

## Supplemental Information

### Alteration of Visual Perception prior to Microsaccades

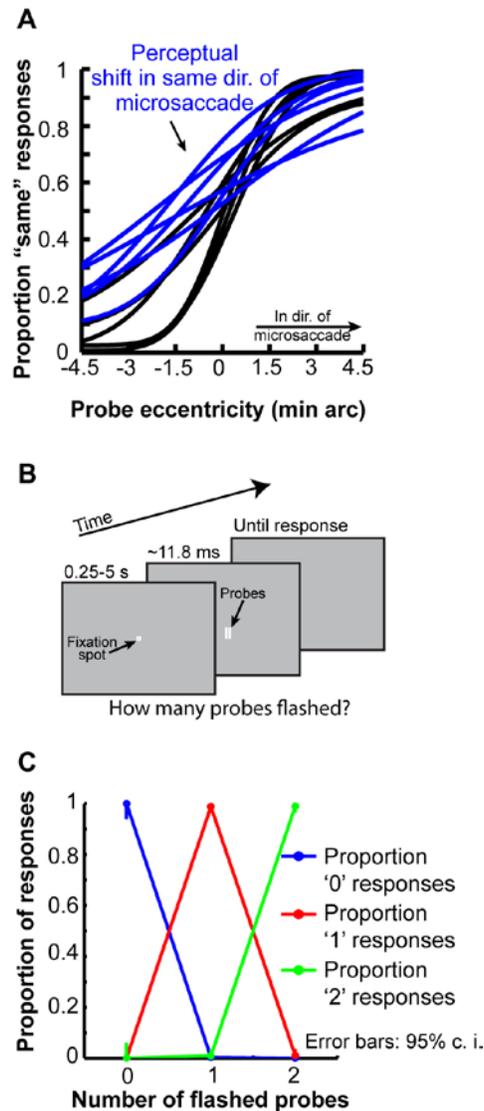
Ziad M. Hafed

#### Inventory of Supplemental Information:

The supplemental information for this manuscript includes 6 figures (ordered below according to the main figures to which each relates):

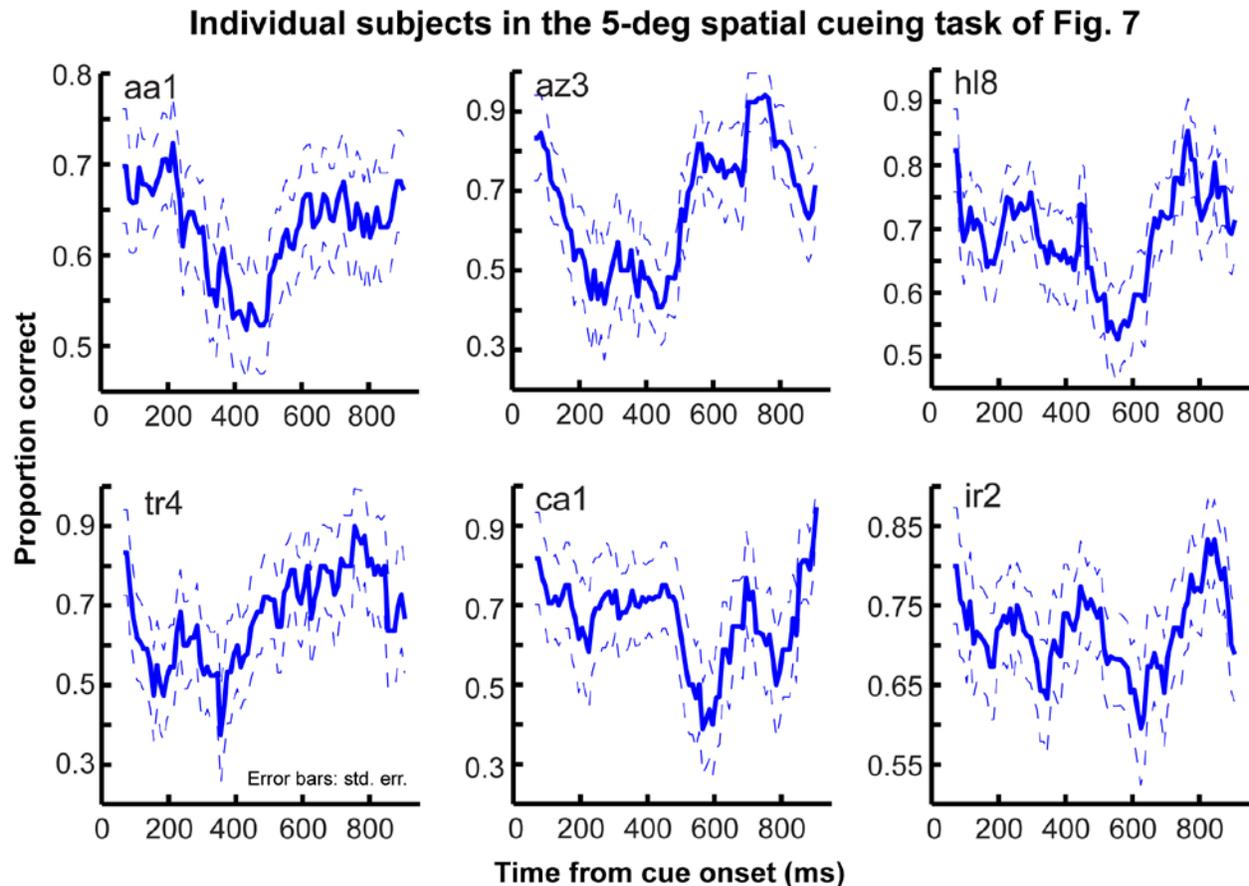
- **Fig. S6** is related to **Fig. 1** and shows evaluations of microsaccade detection performance in my analyses
- **Fig. S1** is related to **Fig. 2** and shows results from individual subjects, as well as results from a relevant control experiment
- **Fig. S4** is related to **Fig. 3** and shows results with microsaccades opposite an eccentric stimulus in addition to towards it
- **Fig. S5** is related to **Fig. 5** and shows results with microsaccades opposite an eccentric stimulus in addition to towards it
- **Fig. S2** is related to **Fig. 7** and shows results from individual subjects
- **Fig. S3** is related to **Fig. 8** and shows the generality of the result of Fig. 8, including to other behavioral tasks (also shows data from an individual monkey subject)

