A Recurrent Network Model of Eye-Position Effect on Auditory Receptive Field

William Tam and Kechen Zhang
Department of Biomedical Engineering
Johns Hopkins University School of Medicine
720 Rutland Ave, Traylor Bldg 426
Baltimore, Maryland 21205

Abstract

Visual and auditory systems use different reference frames to code stimuli: early vision is eye-centered, while early audition is head-centered. To direct saccade towards an auditory target, auditory signals have to be transformed into eye-centered coordinates in the superior colliculus (SC), where auditory receptive fields (RF) can indeed be shifted with the eyes. We propose a recurrent network model with separate excitatory and inhibitory neuronal populations for combining the incoming signals using the approximate multiplicative property of the network. The model may provide a robust and biologically more realistic computational mechanism for the eye-position effects.

Introduction

Early in the sensory pathways, each sensory system has its own frame of reference for encoding incoming stimuli. For visual system, the neural coding is based on information about both the eye-position and the locus of retinal stimulation. However, for the auditory system, the neural coding is based on head-centered cues such as inter-aural differences in the timing and intensity of the coming sound waves. Because of different encoding methods, there needs to be an integration of different sensory information before any comparison can occur. Therefore, area in the brain such as the SC provides a means for combining different sensory inputs.

Based on the extracellular recordings of the primate SC cells conducted by Jay and Sparks, the spatial location of auditory RF is significantly altered by the position of the eyes. They discovered that the average magnitude shift of the auditory RF is estimated to be half the changes in the eye-position. [1] In addition, evidence from microstimulation, lesions and neuroanatomy suggests that SC has access to an eye-position signal.[2,3] Several research groups have modeled after this frame shift phenomenon. [4,5] However, their work seems to lack realism to the biological properties of the SC neurons. The proposed SC recurrent network is an extension to Salinas and Abbott's proposed model in the parietal cortex[6], and this model is for replicating the experimental recordings done by Jay and Sparks.

The Model

The SC reccurent network (Figure 1) is constructed from N individual model neurons that mimic the response of SC neurons to auditory stimuli from various directions and different eye-positions. Each SC neuron is proposed to have a preferred direction, which is the same as the neurons that it receives afferent inputs from. These inputs encode information such as the sound intensity, sound location and eye-position. We denote the total afferent input to neuron i of the SC with $h_i = h_i^A(x) + h_i^E(y)$. The auditory and eye-position inputs are both modeled with

Gaussian functions, with maximum values $h^A_{\max}$ and $h^E_{\max}$, widths of $2\sigma_A^2$ and $2\sigma_E^2$, and preferred directions, x_i and y_i, respectively. These Gaussian functions are described by these two equations:

$$h_i^A(x) = h^A_{\max} e^{\left(-\frac{(x-x_i)^2}{2\sigma_A^2}\right)} \text{ (auditory input) and } h_i^E(y) = h^E_{\max} e^{\left(-\frac{(y-y_i)^2}{2\sigma_E^2}\right)} \text{ (eye-position input).}$$

Within the SC recurrent network, the firing rate of each neuron i, in addition to being influenced by h_i, is also affected by an additional recurrent input $\sum_j W_{ij} r_j - C(\sum_j r_j)^2$. The first part is the excitation that goes into neuron i, while the latter part inhibits neuron i with the help of an additional neuron C_{in}. r_j is defined as the firing rate of neuron j in the network, while W_{ij} and C are synaptic weights for the connections between neurons. For excitation, the synaptic weight W_{ij} is given by a Gaussian function,

$$W_{ij} = A_{Ex} e^{\left(-\frac{(x_i-x_j)^2}{2\sigma_{Ex}^2}\right)},$$

where the strength of the connection depends on the difference of the preferred location of presynaptic neuron j and postsynaptic neurons i. For inhibition, the amount is the same for all neurons in the SC network and this level depends on a constant weight C and the activity of the entire network.

Each neuron i in the network fires only if the sum of afferent and recurrent input is higher than a set threshold. Moreover, for larger inputs, the firing rate of neuron i is assumed to increase linearly with the amount over the threshold. The following describes the firing pattern of the neurons in the SC recurrent network:

$$r_i = s\left[h_i + \sum_j W_{ij} r_j - C\left(\sum_j r_j\right)^2\right]_+, \quad s = \begin{Bmatrix} 0, x < 0 \\ x, otherwise \end{Bmatrix}$$

Simulation Result and Remarks

The parameters used for simulation are similar to the ones used by Salinas and Abbott, except both inputs are Gaussian functions. For simplicity, we have modeled both Gaussian functions with the same parameter values. We tested for the response of both the whole SC network and individual SC neurons to directional values ranging from -5 to 5. Figure 2 shows the response of the network to different Gaussian inputs. The eye-position is fixed at 1, while the direction of the auditory stimuli varied. This simulation reveals that with this recurrent network, the response of the SC neural network is the average of the two Gaussian inputs from the sensory systems. In addition, when measuring a neuron's response to the complete spectrum of auditory stimuli direction at various eye-positions, we see a shift in the neuron's receptive field (Figure 3), which is similar to the SC cellular recording findings by Jay and Sparks.

