

Superior colliculus cell types and models of saccade generation

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Recent experiments on the cat and monkey have revealed several different cell types within the superior colliculus, including fixation, burst, and build up cells. During primate saccades, activity remains fixed at one location in burst cells, but spreads across the colliculus in build up cells. New models based on the activity of these cell types suggest their functional roles in saccade generation.

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Introduction

Saccadic eye movements rapidly shift gaze from one part of the visual field to another. The neural system that controls these movements extends from the cerebral cortex to the pons, and includes areas of frontal and parietal cortex, the basal ganglia, the superior colliculus, and regions of the reticular formation of the midbrain and pons. The superior colliculus (SC) is the last step in this system in which a clear map of the intended saccadic movement has been identified: neurons that are active with saccades of different directions and amplitudes form an orderly map in the intermediate layers of the SC.

The amplitude and direction of an impending saccade is thought to depend on the weighted average of the activity of a population of neurons in the SC [1]. This hypothesis was given its most elegant support by Lee, Rohrer, and Sparks [2], who showed that modification of this center of activity by the anesthetic lidocaine altered the direction and amplitude of an impending saccade in predictable ways. In seeming contradiction to this, Munoz, Pélisson, and Guitton [3,4] reported that activity in the SC was not limited to the one part of the SC map related to the amplitude and direction of the impending saccade, but rather that activity moved across the SC map like a moving hill during the course of the saccade. Recent observations in the monkey SC [5] may resolve this apparent contradiction by showing that there are a number of SC cell types supporting different functions. In this review, we will first outline those neuronal elements within the SC that must contribute to saccade generation, and then consider some recent models of the saccadic system that depend on these elements.

SC neuronal activity during saccades

The salient experimental point is that several types of collicular cells are active at different times during saccades. We will consider each of the types recently described, which include fixation, burst, and build up cells.

Fixation cells

Some SC cells increase their discharge rate during periods of active fixation rather than before saccades. It was first recognized that these cells lie in the rostral pole of the SC of the cat [6,7]. Fixation cells in the monkey have the following added characteristics: increased discharge during active visual fixation that is independent of the presence of the fixation target, indicating that the response is not just visual; cessation of activity during saccades with the duration of the cessation proportional to the duration of the saccade; and continued discharge during pursuit as well as fixation, indicating the likelihood of a specific relationship of the pause to saccades, but not to all eye movements [5,8].

The hypothesized function of the fixation cells is the inhibition of the activity of saccade-related cells in the rest of the SC and in the saccade premotor circuitry in the brain stem [5,7]. In the monkey, this hypothesis was tested by altering the activity of these fixation cells with either electrical stimulation or GABAergic drugs [8]. Low frequency electrical stimulation delayed the initiation of saccades, and when applied to the fixation cells on both sides of the brain, saccades were not made until the stimulation ceased. Pulses of stimulation during a saccade interrupted it with a latency of about

Abbreviations

GABA— γ -aminobutyric acid; LFB—local feedback; SC—superior colliculus.

12 ms. Injection of bicuculine (a GABA antagonist) also increased saccadic latency. In contrast, injection of muscimol (a GABA agonist) reduced saccadic latency. The monkey also had difficulty maintaining visual fixation and suppressing unwanted saccades following muscimol injections. A striking consequence of the fixation cells being suppressed by muscimol is that the monkey made very short latency saccades, referred to as express saccades [9], much more frequently than when the fixation cells were functioning normally [10]. These intervention experiments support the hypothesis that the fixation cells in the rostral SC inhibit the generation of saccadic eye movements.

Burst cells

Wurtz and Munoz [11•] provided evidence that the saccade related cells in the monkey SC can be regarded as falling into two general categories, burst cells and build up cells. The burst cells have a very low discharge rate during fixation and a burst of spikes immediately before saccade onset, and are presumably the same neurons studied most intensively since the initial investigations of the monkey SC [12–16]. Burst cells would include the saccade-related burst neurons described by Sparks [17], the visually triggered movement cells that only discharged before saccades made to visual targets [18], and the cells having activity that appeared to be actively 'clipped' at the end of the saccade [19,20]. Burst cells have not been identified in the cat.

Build up cells

Whereas burst cells give only a weak response to the onset of a target and then a burst of activity just before saccade onset, build up cells have a largely sustained discharge between the time of target onset and saccade initiation. These SC cells have been referred to as build up cells because of their slow increase of activity before the saccade. As the build up cells tend to be deeper in the SC than the burst cells, the build up cells might be regarded as falling in a separate, deeper layer within the SC [11•]. The cells regarded as build up cells probably include the cells recorded at increasing depths within the SC [18] and possibly the quasi-visual cells of Mays and Sparks [21].

