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Investigation of Cortical Oscillation Models Within the Visual Cortex

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Abstract

Computer vision deals with algorithms that allow machines to detect, segment, feature extract, and recognize objects in an image. There are numerous applications in medicine, manufacturing, and security for this technology. By studying the visual processes of biological systems, enhancements can be achieved in the development of computer vision algorithms. One biological function of interest involves the oscillatory pulses generated in the primary visual cortex engaged in stimulus-specific oscillatory responses. As a result of these experiments, it can be concluded that these tightly correlated, stimulus-induced oscillations may play a role in the recognition of images. Therefore these cortical oscillations have been modeled to investigate their ability to segment objects in a visual field. This report briefly discusses the visual system and the internally stimulus-dependent oscillations that may lead to identification of images. Emphasis will be on the models that attempt to reproduce this biological phenomena, their computational and behavioral aspects, as well as simulation performance. Detail will be given to their computational and behavioral aspects since it is in these areas that possible improvements can be achieved through more detailed modeling.

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1. Introduction

Modeling of neurons has been used to understand or enhance the performance of many systems. Neuron models allow us to map out the processes of a system, to visualize the flow of information and to investigate the effects of change on a system, and are even used as a diagnostic tool for related systems.

One area that has held the interest of scientists and laypersons involves our own visual system. How is vision achieved? What are the steps in the visual process? Why is our visual system organized in the manner it is? Can this system be reproduced in a nonbiological medium? In the investigation of what makes our visual system work, scientists have observed voltage potentials generated from the primary cortex located in our brain. These potentials oscillate in distinct patterns when different stimuli are applied to our eyes. Can these oscillating potentials be generated outside of biological systems to allow artificial systems to “see”?

In this report, we take a brief look at the anatomy and biological testing of the visual system. Three neuron models are discussed: the general model, Eckhorn’s model, and Johnson’s model.

2. General Anatomy of the Visual System

To understand how the visual system represents images in the visual field and what responses are initiated in the primary visual cortex, we must understand the anatomy of the visual system (see Figure 1). The components of the visual system can be described as the visual field, the visual pathway, and the primary visual cortex (Kandell, Schwartz, and Jessell 1991).

The visual field is the view seen by two eyes without movement of the head. The visual field projects to the retina. Cells from the retina form the optic nerve. Sections of the optic nerve from each eye join together at the optic chiasm, and from there the nerves continue traversing the brain. Fibers from both eyes enter the optic tract and project to the lateral geniculate nucleus (LGN), which

