On Neural Networks Modeling the Choice between Saccades and Pursuits in Oculomotor Movements Across a Single Object

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Abstract

Retinal images are mostly processed according to the salient objects in the scene. It is the job of the oculomotor system to guide the fovea across select points in the environment. Saccades and fixations (also known as pursuits) describe the types of motion that the eye makes as it moves across the scene and are respectively controlled by branches in the oculomotor processing system. Here we create a state specific model of oculomotor control for the tracking of a single object to guide saccades and pursuits in respect to the object. This model represents the processing between higher level visual areas and the premotor cortex by using vector representations of saccades and pursuits in conjunction with the action-gated architecture of the basal ganglia to produce premotor commands. We were able to produce a realistic representation of this voting mechanism with results mimicking previously theorized architectures.

1 Introduction

The oculomotor system is responsible for directing a person's eye gaze across the retinal scenery. Two major types of movements performed by the system are saccades and pursuits[5]. A saccade is a quick burst of movement as the eye travels hundreds of degrees per second across the scene. On the other hand, pursuits are slow and track individual objects. Though, when looking at an object, both pursuits and saccades will happen as the brain scans, or identifies, the object. We refer to the objects in the scene that the brain chooses to look at as being salient, meaning it is important or noticeable. The oculomotor system is then tasked with scanning the "saliency map" (which is just the points of interest in the retinal image) [6].

In this project, we aim to look at the motor occurrences when an individual object is identified. Can we model the switching between fixations and saccades? According to previous research [4], we know that saccades must happen in order for the brain to quickly recognize a salient object. Still, the brain must pursue the object by fixating the eyes on a part of that object. According to Orban de Xivry et al. [1], this process is broken down symbolically by the following illustration:

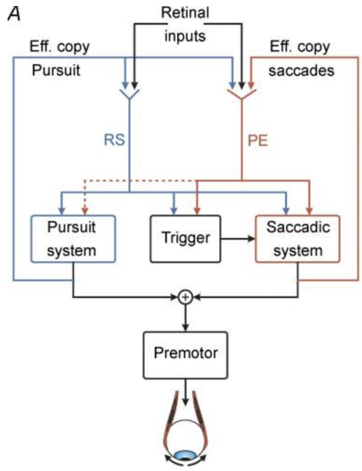

Figure 1. Orban de Xivry et al. [1] model of the oculomotor process behind saccades and pursuits.

In Figure 1, the underlying brain areas are abstracted away, and replaced with a pursuit, saccade system, and a trigger which is responsible for fast switching to the saccadic system. Every action generates efferent feedback to be used by the next input and the final additive output is processed by the premotor functions of the brain to be actualized into eye movements.

The modeling of these systems is useful for understanding how our brain processes a salient image, and is important in the future for possibly modeling this in diseases and robotics.

2 Methods

2.1 Assumptions and Cortical Substructures

In order to model the oculomotor process, we first needed to make some assumptions and abstractions. First, we decided to look at the portion of the pathway downstream from saliency choice. This means our model is limited to eye movements in correlation to a single object. Furthermore, while there are many brain areas involved in eye movement, we used predefined networks for basal ganglia (action gating), thalamus (selection forwarding), and premotor (motor action). The saccadic and pursuit substructures where built as single networks for simplicity, though they would incorporate many brain regions in the human brain.

2.2 Nengo Simulation Outline

To assemble the large scale network, which came out to over 4,000 neurons, we used the Nengo neural simulator (nengo.ai). We encoded position signals and motor representations in their semantic architecture for easy experimentation, though in reality, there would be no semantic meaning, rather only vector encoding. We used their predefined networks for the basal ganglia and thalamus (for decision verification) and created our own vector-based architecture for the pursuit/saccade selection. We followed the outline from Figure 1 and Mulas et al. [2] to create the following graph:

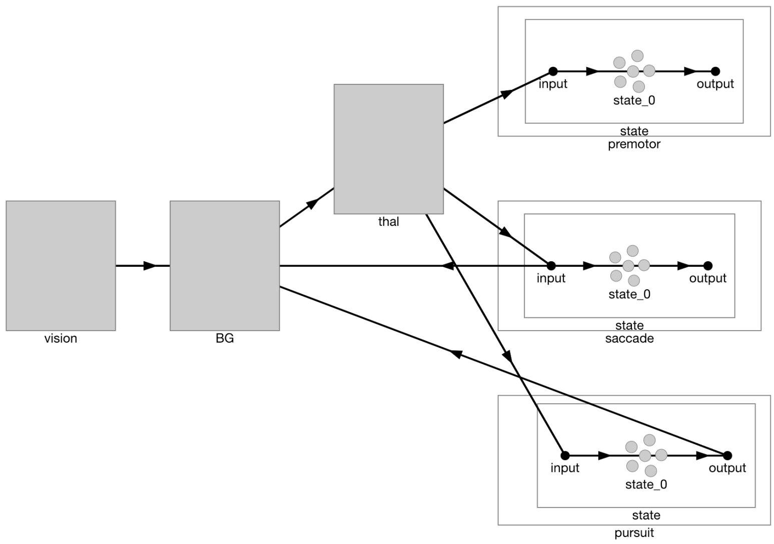

Figure 2. Overview of the multi-network model.

The signal functions here are just a mapping of the voltage output, and are decoded using temporal filters on the spike train to account for post-synaptic activity:

$$f(v_{out}) = v_{out}$$

The Basal Ganglia in the network is responsible for collecting and gating decisions by calculating the dot product of the representation vectors from the pursuit/saccade networks. The best choice is then forwarded to the premotor network.

All neurons in this simulation were leaky-integrate and fire neurons (LIF) with a max fire rate of around 400Hz, with the following differential equation for voltage (directed output)[3]:

$$\frac{dv_i}{d_t}t = -\frac{[v_i(t) - v^{Rest}]}{\tau} + j_i(t)$$

The feedback strength within networks was kept at defaults, which is 0.05 of the output signal (for a recurrent network i.e. basal ganglia, thalamus), except for the pursuit system, which we set network feedback at the synapse to 0.01 and overall feedback at 0.40 which gave the effect of weak short term memory.

2.3 Pursuit and Saccade Systems

The Pursuit and Saccade systems are each composed of 100-neuron ensembles that are responsible for taking thalamic input (modulated by the basal ganglia) and outputting their preferred motor action. The saccadic system has no direct network feedback, which differs from Figure 1, as we used the feedback through the basal ganglia to modulate the recurring saccades. The pursuit system has a medium strength feedback to simulate the perception of a moving object, which we will discuss in detail in the discussion section.

2.4 Data Collection

We experimented on the network using the GUI module for Nengo to manually enter inputs and observe real time output. The inputs were represented semantically and encoded into 2D vectors in the visual system representing change in salience distance points. The outputs were 2D Vectors decoded into SAC/FIX representations using the built in Nengo decoder.

3 Results

3.1 Default state

First we let the system stabilize:

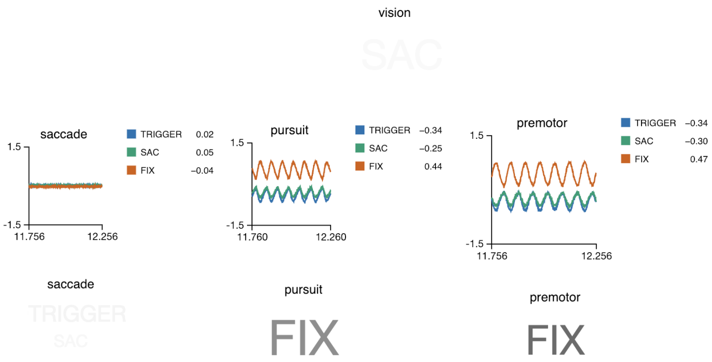

Figure 3. Stable object perception fixation.

3.2 Saccades

Then we derive a saccadic input from the visual system:

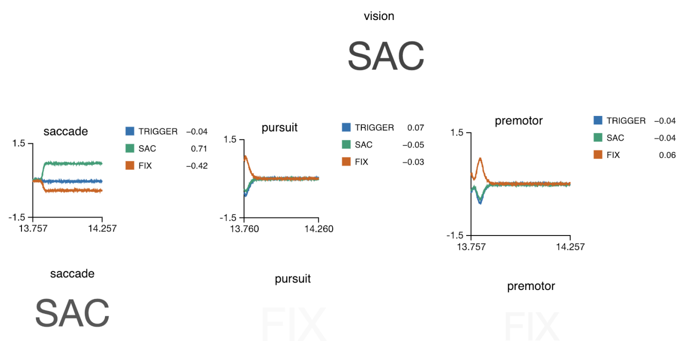

Figure 4. Large difference in salience target primes the system for a saccade.

