

## Concurrent processing of saccades

Robert M. McPeck<sup>1</sup>, Edward L. Keller<sup>1</sup>, and Ken Nakayama<sup>2</sup>

<sup>1</sup>Smith-Kettlewell Eye Research Institute, 2232 Webster St., San Francisco, CA 94115 USA (email: rmm@ski.org; elk@ski.org).

<sup>2</sup>Vision Sciences Laboratory, Department of Psychology, Harvard University, Cambridge, MA 02138 (email: ken@wjh.harvard.edu).

### **Abstract** (100 words):

We summarize several experiments indicating that the saccadic system is capable of simultaneously programming two movements toward different goals. This concurrent processing of saccades can lead to the execution of two saccades separated by an extremely short inter-saccadic interval. This supports the idea of target competition proposed by the target article, but suggests a greater degree of parallel processing. In fact, we provide evidence that concurrent processing of two saccades is not limited to higher-level planning subsystems, but rather, also involves brain regions close enough to the motor output that it can systematically affect saccade trajectory.

### **Please address correspondence to:**

Robert M. McPeck  
Smith-Kettlewell Eye Research Institute  
2232 Webster St.  
San Francisco, CA 94115 USA  
phone: 415-561-1639  
fax: 415-561-1610  
email: rmm@ski.org

We find much to agree with in the target article's proposed model of the saccadic system, particularly with regard to the idea of saccade target selection in a distributed, coarse-coded network with competition among active sites. However, in our work on saccades in visual search, we have made several findings which suggest that the saccadic system's ability to simultaneously program multiple movements may be more extensive than suggested by the model.

We examined saccade target selection using a pop-out visual search task in which subjects make a saccade to an odd-colored target. When the color of the target changes from trial to trial, performance is worse than when it remains the same. This is due to a phenomenon called the "priming of pop-out" which affects saccades in humans (McPeck et al. 1998) and rhesus monkeys (McPeck & Keller 1998), as well as the deployment of focal attention in the absence of eye movements (Maljkovic & Nakayama 1994).

We have exploited this priming effect to provoke a strong competition between target and distractor stimuli in our search task. We find that when subjects make an incorrect saccade to a distractor, such error saccades may be followed by a second saccade to the correct target after only a very short inter-saccadic interval (~10-100 msec; see Fig. 1 for an example). Initially found in human subjects (McPeck et al. 1996), this finding has been replicated in the rhesus monkey (McPeck & Keller 1998). The brief inter-saccadic intervals, often shorter than the latency of express saccades (Fischer & Weber 1993), suggest that the system has processed the two saccades in parallel. According to this view, subjects begin programming a saccade to a distractor, but soon after, become aware of the correct location of the target. As a result, the subject begins

programming a second saccade to the correct target, which is processed in parallel with the initial incorrect saccade. The two saccades are effectively "pipelined" by the system, such that their preparation overlaps in time. The saccade which was programmed first is executed first, and is quickly followed by the second saccade as soon as its programming is complete.

This view is supported by results from the double-step paradigm. Becker and Jürgens (1979) observed that when two sequential, but temporally closely spaced, target steps are presented on opposite sides of fixation, an initial saccade directed toward the first target position is often followed after a very brief fixation by a second saccade to the second target position. The presumption is that programming of the initial saccade is triggered by the first target step, and programming of the second saccade is triggered by the second target step. The short inter-saccadic interval results from the fact that the programming of the two saccades overlaps in time. If this is true, the second saccade should always occur one normal saccadic reaction time after the presentation of the second target step, regardless of when the initial saccade occurs. Becker & Jürgens (1979) confirmed this prediction for horizontal target steps. In our own double-step experiments with target steps in two dimensions, we have also found that the second saccade consistently occurs approximately 200-250 msec after the presentation of the second target step, regardless of the timing of the initial saccade, and across a wide range of inter-saccadic intervals (McPeck 1997). This clearly supports the idea that these two-saccade responses reflect the parallel or "pipelined" processing of two movements, each triggered by the presentation of a target step.

Concurrent processing is not limited to the higher-level planning stages of the saccadic system. In both our search experiments and in our double-step experiments, we observed that when two saccades to different goals are

executed in rapid succession, the first movement of the pair may be hypometric, falling short of the stimulus that it is directed toward. When the fixation interval between the first and second saccades is very brief, this reduction in amplitude of the initial saccade is most prominent (McPeck et al. 1996; McPeck & Keller 1998). This points to an effect of the impending readiness of the second saccade on the execution of the initial saccade.

We have found further evidence for an effect of concurrent processing of a second saccade on the execution of an initial saccade. In the rhesus monkey, we have observed that for two-saccade responses in search, the initial incorrect saccade tends to show a relatively large amount of curvature, compared to saccades to single targets, or even to correct saccades in search (McPeck & Keller 1998). Furthermore, we have shown that these incorrect initial saccades are systematically curved toward the goal of the second saccade (see Fig. 1). This effect of the subsequent saccade goal on the execution of the initial saccade not only supports the idea that the two saccades are processed concurrently, it also provides additional evidence that this parallel processing is not limited to higher-level saccade planning centers. Apparently, the processing of the second saccade involves brain regions close enough to the motor output that it can result in systematic changes in the trajectory of the initial saccade.