**Supplemental Figures:**

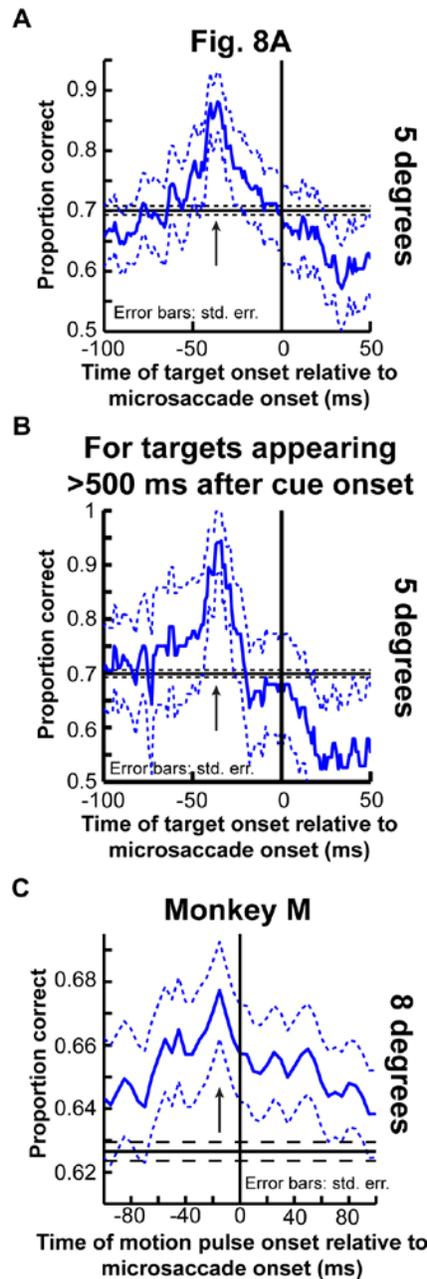


**Figure S1, related to Fig. 2** Changes in spatial localization performance in the main text (Fig. 2) were robust across individual subjects, and they were not due to an inability to see the brief probes. **(A)** An analysis identical to that in Fig. 2C of the main text but shown for six individual subjects (those who participated in at least three sessions each). The black curves show psychometric curve fits when the probes appeared without any nearby microsaccades; the blue curves show the same curves when the probes appeared within 50 ms before microsaccade onset. The perceptual mislocalization shown in Fig. 2C was robustly observed across individual subjects. All other conventions are similar to Fig. 2C. **(B)** To test the ability of subjects to see the brief probes, I designed a control experiment similar to that in Fig. 1 except that subjects were now presented with 0 (20% of the trials), 1 (40% of the trials), or 2 (40% of the trials) probes centered horizontally relative to the fixation spot (the example shown here is with two probes presented). Subjects fixated the central spot and then reported how many probes they perceived. When two probes were presented, they were separated by 2.9°. **(C)** Data from two subjects (817 trials) showing that they had no difficulty in perceiving the brief probes. Most importantly, there

was no increase in the number of '0' reports except when there were physically no probes presented (blue curve). That is, the subjects never reported seeing no probes when 1 or 2 probes were physically shown. These two subjects were among the six shown in panel A. Thus, the performance changes caused by microsaccades in the main text were not due to subjects failing to see the brief probes.