A major difference between burst and build up neurons is in the extent of their movement fields — the area of the field in which saccades are accompanied by increased activity of the cells [14]. Burst cells discharge maximally for saccades close to a given amplitude and direction and less with larger or smaller saccades. In contrast, activity increases for build up cells for any saccades with amplitudes greater than a given value. Also, the timing of the peak discharge relative to saccade onset does not vary with saccade amplitude for burst cells — it always occurs around the time of saccade onset. For build up cells, the time of the peak discharge relative to saccade onset

increases as saccade amplitude increases. What is most important, is that the build up cells in the monkey are very similar to the saccade-related cells described in the cat [3,4,22,23•,24•]. The consequence of this similarity is that the moving hill of activity seen in the cat may have a corresponding phenomenon in the monkey — but only in the build up cells, not in the burst cells.

Sequence of activity during saccade generation

The activity in the SC between saccades is similar in the cat and monkey: the fixation cells at the rostral pole are active, and the saccade-related cells are largely silent. The first activity before a saccade is the gradual increase in discharge rate of the build up cells in the monkey, and in all the saccade-related cells in the cat. This is followed by the burst of activity preceding the saccade in the burst cells in the monkey and the cessation of activity in the fixation cells in both the cat and the monkey. Activity in the saccade-related cells in the cat moves like a hill from caudal to rostral across the SC, but in the monkey there is instead a spread of activity across the build up cells only, rather than across all cells. At the end of the saccade, the fixation cells come on again and the saccade-related cells decrease their activity. This cycle of activity includes all of the cell types within the SC, and forms the basis for the models of the SC considered next.

Models of the superior colliculus

Local feedback loop for saccade generation

Models of saccade generation share a common structure (Fig. 1): a local feedback (LFB) loop [25] that generates the eye velocity command, and a resettable integrator [26,27] that integrates eye velocity to determine how far the eye has already turned, Δ' . The input required by this model is just a desired eye rotation signal, Δ . In several models, the output of the SC has been assumed to provide Δ , the desired ocular displacement [28•], or its derivative [29,30], because the SC is mapped in retinotopic coordinates and the saccade-related burst cells are arranged in a motor map. However, models in which the SC is upstream of the LFB loop and provides its input can explain the role of fixation and burst cells, but not that of the build up cells.

SC models with stationary activity

Recently, several groups have proposed new models of the saccadic system that place the SC within the LFB loop. These models break down into two classes. The first class of models are those that account for the timing of burst cell activity, but not for the spread of activity in the build up cells [19,20,31,32•,33•]. These models are similar, however, in that the SC is inside the LFB loop, functions as both the resettable integrator and the summing junction, and produces motor error as its output

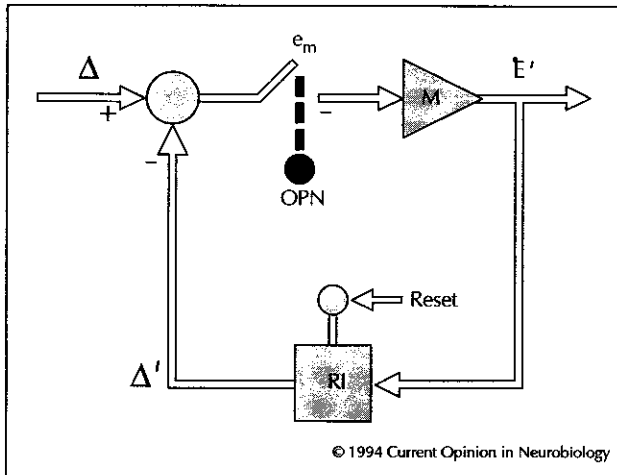


Fig. 1. The local feedback loop for generating saccades. This loop automatically turns a desired ocular displacement into a velocity command to move the eyes. Δ is desired displacement in retinotopic coordinates. The motor error, e_m , is the output of the summing junction. OPN is the omnipause neuron that gates saccade activity. M is the medium lead burst neuron in pons (horizontal bursters) or midbrain (vertical bursters). E' is the efferent velocity command. RI is a resettable integrator that is reset to zero at the end of each saccade. Δ' is the current displacement.

(see Fig. 1). The temporal activity at one stationary locus on the SC would thus generate the motor error signal.

SC models with moving activity

The second class of models also place the SC inside the LFB loop, and in addition have a group of cells across which activity moves during a saccade. Droulez and Berthoz [34] suggested that the SC is inside the loop and provided motor error as its output. In their model, the SC functions as both the resettable integrator and the summing junction. Their model of the resettable integrator is a spatial integrator that moves a discrete hill of

activity across the SC so that its location reflects motor error [35,36].

Lefèvre, Galiana [37], along with Roucoux [38*], also propose a model of the SC in which velocity feedback is integrated to obtain the motor error signal. In the Lefèvre and Galiana model, however, the spatial integration causes activity to spread, rather than move as a discrete hill, during a saccade. The location of the peak of this spreading wave represents the motor error.

