

Unattended motion detection system based on the mammalian retina

Jose A. Martin-Pereda*, Ana P. Gonzalez-Marcos¹

E.T.S. Ingenieros de Telecomunicación. Universidad Politécnica de Madrid
Ciudad Universitaria. 28040 Madrid. Spain

ABSTRACT

Sensing systems in living bodies offer a large variety of possible different configurations and philosophies able to be emulated in artificial sensing systems. Motion detection is one of the areas where different animals adopt different solutions and, in most of the cases, these solutions reflect a very sophisticated form. One of them, the mammalian visual system, presents several advantages with respect to the artificial ones. The main objective of this paper is to present a system, based on this biological structure, able to detect motion, its sense and its characteristics. The configuration adopted responds to the internal structure of the mammalian retina, where just five types of cells arranged in five layers are able to differentiate a large number of characteristics of the image impinging onto it. Its main advantage is that the detection of these properties is based purely on its hardware. A simple unit, based in a previous optical logic cell employed in optical computing, is the basis for emulating the different behaviours of the biological neurons. No software is present and, in this way, no possible interference from outside affects to the final behaviour. This type of structure is able to work, once the internal configuration is implemented, without any further attention. Different possibilities are present in the architecture to be presented: detection of motion, of its direction and intensity. Moreover, some other characteristics, as symmetry may be obtained.

Keywords: mammalian visual cortex, retina, image processing, motion detection.

1. INTRODUCTION

One of the more active topics in the last decades has been trying to discover how interactions between neurons in a brain lead to meaningful patterns of neural activity and ultimately to perception, behaviour, and even intelligence. The main problem concerns the possibility to break down the complexity of the vertebrate brain so that we can gain some understanding of higher integrative brain function. Two obvious ways are to work on either simpler nervous systems or on simpler parts of more complex brains. Both approaches have been and are being successfully taken. The first one deals with invertebrates whose brain contains many fewer neurons. The second one is to study well-defined and perhaps simpler parts of the vertebrate brain. The cerebellum, the olfactory bulb, and the visual system are brain regions that have been the subject of substantial research. The visual system has been particularly attractive, because it is easily stimulated with light and because it is naturally divided between eye and brain.

According to above facts, the mammalian visual cortex constitutes a main topic for biologists, physiologists and neurologists. The reason of this interest is due to several factors. The first one is related to the importance of the vision processes in the relationship between the living beings and their environment. The second one is the large number of functions carried out by the visual cortex. Besides the above facts, the visual cortex possesses other characteristics that justify its study. These reasons are those derived from the previously mentioned great amount of information that is processed and the way is done. The form of processing images in parallel is superior to the way in which it is done by most of the nowadays artificial vision systems. To try to obtain some lessons from the way the visual cortex works can be a very good exercise. These lessons could be adopted and implemented in other systems.

One of the most interesting topics to be studied is the way information is processed. Visual processing in human beings involves the analytical abstraction and separation of sub modalities as well as the integration of the abstract representation of those sub modalities into a unified percept. The abstracted visual image is distributed between many

* Correspondance : jamp@tfo.upm.es

¹ agonmar@tfo.upm.es

different areas. There must therefore be mechanisms for combining the different operations in order to reconstruct some kind of coherent representation of the visual image. This is sometime referred as "the binding problem". Since this must take place over some period of time while we perceive an object, there must be continuing interactions between the different areas, presumably mediated by the rich reciprocal connection between them¹.

Many works have been carried out along this way in the last years. Detailed journal articles describing a variety of neurovision system architectures for preattentive vision, visual perception, object recognition, colour vision, stereo vision, and image restoration are included in [2]. A very interesting selection of technical papers, concerning Neurocomputing, is the two volumes set [3-4]; it contains a wide range of approach to this topic with many of the seminal works.

In the present work we will try to apply these concepts to the detection of particular subjects with special emphasis in very simple configurations where the possible results obtained with them are obtained in other systems with more complex structures.

2. NEUROPHYSIOLOGICAL BASIS OF THE PROPOSED SYSTEM

One the first and more important papers dealing, from a general point of view, with the general aspects of the biological vision system was the work of D. Hubel and T. Wisel⁵. They postulate a functional architecture that may underline the processing of sensory information in the cortex. This work, and a large number of others that follow this one, have set the roots for a better understanding of many visual detection aspects in mammals.

