Cybernetic Models of Pattern Sensitive Units in the Visual System

P. I. Zorkoczy

Department of Ergonomics and Cybernetics, Loughborough University of Technology, Loughborough, Leicestershire, England

Summary. Pattern-specific response in the visual system is represented in terms of a mathematical model and as the response of corresponding sequential circuits. The mathematical model employs standard relations of propositional calculus, with extension to the time domain. It is shown that pattern sensitive units of many types can be generated by successive applications of a generalised contrast operator together with a spatial summation operator. The implications of the models are interpreted in neural terms.

1. Introduction

The experimental study of the visual pathway in various species has been greatly facilitated by recent advances in the techniques of recording from single cells. Electrophysiological data obtained from the retina of the crab (Ratliff and Hartline, 1959), the goldfish (Wagner et al., 1960), the frog (Barlow, 1953; Maturana et al., 1960), the pigeon (Maturana and Denker, 1963), the rabbit (Barlow et al., 1964), the cat (Kuffler, 1953) and the monkey (HubeI and Wiesel, 1960) reveal a remarkable degree of similarity in the response of the optic fibres to controlled spatiotemporal patterns of retinal illumination. Electronmicroscopic investigations e.g., by Villegas (1961) of the retina of the fish, monkey and man, by Kidd of cat and pigeon retinas (1962), also indicate a significant likeness of the detailed structure in the various species.

Fig. 1 is reproduced from Polvak (1944) to show the laminar arrangement and main cell types in the primate retina, which is structurally similar to the retina of many other species. From a functional point of view, our interest is first concentrated on the response of the ganglion cells (Layer 8) and of the related optic fibres (Layer 9) to patterns of illumination of the retina.

Kuffler (1953) has shown that on exploring the receptive field (defined as the area of the retina which must receive illumination in order to cause a discharge in a particular cell) of ganglion cells in the cat's retina with a small spot of light, the response is not uniform over the receptive field but is related to the position of the stimulus. For many cells, the receptive field could be subdivided into two concentric, mutually antagonistic zones. Excitation of part or whole of one of the zones by a sharp increase in luminance or of the other zone by a sharp decrease in luminance caused these cells to respond with a burst of activity. Depending on the relative disposition of the two zones, ganglion cells were classified into "on-centre off-surround" and "off-centre on-surround", the central zone being circular with the surround zone forming a concentric annulus. Excitation of the entire receptive field with uniform illumination evoked little or no response from the cells.

Kuffler has also found some ganglion cells which produced bursts of activity at both the outset and the end of a period of illumination ("on-off" type). All cells investigated could be classified into one of these three categories.

Ganglion cells with on, off and mixed response have also been found in the retinas of the crab, goldfish, frog, pigeon, rabbit, cat and monkey (see references above). In addition, Barlow and his coworkers (1964) have described ganglion cells in the rabbit retina which respond in an on-off fashion to excitation at various points in their receptive field but produce...
sustained firing when the light spot is moved across the field in a characteristic direction. Various cells of this type have been shown to be sensitive to particular speeds of movement of the exploring spot.

Cells with selective response to the direction of movement of a boundary between a light and a dark region have been reported by Maturana and Frenk (1963) in the retina of the pigeon, by Hubel and Wiesel (1959) in the visual cortex of the cat and by Maturana and coworkers (1960) in the retina of the frog.

Data regarding the response of cells at the next synaptic station along the visual pathway, the lateral geniculate nucleus, are far less detailed than those available for the retina. According to Hubel (1963), the data for the cat suggest that no major transformation is carried out on the retinal information at this stage, apart from a further emphasis of the contrast between responses to a small centred spot and uniform illumination of the receptive field.

At the level of the visual cortex the specificity of response becomes more extensive. Hubel and Wiesel (1965) describe the following response types in Areas 17,18 and 19 of the cat's cortex:

a) "Simple cells" which respond best to critically positioned and oriented straight lines on opposing background and to straight line boundaries between light and dark regions.

b) "Complex cells" which are similar in their response to type a) except that the restriction on the exact position of the line in the receptive field is removed. These cells respond with sustained firing to the movement of a line with appropriate orientation in a direction perpendicular to the orientation of the line.

c) "Hypercomplex cells" which have been subdivided into "lower order" and "higher order". In the receptive field of the former two similar lateral zones are separated by an antagonistic central zone the boundaries being parallel straight lines, while the latter appear to respond best to the presence of straight line edges at right angles to each other. As for complex cells, movement of the "optimum excitation" pattern within the confines of the receptive field enhances and prolongs the response.