When the saccade finishes passing through the saccade network after release from the visual network, we get a quick burst from the motor network representing a saccade signal:

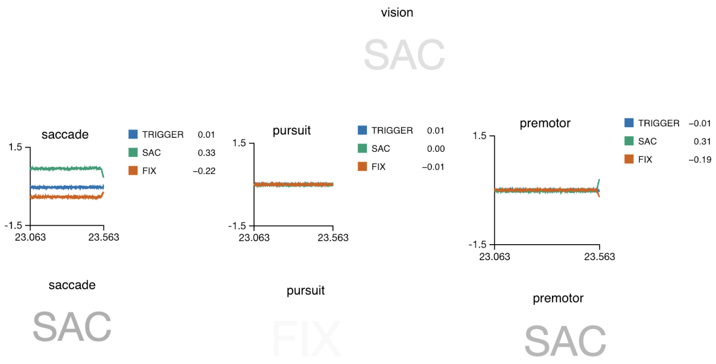

Figure 5. Saccade present in motor network.

The system immediately goes back to pursuit (fixation) after the saccade:

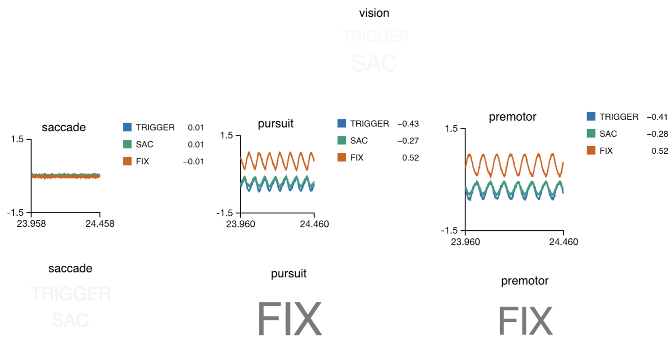

Figure 6. Fixation present as default after saccade.

3.3 Triggers

Lastly, we present a trigger, inspired by the Orban de Xivry paper [1], where we have a quick ”vote” for a saccade:

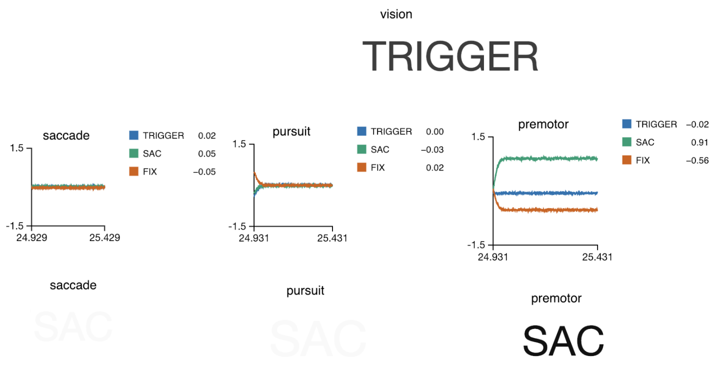

Figure 7. Trigger activation, caused by input disturbance from a pursuit, causes immediate saccade.

As usual, the network at rest returns to object fixation:

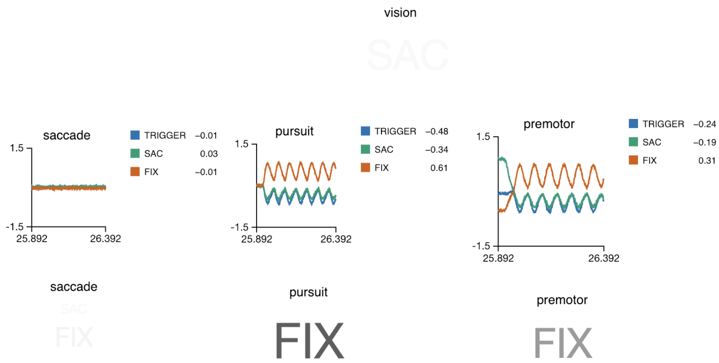

Figure 8. Return to fixation after network trigger.