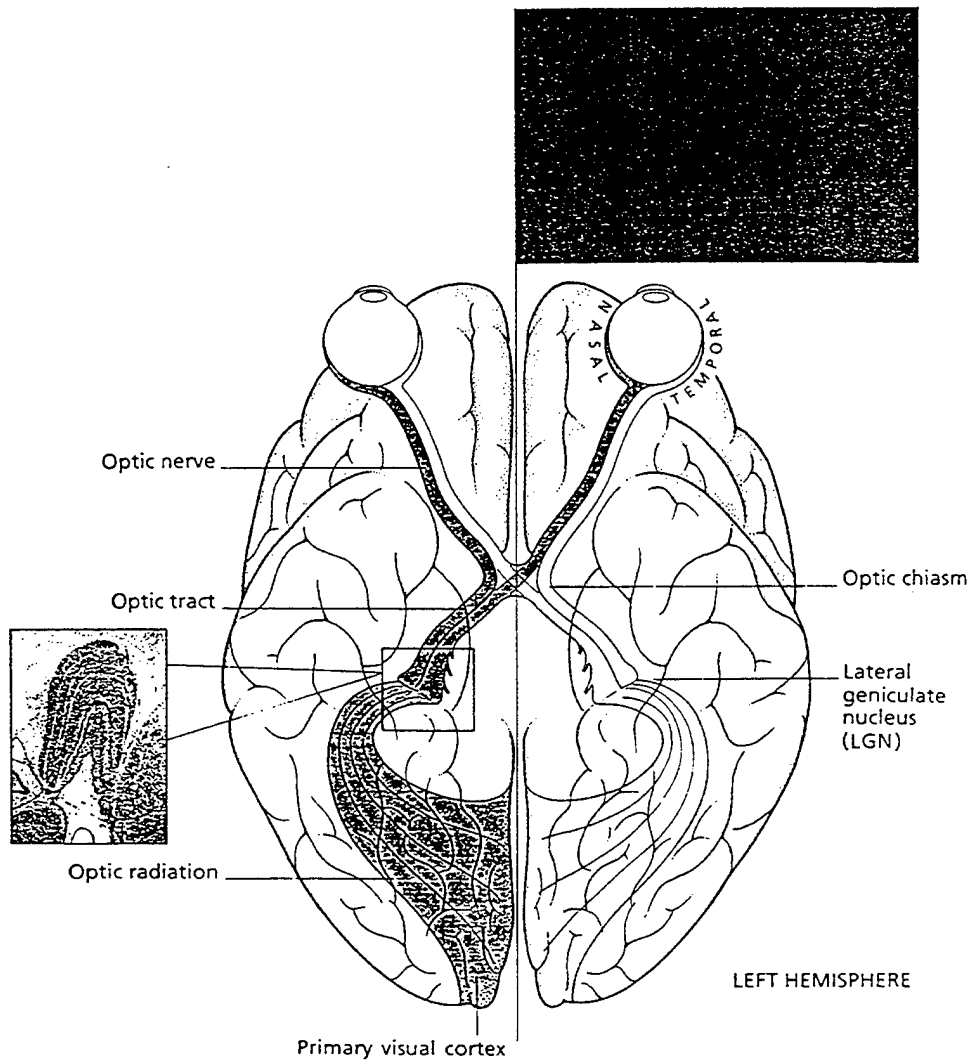


Figure 1. General Biology.

is a section of the cerebral hemisphere. LGN cells project to the primary visual cortex. The primary visual cortex represents the visual field by transforming visual information into linear segments and boundaries. The cells found in the primary visual cortex project to other areas of the brain where “vision” is processed. Cells in the primary visual cortex respond best to stimulus that is linear and has a specific axis of orientation. These excited neurons or cells form the oscillations seen in the visual cortex.

Although the mechanism for the oscillations are unknown, it is suggested that the interaction among a population of synaptically coupled neurons are sufficient for generating oscillations. Experiments also show that when activated appropriately, groups of adjacent cortical neurons change in cooperative interactions. These interactions lead to coherent and periodic patterns of activity.

3. Modeling of Neuron

3.1 General Model. A variety of models for the cortical oscillations found in the visual system have been proposed. These include a general model and models developed by Eckhorn and Johnson (Eckhorn et al. 1990; Johnson 1994). The general model of an artificial neural net (ANN) (Vermuri 1992) is an artificial neuron (AN) that receives inputs from a number of other ANs or from an external stimulus. A weighted sum of these inputs constitutes the argument to a function. The resulting value of the function is the output of the AN. The output mimics the firing of a biological neuron. This output gets distributed along weighted connections to other ANs. Therefore, an AN anatomically models a biological neuron.

This is the basis for modeling of the neuron and neural net. However, each component of the model requires detail. The Johnson and Eckhorn models recreate the neuronal response seen in studies of the primary visual cortex. The first model, Eckhorn's, closely recreates the responses of the biological system. The second model, Johnson's, takes Eckhorn's model and attempts to modify it to use the patterns of the neuronal response to segment images in a visual field.

3.2 Eckhorn's Model. The stimulus-specific response is a series of oscillating voltages at approximately 53 Hz and 60 Hz (Johnson 1994). The findings of Grossberg (1983) and Reitboeck (1983) support the hypothesis that synchronization may be a mechanism for carrying out the linking of local visual features into impressions of objects.

Stimulus-specific synchronization was observed in different cortical areas if the neurons coded common visual features. Signal oscillations are generated in the cortex and can be synchronized by

stimulation of neurons in their receptive fields. These stimulus-specific oscillations are the responses modeled by Eckhorn.

The stimulus-induced synchronous oscillatory potential found to take place in the visual cortex were observed using computer simulations of neural network models. Eckhorn's model (see Figure 2) has two types of synapses: the feeding synapse, which are connected directly to stimulus that drive the neuron; and the linking synapses, which receive auxiliary signals that modulate the input from the feeding synapses (Eckhorn et al. 1990). The linking inputs are then considered synchronizing signals.

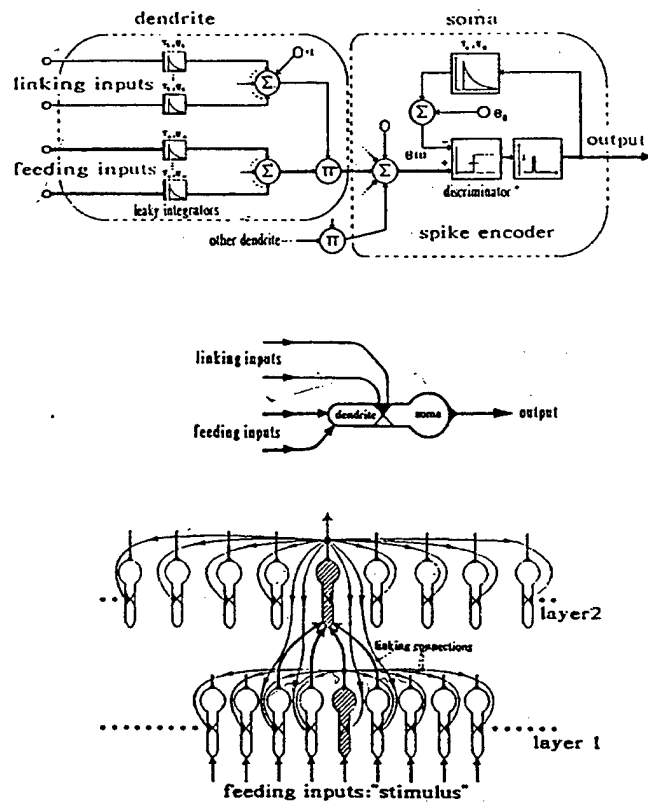


Figure 2. Eckhorn's Model.