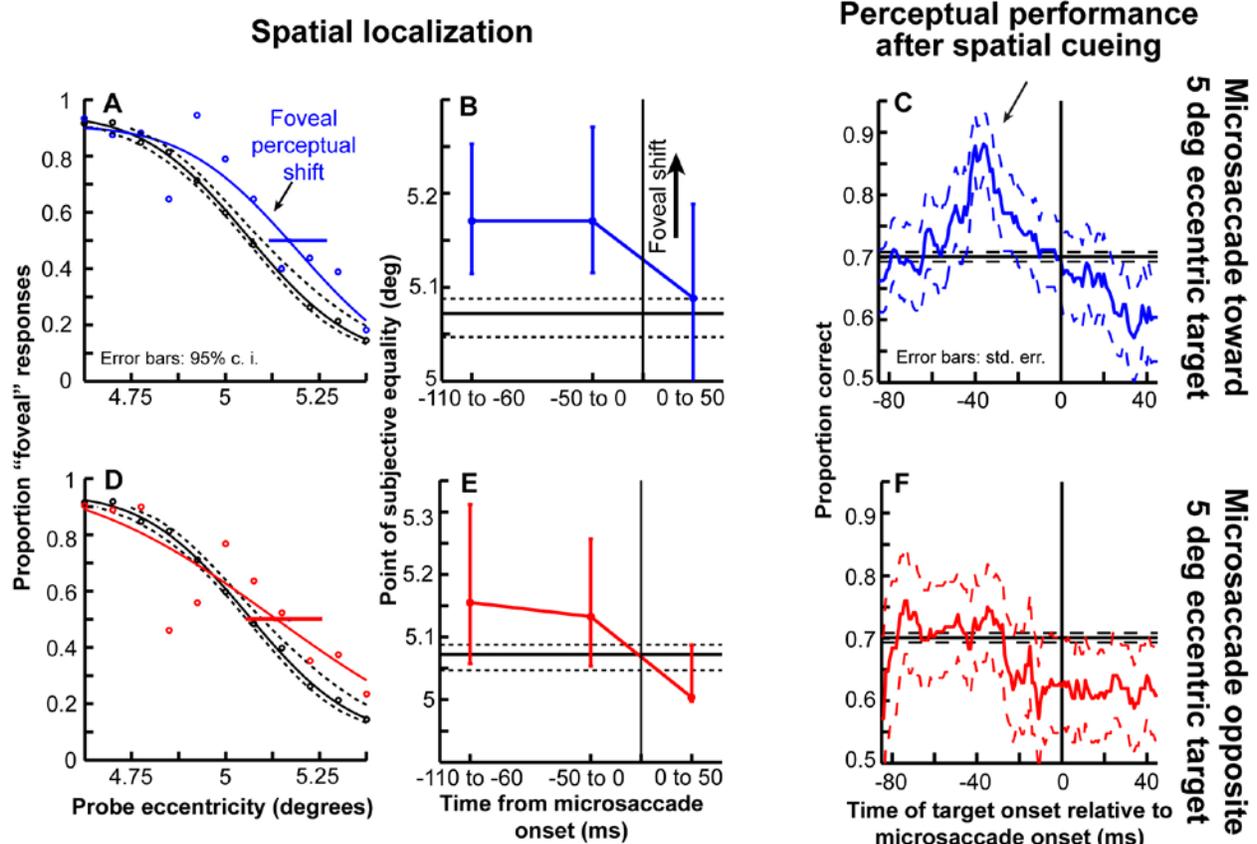


**Figure S2, related to Fig. 7** Changes in visual performance after cue onset in the spatial cueing task were robustly observed across individual subjects. Each panel shows an analysis identical to that of Fig. 7B of the main text, but now for individual subjects (the three-letter identifier in each panel is a unique, random code assigned to each participant in my study, and it does not correspond to subject names or initials). The panels corresponding to subjects az3, tr4, and ca1 show data from a single behavioral session, and the remaining panels show data from subjects who participated in multiple sessions. As can be seen, all panels show a clear oscillation in visual performance after cue onset, consistent with Fig. 7B of the main text (and consistent with previous published reports). Importantly, these oscillations were observable even within a single behavioral session (subjects: az3, tr4, and ca1). Thus, just like the localization data (Fig. S1A), performance in the spatial cueing task was repeatable across individuals. These results are similar to those in (Landau and Fries, 2012), but my results in the main text (Fig. 7D and Fig. 8) demonstrate that the oscillations in visual performance after cue onset can be (at least partially) explained by pre-movement changes in the state of the visual system caused by impending microsaccades. Error bars in all panels denote the standard error of the binomial proportion.

