## Dendritic-Tree Anatomy Codes Form-Vision Physiology in Tadpole Retina

Abstract. In tadpole frog retina, the development of four classes of visual form detectors matched the growth of four types of ganglion cell dendritic trees. From this correlation of electrophysiology and anatomy we concluded that the structure of retinal ganglion cell dendritic trees provides the code for detection of visual shapes.

Current physiological studies of nerve networks may provide the neural basis for explaining behavior (1). For example, electrophysiology of the visual system has led to the following hypothesis: the detection of a shape requires the activation of many parallel neurons which converge and summate onto the dendritic tree of a neuron of a higher order; the latter (form-de-

A.ADULT FROG		B.TADPOLE FROG	
PHYSIOLOGY	ANATOMY	PHYSIOLOGY	ANATOMY
Class 1 edge detector	Constricted Tree	Class 1 edge detector *	Constricted Tree *
Class 2 convex edge detector	E Tree	Class 2 convex edge detector +	E Tree +
Class 3 moving contrast detector	H Tree	Class 3 moving contrast detector	H Tree
Class 4 dimness detector	Broad Tree	Class 4 dimness detector	Broad Tree

Fig. 1. Responses of ganglion cell axons in the optic nerve (physiology) and correlated ganglion cell dendritic tree structure (drawings of Golgi anatomy). The classes are defined as follows: classes 1, 2, and 3 respond best to a particular moving or stationary form, whereas class 4 responds to decreasing light intensity. (A) shows the correlation of physiology and anatomy proposed by Lettvin *et al.* (3) for adult frogs. (B) shows the correlation of physiology and anatomy in tadpole frogs reported in the text. \* Class 1 responses and constricted trees are both absent in the tadpole.  $\dagger$  Class 2 responses and E ganglion cell dendritic trees are found only at the equator of the tadpole retina (that is, absent from periphery of tadpole eye). All other entries in this figure are uniformly distributed throughout the retina (that is, all four classes and tree types in the adult frog, classes 3 and 4 and types H and broad tree in the tadpole frog are all uniformly distributed).



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tector cell) is excited only when appropriate converging input neurons are simultaneously active (2). However, much needed anatomical evidence for this physiological hypothesis is lacking. Our report, which correlates the anatomy and physiology of the tadpole retina, supports the hypothesis by showing that the anatomy of ganglion cell dendritic trees codes for the vision of shapes. To date, all correlations of dendrite anatomy and form-vision physio'ogy have been based on weak evidence (3, 4). One such correlation for adult frog retina (3) is illustrated in Fig. 1A where four types of ganglion cells were matched to four classes of form detectors in the optic nerve: retinal ganglion cells with constricted dendritic trees were matched to class 1 detectors, E dendritic cells to class 2 detectors, H dendritic cells to class 3 detectors, and ganglion cells with broad dendritic trees to class 4 detectors (5). According to this correlation, for example, a moving insect is detected by a class 2 optic nerve fiber in the frog because the excitation of hundreds of parallel neurons in the outer layers of the retina produces spatial summation onto the dendrites of an E-type ganglion cell in the inner retina. However, the evidence for the matching of physiology and anatomy in Fig. 1A is weak (3, 6). We therefore extended the studies of the adult frog to the tadpole and obtained new information which strongly supports the correlation proposed in Fig. 1A.

Visual detection of form was studied by electrophysiology in 210 tadpole frogs (*Rana catesbeiana, R. pipiens,* and *R. clamitans*), in premetamorphosis (stages X to XVI), immobilized with tubocurarine and given xylocaine subcutaneously for local anesthesia. The eyes were submerged in water so as to look out through the flat wall of a lucite chamber at a screen 25 cm away (7). Extracellular electrical recordings were obtained with platinum black microelectrodes (8) from 1854 single fibers in the optic nerve (that is, axons of retinal ganglion cells).

Tadpole responses were similar to

Fig. 2. Photomicrographs (at the same magnification) of the three types of ganglion cells found in the tadpole retina stained with the Golgi method. (Upper) An "E" tree ganglion cell. (Middle) An "H" tree ganglion cell. (Lower) A "broad" tree ganglion cell. (Lower) A "broad" tree ganglion cell. The photographs cannot be in sharp focus because the specimen is 100  $\mu$ m thick. The cell body of the "H" cell is obscured by silver crystals on the inner surface of the retina.

those reported in the adult frog for classes 2, 3, and 4 (9). The major differences between tadpole and frog were (i) the absence of class 1 fibers in the tadpole (10), and (ii) the absence of class 2 fibers in the periphery of the tadpole retina (class 2 responses were only present at the equator of the retina, whereas the adult frog exhibits responses in all regions of the retina).

