

## Evidence That Cut Optic Nerve Fibers in a Frog Regenerate to Their Proper Places in the Tectum

**Abstract.** The frog's retina projects into the superficial neuropil of the opposite tectum in four functionally different layers of terminals. Each layer displays a continuous map of the retina in terms of its particular function. The four maps are in register. The fourth-dimensional order is reconstituted after section and regeneration of the optic fibers.

Sperry (1) pointed out that the results of his experiments on optic nerve regeneration in adult frogs were consistent with specific reconnection of the optic fibers. He proposed that each individual neuron grew back to its original terminus in the tectum, for the behavior after visual recovery was as if the nerve had not been cut. In addition to the behavioral evidence, he produced scotomata in predicted quadrants by fairly large tectal lesions in frogs that had regrown their optic connections. The implications of his proposal are so odd that, while his elegant experiments were accepted, the interpretation was much disputed. Furthermore, the experiments with tectal lesions cannot be considered conclusive, since, by destroying part of the tectum, the ability of the animal to respond is also impaired. The purpose of this communication is to give electrophysiological evidence in support of Sperry's hypothesis.

We have developed a technique for recording single fibers in the frog's optic nerve and single terminal bushes in the tectum (2). In this work we have found that normally the frog's tectum has the following organization. The fibers of each optic nerve cross completely in the optic chiasma and enter the opposite colliculus after dividing into two bundles. One is rostromedial; the other, caudolateral. They sweep over the surface and are distributed in several layers in the outer neuropil that forms the superficial half (250  $\mu$ ) of the tectal cortex (Fig. 1). Most tectal cell bodies lie below this neuropil and send their main dendrites through it up to the pial surface. The axons of the majority of these cells form a narrow stratum that lies immediately above the compact layers of cell bodies. The optic fibers end in a systematic way both along the surface and in the depths of the superficial neuropil, mapping the retina in a pattern that is constant from animal to animal. There are four layers of these optic fiber terminals, which we have thus far identified only physiologically. Each displays a continuous map of the retina with respect to each of the four following operations on the image at the receptors. The four maps are in register with each other and

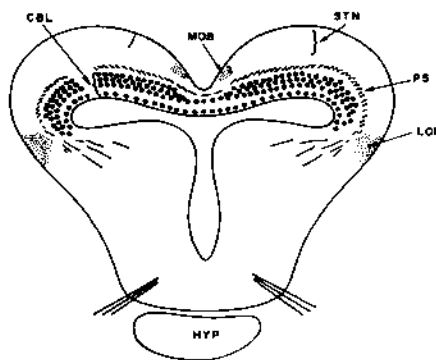


Fig. 1. Transverse section of the tectum of the frog at the level of the oculomotor nerves. CBL, cell-body layers; MOB, medial optic bundle; STN, superficial tectal neuropil; PS, palisade stratum; LOB, lateral optic bundle; HYP, hypophysis.

show position on the retina according to the cartography of Gaze (3).

The first layer of terminals is formed by those elements each of which is sensitive to moving or maintained contrast within its receptive field. The sharper the contrast, the better the response. These are equivalent to Hartline's (4) and Barlow's (5) "on" fibers. The second layer is made up of terminals of units each of which detects a moving or recently stopped boundary within its receptive field, provided there is a net positive curvature of the edge of the darker phase. Such a fiber will not respond, for example, to a straight-edge boundary moving across its receptive field or to a preestablished edge within that field. Both of these strata represent the endings of the unmyelinated fibers of the optic nerve.

The third layer is made up of terminal bushes from "on-off" fibers.

The fourth layer is composed of endings from "off" fibers.

The layers of endings are distinct in depth, and with the exception of the first and second layers they rarely merge at the transition zones. In this conspicuous order, both along the surface and in the depths, the area of the retina "seen" from any point in the superficial neuropil is, at most, 10° in radius. Most of the ganglion cells whose terminals appear at that point are crowded toward the middle of that area.

For the purpose of testing Sperry's hypothesis of the specific regrowth of the optic fibers after section of the optic nerve, we cut one optic nerve in several adult frogs (*Rana pipiens*), ensuring the complete separation of the two stumps. At the end of 2 months the first signs of visual recovery were apparent, but full use of the eye did not occur for another month. When the visual recovery seemed complete, we exposed the colliculi and tested the initially de-

afferented colliculus for mapping of the retina. We found that the map had been regenerated along the surface, although the ganglion cells from whose terminals we were recording at any point were now spread over an area about two times as large as normal. The separation of operations in depth was also restored, and there was no sign of confusion between the operational layers.

The specific regrowth of the terminals to their proper stations cannot be explained by saying that an initial orderly array of fibers in the optic nerve crudely orders the fibers again at the time of regeneration. The fibers in the nerve simply are not in order *ab initio*. Any two contiguous fibers can come from the most widely separated points on the retina (2, 6).

This finding strongly supports Sperry's hypothesis that optic-nerve fibers grow back to their original destinations. They do so in an even more highly specific way than he proposed; the regrowth of the termini is also proper in depth (7).

*Note added in proof.* After this manuscript was prepared we noted that R. M. Gaze, of the University of Edinburgh, has presented to the Physiological Society similar findings in *Xenopus laevis* (8). He, however, has not studied the reconstitution of the distribution in depth of the optic fibers.

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### References and Notes

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