Lovejoy et al., 2009) were instrumental in preserving task performance because large stimuli require less attention to pursue than does a small spot (e.g., Heinen et al., 2011). The attention freed up by pursuing large stimuli may then be used to perform a secondary task (Jin, Reeves, Watamaniuk, & Heinen, 2013; Jin et al., 2014).

Evidence that pursuit of our stimuli required attention would have been obtained if pursuit had been impaired by the identification task even though performance on the identification task was not impaired, but this was not the case. Instead, our data show that pursuit improved (i.e., had higher steady-state gain and fewer saccades) when observers performed the identification task relative to when the stimulus was merely pursued. This was true even when identification task difficulty was high enough to degrade task performance. However, we do not believe that performing the identification task improved pursuit per se. Performing the task may have simply increased observer motivation, leading to higher gain and fewer saccades. Alternatively, having to perform the identification task may have helped observers keep their gaze centered on the stimulus so that attention could be symmetrically allocated across it, thus maintaining higher pursuit gain. This could enable optimal performance on the identification task. Saccade frequency may have been reduced by spreading attention peripherally, away from the foveal target, consistent with recent work showing that pursuing and performing a peripheral task on a multispot stimulus reduces saccades (Heinen, Potapchuk, & Watamaniuk, 2014a, 2014b).

## Conclusion

In the present study, we use a character identification task on arrays with different set sizes and character spacing to show that identification performance, although it decreased with eccentricity, was symmetric about the pursuit target. This implies that attention was not preferentially distributed in the direction of pursuit. Crowding and set size impaired identification, effectively limiting the spatial range of attention allocation. Moreover, attention allocation was no different when the same identification task was performed on a stationary stimulus, suggesting that engaging the pursuit system does not additionally limit the spatial distribution of attention. The results indicate that pursuit of large stimuli does not share attention with the identification task.

*Keywords:* smooth pursuit, eye movements, human, set size, crowding

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Corresponding author: Scott N. J. Watamaniuk.

Email: scott.watamaniuk@wright.edu.

Address: Department of Psychology, Wright State University, Dayton, OH, USA.

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