Figures and Graphs

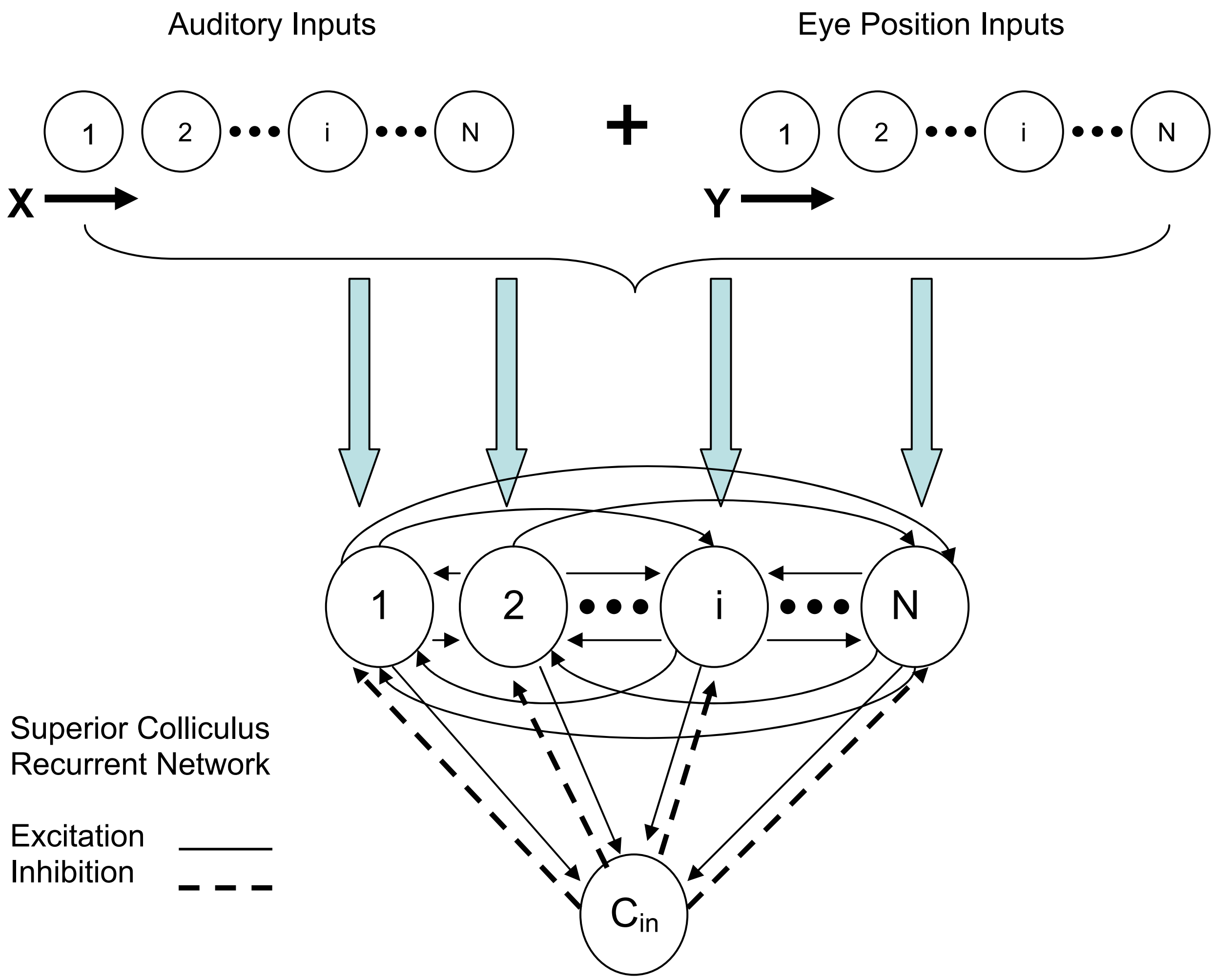

Figure 1. Superior Colliculus Recurrent Network Model. Auditory and Eye-Position Inputs are combined linearly and added into the respective neuron in the SC. X and Y are the location of incoming auditory and eye-position stimuli, respectively. All the neurons within the network mutually excite one another and an additional neuron C_{in}. The C_{in} neuron sums up the activity of the network and inhibits each of the SC neurons.