To summarize, we argue that two saccades to different targets can be processed concurrently and executed in rapid succession. Furthermore, this parallel processing engages even the lower levels of the saccadic system, as evidenced by the systematic effects of the processing of the second saccade on the amplitude and the curvature of the initially executed saccade. Several recent studies of search indicate that subjects often program an initial saccade before visual analysis at the current site is complete (Hooge & Erkelens 1996; Hooge & Erkelens 1998; Zelinsky 1996). The ability of the system to program two

saccades concurrently makes this seemingly sub-optimal search strategy more understandable: since concurrent processing reduces the penalty for an initial incorrect goal selection, it encourages an early saccade based on the probable target location rather than a slower, more conservative search strategy.

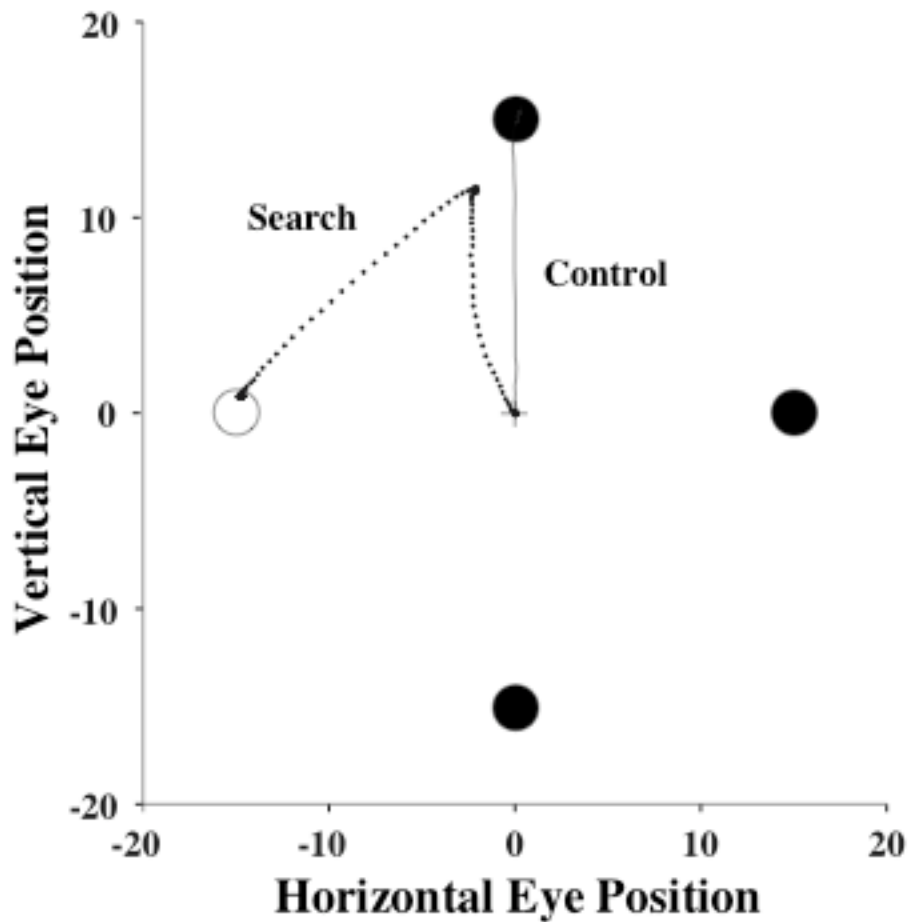
Supported by NIH EY06881 to RMM, EY08060 to ELK, and AFOSR F49620-92-J-0016 to KN.

## References

- Becker, W. & Jürgens, R. (1979) An analysis of the saccadic system by means of double step stimuli. *Vision Research* 19:967-983.
- Fischer, B. & Weber, H. (1993). Express saccades and visual attention. *Behavioral and Brain Sciences* 16:553-610.
- Hooge, I. T. & Erkelens, C. J. (1996). Control of fixation duration in a simple visual search task. *Perception and Psychophysics* 58(7):969-76.
- Hooge, I. T. & Erkelens, C. J. (1998). Adjustment of fixation duration in visual search. *Vision Research* 38(9):1295-302.
- Maljkovic, V. & Nakayama, K. (1994). Priming of pop-out: I. Role of features. *Memory and Cognition* 22(6):657-672.
- McPeck, R.M. (1997). Saccades in visual search. Doctoral Dissertation, Harvard University.
- McPeck, R. M. & Keller, E. L. (1998). Concurrent processing of saccades in visual search results in curved saccades and short inter-saccadic intervals. *Neuroscience Abstracts* 24(1): 672.
- McPeck, R. M., Maljkovic, V., & Nakayama, K. (1998). Saccades require focal attention and are facilitated by a short-term memory system. In press, *Vision Research*.

McPeck, R. M., Skavenski, A. A., & Nakayama, K. (1996). Saccades in a visual search task show concurrent programming. *Investigative Ophthalmology and Visual Science (Suppl.)* 37(3):S471.

Zelinsky, G. J. (1996). Using eye saccades to assess the selectivity of search movements. *Vision Research* 36(14):2177-87.



**Figure 1.** Dotted trace shows an example of a two-saccade response in visual search. Initial fixation is in the center and is marked by a plus-sign. The first saccade is directed up, toward a distractor. After a 45-msec fixation, a second saccade is made to the target. Note that the first saccade falls slightly short of the distractor and is curved toward the goal of the second saccade. For comparison, the solid trace shows a typical saccade to a single target at the same position as the distractor stimulus. (Rhesus monkey, magnetic search coil sampled at 1000 Hz.)