The model neuron has dynamic synapses represented by leaky integrators. During a synaptic input pulse, the integrator is charged and its output amplitude rises steeply. This is followed by an exponential decay determined by the time constant. The spike encoder is also represented by a leaky integrator and includes a differential amplitude discriminator and a spike former. The amplitude discriminator triggers the spike former when the input exceeds a variable threshold. The output of the neuron immediately charges the leaky integrator and raises the value of the threshold. This new threshold value exceeds the input, preventing an output immediately following a previous output. The elevated threshold produces the refractory period in the spike generator, so that another output is not generated until the threshold value decays below the membrane potential.

Eckhorn believes that the concept of a modulatory synapse is supported by modulation seen in real neurons. These modulations may be achieved by changing dendritic membrane potentials through voltage-dependent channels that affect synaptic efficacy. From the simulations, feeding signals with modulation causes the model to respond initially with irregular receptive discharges but, subsequently, the neurons mutually synchronize their activity through the linking connections. This supports the phase locking of stimulus-induced synchronizations in the simulation.

3.2.1 Computational Aspects. Eckhorn's neural network consists of two layers of neurons. The bottom layer (layer 1) consists of several neurons. Each layer 1 neuron receives inputs from the stimulus as feeding inputs and input from the four closest neighboring neurons as linking inputs. Layer 2, the top layer, also consists of several neurons. Each layer 2 neuron receives feeding inputs from the four closest neurons in layer 1 and four linking inputs from its four closest neighboring neuron in layer 2. Furthermore, each layer 2 neuron sends feeding inputs to the four closest layer 1 neurons. Eckhorn models his individual neuron as a dendrite and soma, with the output being a pulse and the input being the feeding and linking inputs. The linking inputs and feeding inputs are modeled as leaky integrators. Each neuron is modeled to have multiple feeding and linking inputs. The linking inputs are added to a constant value of 1 then multiplied with the feeding input to form the input to the soma. The soma is modeled as a spike encoder. The spike encoder is where the output from the dendrite is compared with a preset threshold value. If the value is greater than the threshold, the amplitude discriminator triggers the spike former to output a pulse. This output is fed

back into the system to change the value of the threshold to prevent the generating of additional pulses.

3.2.2 Behavioral Aspects. Eckhorn believes his model supports synchronization as a way to achieve perceptual feature linking. To bring neuronal mechanisms of feature linking into correspondence with perceptual functions, Eckhorn introduces the concept of a local neural assembly linking field. This linking field is that area in the visual space where appropriate local stimulus features can initiate synchronizations in the activities of that assembly. If this concept can be supported, then synchronized patterns of neural response can be used to identify visual images. It has been seen that sensory systems that received well-timed signals might be dominated by stimulus-forced synchronization. Other systems may employ a mechanism of synchronized activity for oscillations and coding in the system.

3.3 Johnson's Model. Johnson's (1994) model is a modified version of Eckhorn's model. It only models a 1-layer network, but with multiple receptive fields. Johnson's model includes a dendritic tree section, a linking section, and a pulse generator section. The dendritic tree is similar to Eckhorn's dendrite. The dendritic tree includes the feeding inputs from other neurons as well as the linking inputs from other neurons. The difference in this section is that the linking inputs are multiplied by a variable beta before the constant is added. Then this value is multiplied with the feeding input in the linking section. Moreover, in the linking section, linking inputs from other receptive fields are multiplied with the inputs from the current receptive fields. This value is then summed with inputs from other dendrites. The pulse generator section includes a threshold discriminator that triggers the pulse former to output a pulse when the membrane potential exceeds the threshold value. As in Eckhorn's model, the output is fed back to change the value of the threshold.

3.3.1 Computational Aspects. It is helpful to look at an individual neuron from Johnson's model to describe what functions beta and tau-c perform. These variables are experimental and have not been shown to model biological parameters. Beta is called the weak linking variable. It sets the strength of the linking inputs' effect on the feeding inputs. Tau-c is the time constant that defines

the pulse capture zone. This zone indicates a period of time where a linking input can influence the frequency of the output pulses.