4 Discussion

With varying amounts of success, we created a network of neural networks to simulate a portion of the oculomotor system, specifically, the system in place in between saccadic jumps on a portion of a saliency map. Here, a single object is being traced by the visual system, and the premotor network is being activated in a sequence of pursuit and saccade events.

The LIF neurons worked well to produce clean output with a noisy individual signal, which is what we would see in a biological brain.

4.1 Default Fixation in Thalamus and Basal Ganglia

As we can see in figures 3,6, and 8, the steady state of the premotor network is a medium vote for pursuit. This was designed as the baseline for the hypothetical object we are tracking. The pursuit signal is not constant (from looking at the waveform), and this is because the signal itself, in its default form, is propagated through the basal ganglia and back to thalamus as feedback, as the pursuits recurrent feedback is set to be very weak.

4.2 Saccadic activity

Once the visual system encounters enough activity triggering a saccade signal (which we entered manually), the saccade network quickly represents this signal and will hold it until the thalamus (gated by the basal ganglia) relays it to the premotor network, as happens in figure 4 going to figure 5. The saccade signal only lasts a few milliseconds in simulation, and the state returns to fixation (figure 6). This mimics the biolgical speed of the saccade, which tend not to last long, but have a burst-like nature, and are spaced between longer periods of pursuits.

4.3 Visual triggers

Lastly, a trigger coming in from the vision (say a new salience point on the same object) will immediately be relayed through the basal ganglia as a saccade vote, and hold the premotor network in the saccade signal (figure 7). Once again, the absence of the trigger returns the premotor network to a pursuit signal from the pursuit network as to model the intermittent period of saccades.

4.4 Notable Signal Qualities

In the default state, the pursuit signal is in constant unbalance (figure 9), yet the premotor network maintains the signal as it's constant choice.

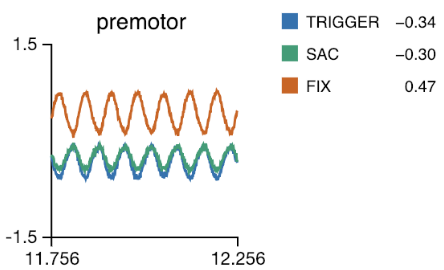

Figure 9. Pursuit signal in premotor network.

This is because of the activity of the basal ganglia weighting the SAC/TRIGGER signals as an expected occurrence, and thus the vote for a pursuit is not necessarily very strong without implicit pursuit signal upstream.

On the other hand, the saccade signal during a trigger is clean and undisputed (figure 10) as the system needs to have a strong and fast reaction to a sudden change in object tracking that is not pre-meditated.

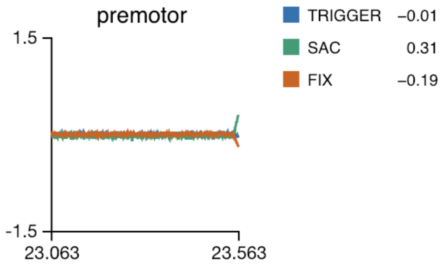

Figure 10. Saccade signal in premotor network during saccade event.

The activity of the premotor network flattened out before the saccade signal left the vision network, and caused a temporary spike during release (seen at the end of the figure) because the thalamus is relaying the signals recurrently leaving out the premotor network, thus activity dies down as the premotor network does not have any network feedback.

4.5 Basis of the model

These results are based in part on the figure 1 model, and are built to emulate the functionality of that system in a very specific state of single object tracking. This system has many pieces that are not close to the biological model, though with time, it can be modified to be more representative by building out the saccade and pursuit networks with the underlying eye fields and motor fields. This will yield the effect of more complex saccade and pursuit reactions in both the basal ganglia and premotor networks (including input/output from the frontal and parietal eye fields).

5 Summary

In conclusion, we were able to successfully produce a premotor, post salient network for an oculomotor system in a single object tracking state.

The model here is not very biologically accurate. We traded off biological accuracy for ease of implementation. Still, this model is a precursor for another model with more networks representing the other cortical structures for the oculomotor system in any state.

Finally, we take an important note that biological accuracy of the underlying networks in the model are important to maintain (which is easy thanks to Nengo) as it is these emergent features that we essentially analyze.

References

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