Groups of neurons in the visual cortex process information

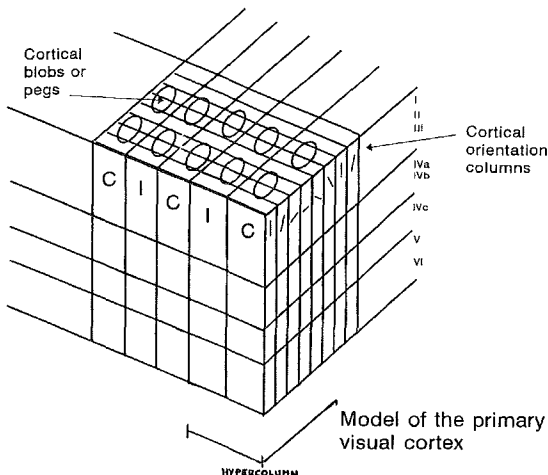


Figure 1.- Structure of the primary mammalian visual cortex.

about form, contrast, movement, and colour of objects in the external world. In the primary area, known as V₁, area 17, or striate cortex, neurons ignore uniform illumination. Those involved in the initial stages of pattern recognition require highly specific shapes or forms – in particular lines or edges with a certain orientation or position on the retina. Some categories of neurones are specialized to respond to angles or corners or to movements in one direction but not in other (Fig. 1). According to the type of information they carry, cortical neurons have been classified as simple and complex. Individual cortical neurons receive inputs from corresponding areas of retina in both eyes, with similar receptive field organization. Neighbouring simple and complex cells share common

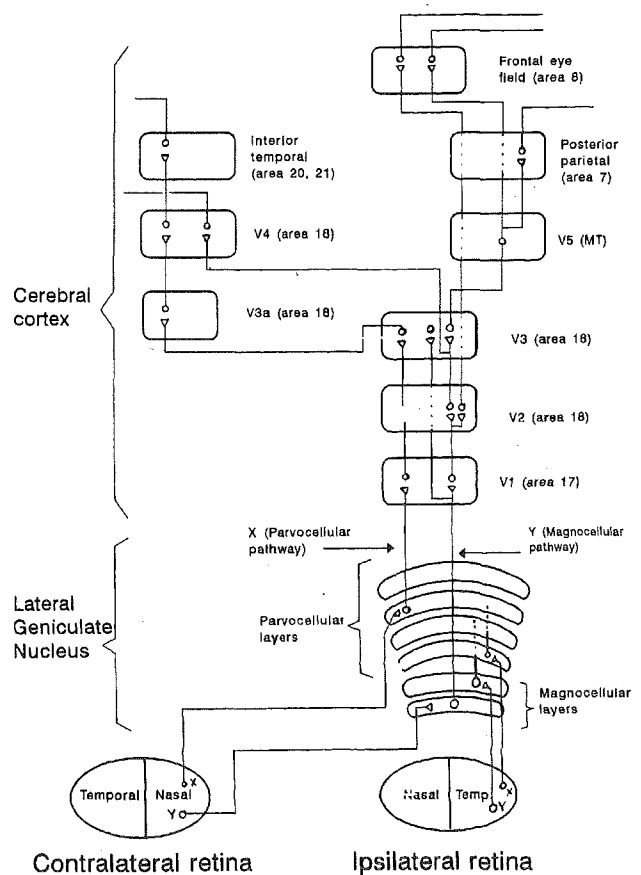


Figure 2.- General scheme of the different pathways at the visual cortex.

functional properties; such cells are stacked in the form of columns that turn at right angles to the cortical surface. Within these columns, cells that deal with colour are grouped in separate clusters known as blobs. Most blob cell' receptive fields are circular. Aggregation of cortical neurons with related receptive field positions and functional makes it easier for them to interconnect so that they can perform the type of analysis required of them. Maps in visual areas of the cortex are not simple representations of the retina.