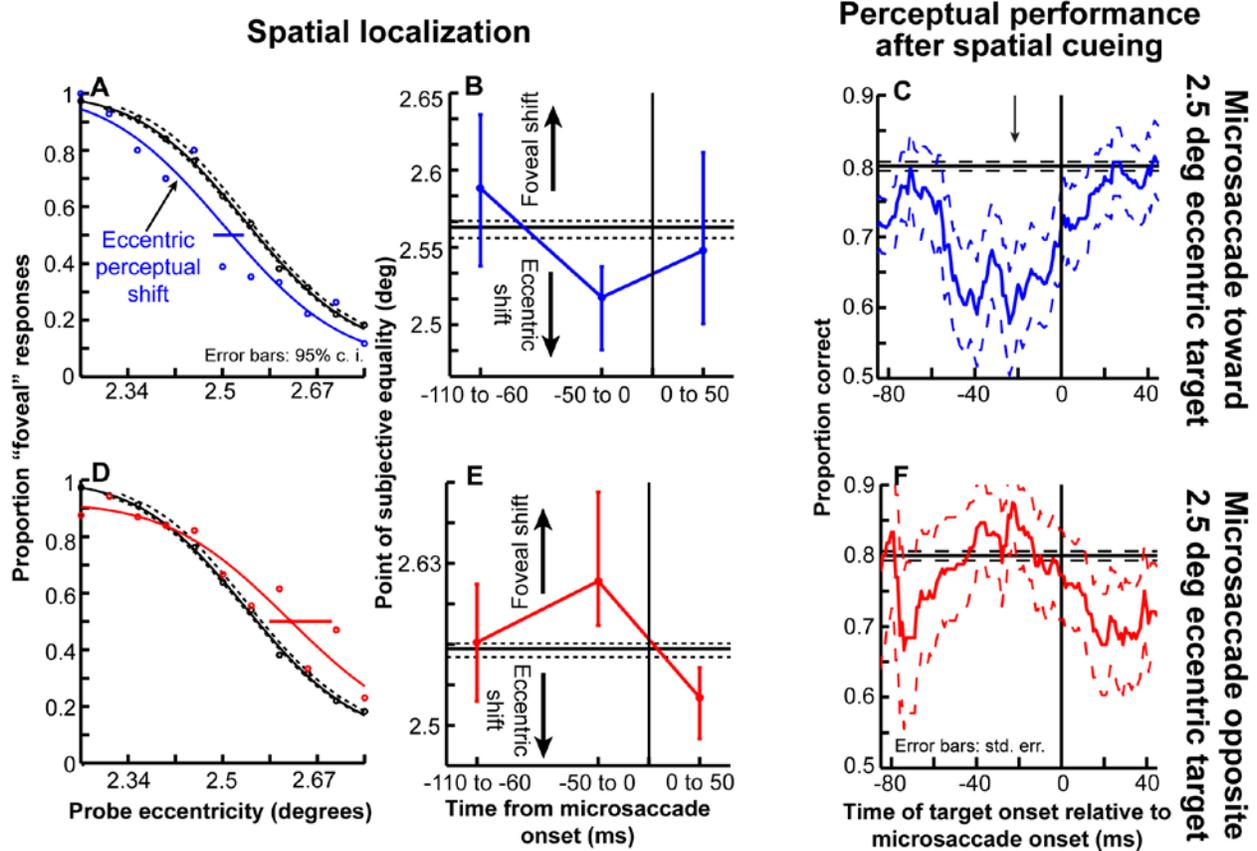


**Figure S3, related to Fig. 8** Generality of the finding that visual performance is altered before microsaccades in covert attention paradigms. **(A)** A replication of Fig. 8A of the main text showing how pre-microsaccadic performance is higher for peripheral locations in the spatial cueing task. **(B)** A similar analysis to that shown in **A** but now restricted only to trials in which the landolt-square (target) appeared after more than 500 ms from cue onset. Comparison to the data shown in panel **A** reveals that the same result was observed for such ‘late-target’ trials. Thus, this analysis explains the rebound in performance I saw in Fig. 7B of the main text long after cue onset. **(C)** Re-analysis of recently published data from a spatial cueing task in monkey (Hafed et al., 2011), but now in a format to test for a possible role of microsaccades. Even

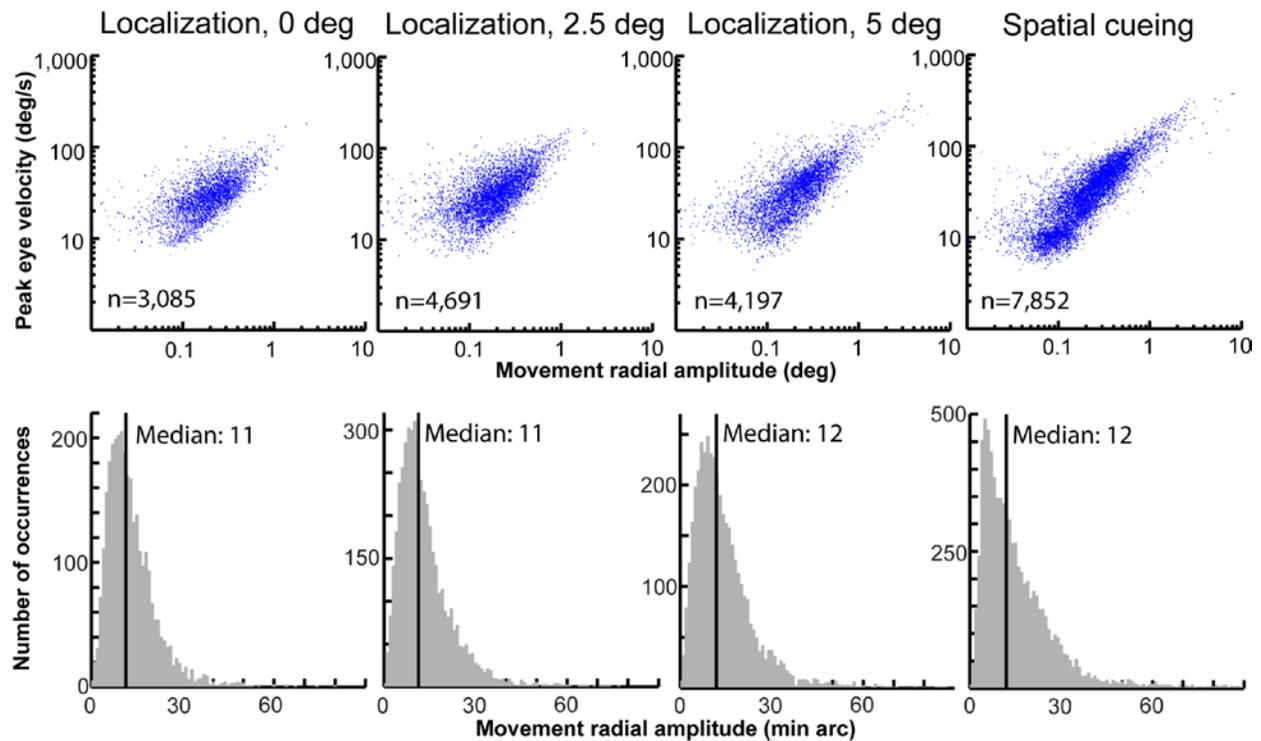
though the monkey was performing a different perceptual discrimination (motion direction, rather than acuity discrimination of the opening of a Landolt-square), the monkey still showed increases in perceptual performance when the motion pulse started in the 50 ms prior to microsaccade onset, just like the humans in my current study. More specifically, the monkey's performance when the motion pulse started in the final 50-ms interval before microsaccade onset was significantly higher than its performance without microsaccades ( $p < 0.05$ ;  $\chi^2$  test). In **C**, the black line shows the performance of the monkey when no microsaccades occurred within 250 ms from motion pulse onset. Other details of the analysis are identical to those described earlier (Hafed et al., 2011). Thus, pre-microsaccadic changes in visual perception can alter visual performance in monkeys, and they can also do so in perceptual tasks beyond just the Landolt-square discrimination I used with my human subjects.