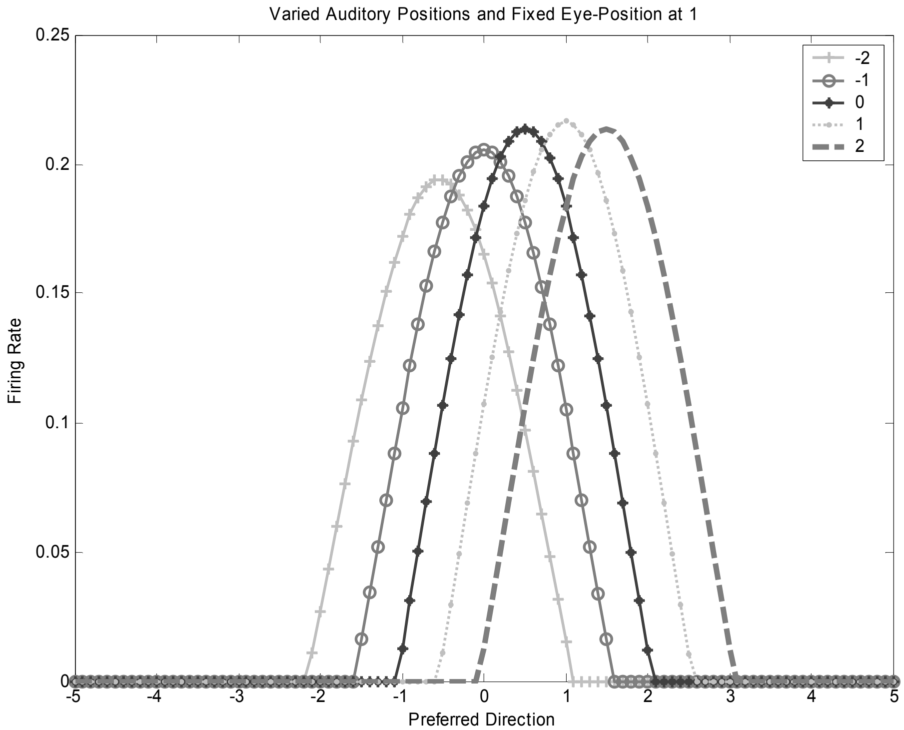

Figure 2. The response of the whole SC network to a fixed eye-position at 1 and varied auditory positions. X-axis denotes the neuron's the preferred direction, while the y-axis represents the firing rates of these neurons.

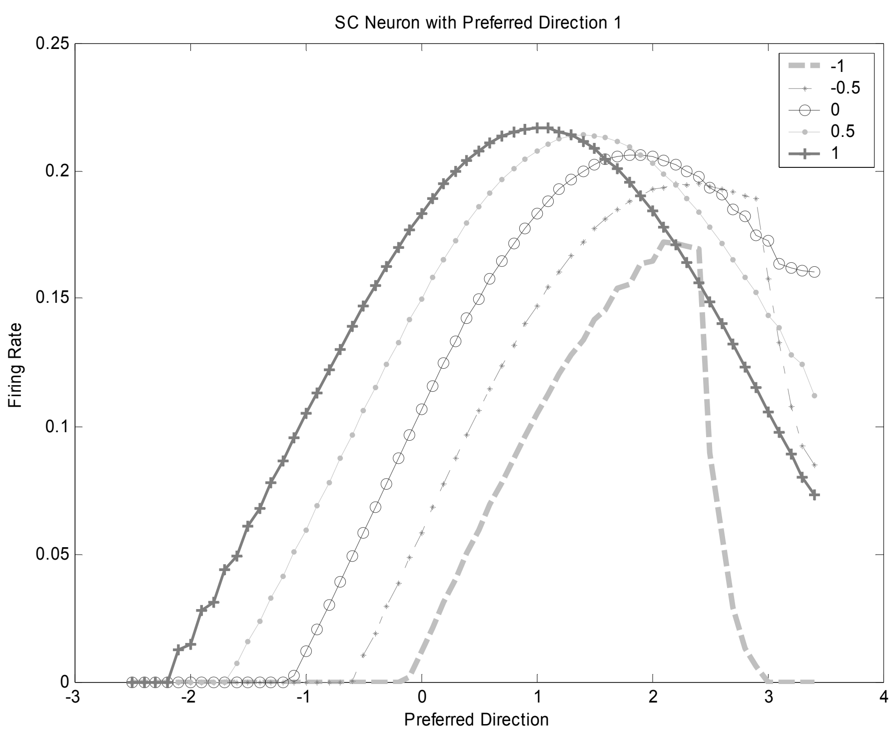

Figure 3. Response of an individual SC neuron (Preferred Direction = 1).

References

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