Several lines of evidence indicate that specialized lines of transmission project from relay to relay through the primary visual cortex and then on to the higher visual areas known as V_2 , V_3 , V_4 , and V_5 . These pathways, each of which is primarily concerned with information about depth, movement, colour, or form, are supplied by inputs originating from one of the two division of the lateral geniculate nucleus. The two main pathways, parvocellular and magnocellular, have different characteristics concerning the type of information they transmit (Fig. 2). Parvocellular is concerned with form and colour, and have small receptive field. Neurons in the magnocellular pathway have larger receptive fields and detect small changes in contrast. Higher regions of the cortex such as V_4 and V_5 contain cells responding mainly to colour or to movement.

3. STRUCTURE OF THE FUNDAMENTAL BUILDING BLOCK OF THE SYSTEM

As it has been pointed out before, a simple cell has been the basis for the architecture of the proposed system. This cell has been employed by us as the main block for some structures in optical computing⁶⁻¹². Its characteristics have been presented in several places and they may be synthesised as follows. The basic structure is shown in Fig. 3. It is composed by two non-linear elements: an on-off device and a SEED-like device. Their characteristics are shown at the inset of Fig. 3. It has two signals input, I_1 and I_2 as well as and two control signals, h and g . The output is a set of fourteen pairs of signals, Boolean functions of the inputs. When some feedback is added, for instance connecting a part of the output from O_1 as control signal to the P device, as well as a multilevel periodic input, some non-linear behaviour is obtained. Under certain conditions it is possible to obtain even a chaotic signal. Moreover, with no input, a periodic situation appears being the period a function of the feedback delay time.

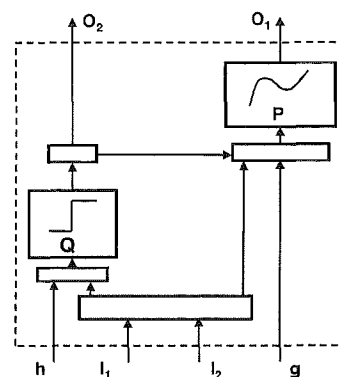


Figure 3.- Basic structure of the elemental block for the retina and visual cortex architectures.

Under certain conditions it is possible to obtain even a chaotic signal. Moreover, with no input, a periodic situation appears being the period a function of the feedback delay time.

4. BASIC BEHAVIOUR OF THE RETINA

Because the retina is the first place from where the external sensations go into the living beings, it deserves to be the first place for an initial processing of the signal.

The retina is quite different from any of other mammalian sense organs in that a good deal of the neural processing of the afferent information has already occurred before it reaches the fibres of the optic nerve. The fibers of the optic nerve are in fact two synapses removed from the retinal receptors, and particularly as far as the rods and cones in the periphery are concerned, there is considerable convergence of information from large groups of receptors. What happens is that receptors synapse with bipolar cells, and these in turn synapse with the million or so ganglion cells whose axons form the optic nerve. These two types of neurons form consecutive layers on top of the receptor layer and are mingled with two other types of interneuron that make predominantly sideways connections. These are the horizontal cells at the bipolar/receptor level, and the amacrine cells at the ganglion cell/bipolar level.

Some other facts have to be pointed out. They are concerned with the way the neurones work. First, three of them, namely photoreceptor, horizontal and bipolar cells, respond to light by means of hyperpolarization. These neurons do not produce action potentials. The second group, amacrine and ganglion cells, show a large variety of responses. They are action potentials in every one of the cases as well as depolarizing. Different types are reported in the literature¹³⁻¹⁴. The amacrine cells show transient depolarizing responses, including what are apparently all-or-nothing action potentials,

