Rev.Acad.Canar.Cienc., III (Núm. 2),89-94 (1991)

THE NATURAL DESIGN OF VISUAL MACHINERY

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Abstract

The main way to decipher functions associated to neural structures is to determine what messages are sent by the neurons and how they are coded. So far, the only way to find out microscopically what is going on in a cell is to record its electrical activity. As we move from receptors along the nervous system, the degree of semantic complexity of the input increases. Function becomes fuzzy. An alternative methodology, analyzing the structure that optimizes a function is presented here, showing that an optimality criterion may be applied to photoreceptors in several animal species.

Key words:Rod vision, Optimality, Detectors, Semantic complexity.

Introduction:Photoreceptors.

Photoreceptors are one of the "sensitive frontiers" of the living with the physical world. Rods and cones are transducers that absorb photons and produce electric responses whose amplitude and duration depend on intensity and wavelength of the absorbed light. Rods are specially sensitive cells, since they are able to have a response as the consequence of a single photon absorption. The molecules of rhodopsin, the photopigment that captures photons, are placed on discs inside the rod Outer Segment (O.S.). These molecules suffer spontaneous isomerizations that are indistinguishable from single photon responses. This produces false alarms. On the other hand there is some continuous electrical noise due to the ongoin activity of the transduction biochemistry.

Then, photon absorption and transduction biochemistray present two competing demands to take into account in the design of a rod O.S.: the shorter it is, the less noise is generated, and the emitted signal will be cleaner, but the probability of photon absorption will decrease. For a longer O.S., this last probability will increase, as will the noise as well.

The Useful Response Signal.

Let us define the function R, Useful Response Signal, as follows:

$$R = (1-\exp(-as))\,(1-Ds/(TL))\,A - Ns/L \qquad [1]$$

The first bracket on the right of [1] is the photon absorption probability given by the Beer-Lambert law, being “a” a measure of the optical density and s the O.S.

length considered as a variable. The second bracket excludes the posiibility of a spontaneous isomerization of the rhodopsin (D being the duration of a spontaneous isomerization or single photon response- the reader shall remind both responses are indistinguishable- that occurs once every T seconds) per unit length of O.S.. The product of both brackets by A (amplitude, in picoamps, of single photon response) gives the expected response excluding false alarms. From this, we subtract the continuous thermal noise, Ns/L, the noisy background a reliable signal shall overcome.

The original mathematical treatment was done by Leibovic (1) refering only to the rod outer segments of Bufo Marinus (Tropical Toad). Equation [1] represents a generalization in order to extend the criterium to other species. The values of all parameters are taken from experimental literature, when possible. All data sources can be found in (2).

Optimum length.

Outer Segment length is optimized by maximizing R in eq. [1], i.e., differentiating R with respect to s. For

$$dR/ds=0$$

in [1] the optimal can be found from:

$$\exp(-as) = (AD + NT) / (A(D+aTL-aDS))$$

Here we shall only quote some of the results applying this criterion to several species, and the reader is referred to (1) and (2) for a complete analysis and mathematical justification of the optimality criterium.

Specie	B.M.	R.P.	M.F.
Experimental Length (microns)	60	58	25
Theoretical Predicted Length (microns)	65.2	61.4	29

Table 1

B.F.: Bufo Marinus (Tropical Toad)

R.P.: Rana Pipiens (Frog)

M.F.:Macaca Fascicularis (Monkey)

Table 1 shows that the theoretical results are quite close to the experimental measurements in species with a duplex retina and sensitive night vision. For other retinae, like the one of the skate, the criterium is not supposed to work, since the all rod retina of these sea animals has to function over the whole physiological range, not only the dim light vision but also at the photopic level. These results can be interpreted as follows: rod O.S. of well developed duplex retinae are optimized for the detection of one or two photons, and the cells are designed to be reliable detectors of the smallest possible amount of light. This optimality criterion only applies to those rods which function as sensitive photon detectors. Nature, using evolution, has designed these sensitive transducers where no characteristic is extra, nothing is arbitrary, not even their length. The form, that encloses a function is significant at this level of visual information processing.

Conclusion.

The example of the design of visual transducers gives us a hint of the complexity we should look for at more central levels of the Nervous Systems (3), the significance of neuronal functioning in nets and the kind of questions we should ask about nervous systems. The evolutionary design has originated cells, structures and meanings that are inseparably linked and this oblihues us to be careful when we use artificial models that we hope include natural characteristics that have been improved generation after generation for hundreds of thousand of years.

References.

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Recibido: 10 de Diciembre de 1991