We next attempted to correlate these physiological differences with anatomical findings. In Golgi silver stains (11) of 22 tadpole retinas we found only three of the four ganglion cell types in the adult frog-the "E" type, the "H" type, and the "broad" type (Fig. 2); the constricted ganglion cell tree of the frog was absent in the tadpole. This result coincides with the absence of class 1 responses (Fig. 1B). Also, the E type cells were absent from the periphery of the tadpole retina (that is, they were only found at the equator of the tadpole retina). This result matches the physiological distribution of class 2 responses (Fig. 1B). Finally, the H and broad-type ganglion cells were both found in all regions of the tadpole retina, which correlates with the distribution of physiological responses of classes 3 and 4 in tadpoles (Fig. 1B). In contrast, all four types of ganglion cells and classes of responses are uniformly distributed throughout the retina of the adult frog (Fig. 1A). Thus the development of the four classes of visual form detectors matches the growth of each type of dendritic tree. These results strongly support the hypothesis of Fig. 1A, especially for classes 1 and 2. Our data are also consistent with that hypothesis for classes 3 and 4, although we cannot pinpoint class 3 to H trees and class 4 to broad trees (see 12).

We therefore conclude that the shapes of the dendritic trees of the ganglion cell provide a code for visual recognition of form; the code probably determines the convergence and summation onto the ganglion cell from dozens of bipolar and amacrine cells in the outer layers of the retina (12). Since bipolar and amacrine cells also have a pronounced field organization, the code in the ganglion cell must be composed of the summation of the codes from earlier stages. Our work, in conjunction with the network analysis of outer layers of amphibian retina (13), should lead to a complete description of vision in terms of network anatomy and physiology. Only in this

manner can we hope to work out the neural basis for understanding behavior (14).

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   Class 5 responses, which were reported in the adult frog [H. R. Maturana, J. Y. Lettwin W. S. McCulloch, W. H. Pitts, J. Gen. 1000 (2000) will be omited the sense of the sense vin, W. S. McCulloch, W. H. Pitts, J. Gen. Physiol, 43 (Suppl.), 129 (1960)] will be omit-ted from this report, because they were rarely found in the adult frog and were completely
- absent from our results in the tadpole frog. 6. The correlation by Lettvin *et al.* (3) of frog anatomy and physiology was based on three arguments. (i) There were four types of ganglion cell trees and four classes of responses. Since it was impossible to study the anatomy and physiology of the same cell, they could only attempt correlations based on (ii) and (iii). (ii) Conduction velocity of each class matched the soma size of each ganglion cell type; however, there was much overlap of velocities and cell size was a crude esti-mate. (iii) The size and shape of receptive fields of each class matched the spread of the dendrites of each ganglion cell type; however, amacrine cells have recently been shown to have a marked effect on receptive

field size of ganglion cells [J. E. Dowling, Proc. Roy. Soc. London, Ser. B 170, 205 (1968); F. S. Werblin and J. E. Dowling, J. Neurophysiol. 32, 339 (1969)]. Also measure-ment of field size is highly inaccurate [G. H. Jacobs, Brain Res. 14, 553 (1969)].

- 7. Using retinoscopy, we determined that the tadpole was emmetropic with this arrangement, whereas it is myopic in air. By the same technique we found adult frogs to be emme-tropic in air and hypermetropic in our lucite chamber.
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- 10. It is improbable that our electrodes simply missed small class 1 fibers because of size, since we easily recorded from the equally small fibers of class 2 (conduction velocity 0.1 to 1.0 m/sec).
- We used the Colonnier modification of the Golgi rapid method [M. Colonnier, J. Anat. 98, 327 (1964)]. 11.
- 12. In general, the lack of silver staining of a cell type is not absolute proof of the absence of this cell in the tissue. However, in our experiments, the close correlation of anatomical and physiological distributions indicates that the lack of staining does indeed reflect the absence of a cell type.
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- 14. An account of tadpole retina outer layers will be presented elsewhere (B. Pomeranz, in preparation).
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## Synthesis of Amino Acids by the Heating of Formaldehyde and Ammonia

Abstract. The heating of formaldehyde and ammonia yields a product that, on hydrolysis, is converted into seven amino acids: aspartic acid, glutamic acid, serine, proline, valine, glycine, and alanine. Glycine is the predominant amino acid. Inasmuch as formaldehyde and ammonia have been identified as compounds in galactic clouds, these experimental results are interpreted in a cosmochemical and geochemical context.

The finding of formaldehyde (1)and ammonia (2) as interstellar molecules provides a relatively factual basis for the existence of precursors of amino acids in the galaxy. In some of the sources of microwave radiation identified, both formaldehyde and ammonia are present (3); reaction of the two is more easily visualized as a consequence of this coexistence. The conversion of formaldehyde and ammonia to glycine and alanine by ultraviolet radiation has been reported by Reid (4), whereas the formation of serine, glycine, glutamic acid, alanine, valine. phenylalanine, and isoleucine from ammonium chloride and formaldehyde by

ultraviolet radiation has been reported by Pavlovskaya and Pasynski (5). The Russian authors reported also "basic amino acids," but these latter might have been amines including hexamethylenetetramine (4).

Experiments in producing amino acids by subjecting formaldehyde and ammonia to heat instead of high-energy radiation were undertaken by us for several reasons. Heat is generally less destructive than high-energy radiation and is easily controlled, nearly always being used in the organic chemical laboratory for this reason (6). Heat has been the form of energy which has yielded a relatively comprehensive the-