**Figure S4, related to Fig. 3** Localization and cueing task performance around the time of microsaccades of different directions. (A-C) Performance at 5 degrees around the time of a microsaccade directed toward the eccentric location of either the probe (in the localization task) or the acuity target (in the spatial cueing task). These panels are identical to those from the main text (Fig. 3B, D and Fig. 8A), and they show that prior to the microsaccade, spatial percepts were more foveal (A, B) and perceptual performance in the cueing task was higher (C) than with no microsaccades. (D-F) Similar analyses but now for the probe (D, E) or acuity-target (F) appearing around the onset of a microsaccade in the opposite direction. As can be seen, relative to the black ‘no microsaccade’ baseline, localization performance was not affected by an opposite microsaccade (D, E) (but it was somewhat noisier), and neither was perceptual performance in the spatial cueing task ( $p > 0.05$  in the 50-ms pre-microsaccade interval;  $\chi^2$  test) (F). Thus, the similarity between changes in spatial perception and changes in attentional cueing performance described in the main text also persisted for movements of different directions. Error bars in the localization data (A, B, D, E) indicate 95% confidence intervals, and those in the cueing task (C, F) denote the standard error of the binomial proportion. In all panels, black curves indicate performance with no microsaccades around the time of the brief probes (localization task) or acuity targets (spatial cueing task).



**Figure S5, related to Fig. 5** Similar to Fig. S4 but at 2.5 degrees of eccentricity. At this eccentricity, a movement toward the eccentric location was associated with a ‘more eccentric’ percept in spatial localization (**A**, **B**) and a concomitant decrease in perceptual performance in the spatial cueing task (**C**). For movements opposite (lower row), the percept during the localization task was not ‘more eccentric’ (**D**, **E**) and perceptual performance in the spatial cueing task did not decrease (**F**). Thus, even at 2.5 degrees, the similarity between changes in spatial perception in the localization task and perceptual performance in the spatial cueing task persisted for movements of different directions. The top row (**A-C**) replicates data shown in Fig. 5B, C and Fig. 8B of the main text. All other conventions are the same as in Fig. S4.



**Figure S6, related to Fig. 1** Evaluating microsaccade detection. The top row shows the main sequence relationship of microsaccades for each of the experiments I ran. The main sequence relationship for microsaccades and saccades is a plot of movement peak velocity against movement amplitude (Zuber et al., 1965). In all experiments, the expected monotonic relationship was observed, confirming the reliability of microsaccade detection in my data. Note that in the localization panels, I only included microsaccades within 200 ms from probe onset (not from entire trials), and in the spatial cueing panel, I only included movements from cue onset until target onset. The bottom row shows the amplitude distribution of the microsaccades in the top row. In all data sets, the median microsaccade amplitude was 11-12 min arc, consistent with prior reports (Hafed et al., 2009; Hafed and Krauzlis, 2010), and the amplitude distribution showed the expected skewness to small eye movements. Thus, these analyses, combined with the main text, demonstrate that even the smallest possible microsaccades can alter spatial perception and thereby mediate visual performance changes previously attributed to covert attention. Note that these results compellingly extend previous results on the influence of “small saccades” on perceptual mislocalization (Lavergne et al., 2010) down to the smallest possible eye movements.