In this model, beta (the weak linking variable) is set to zero when there is no feedback from the neighboring neurons (no linking input). When there is feedback, beta is greater than zero. To understand this concept, the output of a single neuron with beta equal to zero is examined. With beta equal to zero, the membrane potential is equal to the feeding input only. When the membrane potential exceeds the threshold value, a pulse is generated. This is the same way Eckhorn's model operates.

Now consider when beta is greater than zero. A linking input can add to the membrane potential, causing the membrane potential to increase. This causes a pulse to occur sooner than expected, implying that the linking input (or the feedback from the neighboring neurons) has changed when the pulse occurs. The linking input synchronizes the pulses to some desired pattern. This effect of the linking input is also found in Eckhorn's model, however, the linking input is multiplied by a constant of 1, not beta. Thus, in Johnson's model, the linking inputs for the current neuron can be arbitrarily weighted differently from linking inputs of neurons in other receptive fields. Since these weights are not from biological responses, they do not represent synaptic strengths generated by a specific stimulus. Therefore, this model does not use these weights to represent data.

3.3.2 Behavioral Aspects. Johnson (1994) proposes that the periodic pulses that are generated by a particular stimulus can be used to identify segments of an image. Each small section of an image would produce its individual pulse train (see Figure 3). As the field of view is expanded, it would produce its individual pulse train until the entire scene is covered. The smaller pulse trains would actually become subgroups within the pulse trains produced by the larger section of the scene. Therefore, a supergroup pulse train would represent the entire scene that consists of subgroups of pulse trains at each level of the expanded view.

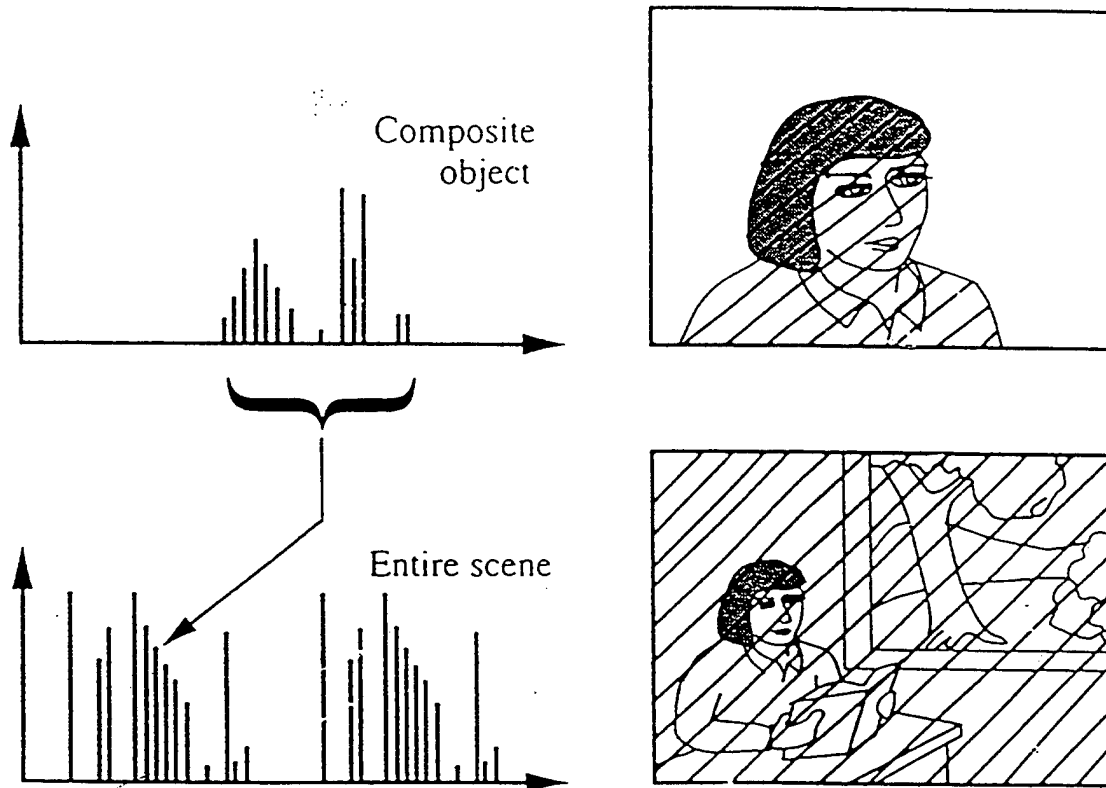


Figure 3. Behavior of Pulse Train.

4. Conclusion

This report has presented three models that attempt to describe the oscillations produced in the primary visual cortex. Even though these models do not model the biological system, they do allow exploration into the response of the visual system. Further modeling can be done to incorporate more of the functionality of the real biological system. These enhancements may provide a more accurate system for segmenting objects.

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