All of these new models (whether or not the activity spreads) share the properties that the output of the SC is the motor error signal and that a velocity signal is fed back and integrated in the SC. One problem with these models is that they all place the summing junction for determining motor error in the SC. However, electrical stimulation of the SC just before or during a saccade causes the saccadic trajectory to be redirected toward a new goal [39]. Such redirected saccades can even reverse direction. For example, stimulating the left SC near the end of a rightward saccade can cause the saccade to turn back to the left. Keller *et al.* (EL Keller, EJ Fitzgibbon, ME Goldberg, Soc Neurosci Abstr 1990, 16:899) showed that the site in the right SC associated with this leftward component did not become active. Thus, the left SC somehow generated that leftward movement. Saccadic models that place the LFB loop's summing junction within the SC would need a negative output to generate such a redirected saccade.

A new SC model

Recently, Optican [40*] has proposed a model of the SC that places the summing junction that computes the motor error downstream from the SC, in the pontine circuits of the brain stem. This downstream summing junction avoids the need for the SC to generate a negative motor error signal. In the new model, the SC is organized into vertical modules that span the burst and build up layers (Fig. 2). The fixation zone is shown as a rostral

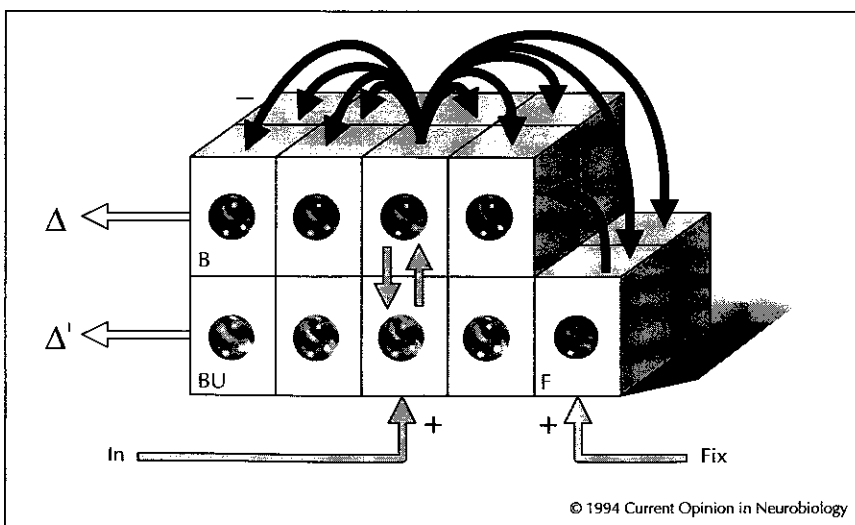


Fig. 2. Model of interactions among three saccade-related cell types in the intermediate layer of the SC. Vertical modules span burst (B) and build up (BU) layers. Neurons in the rostral fixation zone (F) receive a command to fixate (Fix), and inhibit the other modules. Build up (BU) neurons receive cortical inputs (In) at a locus on the SC motor map corresponding to the desired ocular displacement. The burst neurons (B) act as a winner-take-all network that selects the desired ocular displacement, Δ , the locus of peak activity among the build up neurons. The build up neurons (BU) act as the resettable integrator of the local feedback loop, providing Δ' . Thick arrows show excitatory (light gray) and inhibitory (dark gray) connections.

extension of the build up layer. Between saccades, the fixation cells receive a constant command from cortical areas that keeps them active. The fixation cells inhibit the other vertical modules, so their cells are off. Before a saccade begins, build up cells receive excitatory input from cortical areas that determine the desired ocular displacement. The build up cell population at the appropriate locus then becomes active, with a level of activity that represents the balance of the excitation from the input and the inhibition from the fixation cells.

When the cortical fixation input is withdrawn, the fixation cell activity decays away. At some point, the excitatory input to the burst cells from the build up cells will exceed their inhibition from the fixation cells, and the burst cells will begin to fire. The active locus in the burst layer is determined by the balance between the excitation feeding up from the build up layer, and lateral inhibition within the burst layer. The burst layer functions as a modified winner-take-all network that selects the saccade goal, Δ . During the saccade, velocity feedback to the build up cells causes their activity to spread rostrally. Thus, the build up cell activity represents the spatial integration of the feedback velocity, or Δ' . The motor error is computed in the brain stem as the difference between Δ and Δ' signals from the SC.

Conclusions

Results in the cat and monkey suggest that at least three distinct cell types in the intermediate layers of the SC interact to control saccades. Recent models place the SC inside the LFB loop of the saccadic system, and propose functional roles for each of those three SC cell types. The fixation neurons prevent saccades, the burst neurons select the desired eye displacement, and the build up neurons spatially integrate velocity feedback to determine how far the eye has already turned. The different models highlight three critical questions open to further experimental testing: is the SC within the LFB loop, where is the summing junction, and does the activity of the build up cells spread as a function of eye velocity?

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