In the present paper an attempt will be made to utilise the neurophysiologist's concepts of "adequate stimulus" and "optimum excitation" for cells in the visual system in establishing an analogy between such pattern-specific cells and some sequential switching circuits whose behaviour can be described in precise mathematical terms. The utilisation of the framework of mathematical logic in this context has been suggested by Bartlow and Levick (1965), in seeking an explanation for directional movement sensitivity in ganglion cells.

Section 2 provides a description of the models in terms of standard logic operations and as corresponding sequential circuits. It is shown that pattern-specific units of many types can be generated by successive applications of a generalized contrast-operator together with a spatial summation operator.

In Section 3 the implications of the model are discussed and an interpretation of the formalism in neural terms is presented.

2. The Models

The models are based on the experimental findings summarised in the previous Section, and on the observation made by neurophysiologists (e.g., Hubel, 1963) that the response at any stage in the processing of visual information is closely related to the response at the immediately preceding stage.

The primary input to the visual system is the pattern of illumination projected on the retina by the optical system of the eye. The receptor layer may be considered to act, in the first instance, as a set of independent transducers converting light to electrical energy. In an analogous fashion, the physical model consists firstly of a set of independent input points arranged in a plane. The input is an excitation pattern applied to some subset of this set at instants on a regularly subdivided time scale. The distribution of excitation is represented in terms of the relative excitation of pairs of neighbouring input points using a binary scale where 1 indicates that excitation is present while a 0 implies no excitation at a particular instant of time.

In formal terms this relative excitation is expressed in terms of a "contrast operator" $S(a,b)$ as:

$$S(a,b) = a \times \bar{b},$$

with symmetrical extensions to the time domain:

$$T_1(a,b) = a \times \bar{b}^*$$

and

$$T_2(a,b) = a^* \times \bar{b},$$

where $(a,b)$ is an ordered pair of binary variables,

$\times$ denotes logical disjunction which gives the value 1 at time $t$ if and only if the variables it connects each have the value 1 at time $t$, otherwise it gives 0;

for any binary variable $n$

$\bar{n}$ represents negation which gives the value 1 at time $t$ if and only if $n$ has the value 0 at time $t$, otherwise it gives 0, and

$n^*$ gives the value 1 at time $t$ if and only if $n$ had the value 1 at time $t - 1$, otherwise it gives 0 ($n$ delayed by unit time).

Then $S(a,b)$ will have the value 1 at time $t$ if and only if $a$ is 1 and $b$ is 0 at time $t$, in other words if a difference in excitation is present at time $t$.

For the particular case when $a = b$, $S(a,a)$ is permanently 0, but the operations of (2) are still meaningful and they become:

$$T_1(a) = a \times \bar{a}^*$$

and

$$T_2(a) = a^* \times \bar{a}.$$

By definition, $T_1(a)$ has the value 1 at time $t$ if and only if $a$ is 1 at time $t$ and it was 0 at time $t - 1$, in other words when $a$ changes from 0 to 1 at time $t$.

The state diagram of a sequential machine representing $T_1(a)$ is shown in Fig. 2a. The state $Q_0$ is attained when the previous input was a 0, while $Q_1$ is reached when the preceding input was a 1. Thus, the present output depends on both the present input and the preceding input. Each transition between states takes unit time, since the time delay is equal to one time unit, and so a 1-output is maintained on each occasion for one time unit.

$T_2(a)$ has the value 1 at time $t$ if and only if $a$ is 0 at time $t$ and it was 1 at time $t - 1$, that is when $a$ changes from 1 to 0 at time $t$. Fig. 2b is the state diagram of a sequential machine representing $T_2(a)$. A 1-output is again maintained for only one time unit.