at the onset or cessation of light. Ganglion cells could be divided into three types according to their response to illumination. 'On' units respond to the onset of illumination, 'off' units respond to the cessation of illumination, and 'on-off' units respond to both onset and cessation. Another classification is made on the basis of the action potentials produced in response to stimuli. Most cells produce 'transient' responses, with just a few action potentials immediately after a change in illumination. They are called α cells. On the contrary, β cells give sustained responses to light. Several retina models appear in the literature following this lines¹³⁻¹⁵. The studied configuration in this paper appears in Fig. 4 and it was partially reported by us⁵⁻⁸. Just two photoreceptors have been taken. This configuration is similar the one proposed by Dowling¹⁵ to summarize the activity of the various retinal cells. As it can be seen, the receptor on the left is illuminated with a brief flash of light imposed on a dim background that illuminates both receptors, R1 and R2. A large response is observed in the stimulated receptor whereas the adjacent receptor that is not illuminated (right receptor) shows only a small response that probably reflects mainly the electrical coupling between the photoreceptor cells. Bipolar and horizontal cells are both activated by the receptors. The scheme of Fig. 4 shows that bipolar cell B1 is polarized strongly in a graded and sustained fashion by direct contacts with receptor R1. Moreover, this bipolar cell potential is antagonized by horizontal - bipolar cell B2 interaction. Bipolar cell B2 responds to indirect (surround) illuminations by depolarizing. As it can be seen, the switch from hyperpolarizing to depolarizing potentials along the surround illumination pathway occurs at the horizontal - bipolar junction.

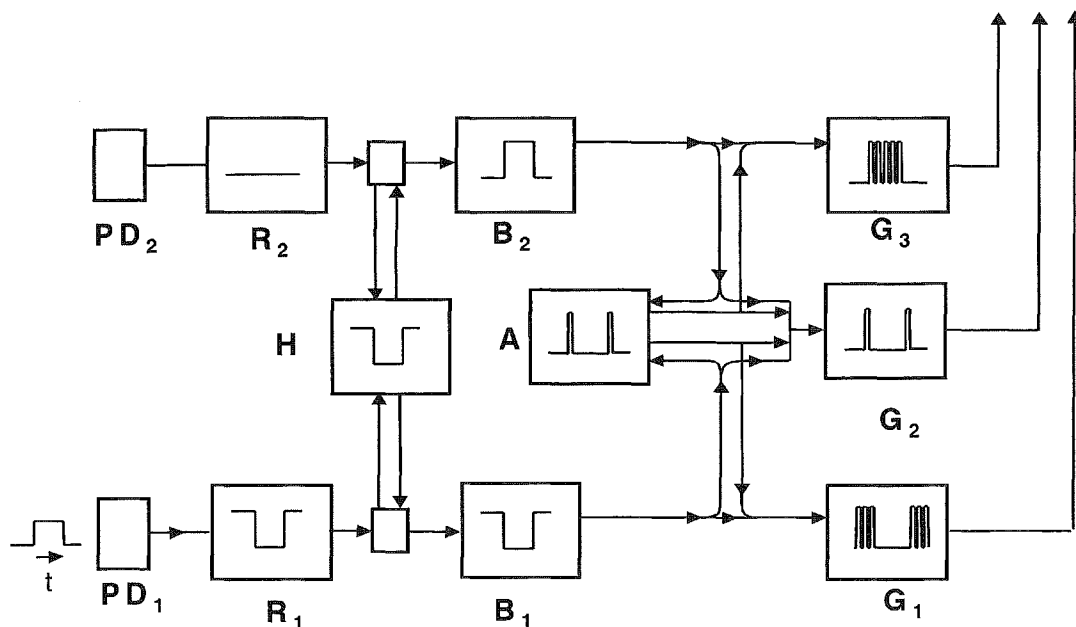


Figure 4.- Basic configuration employed as primary structure of the mammalian retina.

Amacrine cell, A, responds to light mainly with transient depolarizing potentials at the onset and cessation of spot illumination. The responses of the two basic types of ganglion cells found in the vertebrate retinas appear to be closely related to the responses of the input neurons to the ganglion cells. The G1 ganglion cell has a receptive field organization very similar to that of bipolar cells. Central illumination hyperpolarizes both the bipolar and ganglion cells, B1 and G1, in a sustained fashion, and surround illumination depolarizes the bipolar B2 and ganglion G2 cells in a sustained fashion. This type of ganglion cells appears to receive most of its synaptic input directly from the bipolar cell terminals through excitatory synapses. The ganglion cells illustrated in Fig. 1 are off-centre cells but there are some other types present in the vertebrate retinas. Ganglion cell G2 responds transiently to retinal illumination, much as the transient amacrine cells do. This type of response is the one adopted in our model.

Although this model is a very simple one, it is very useful to implement most of the functions performed at the mammalian retina. More complicated models can be obtained directly from this one.

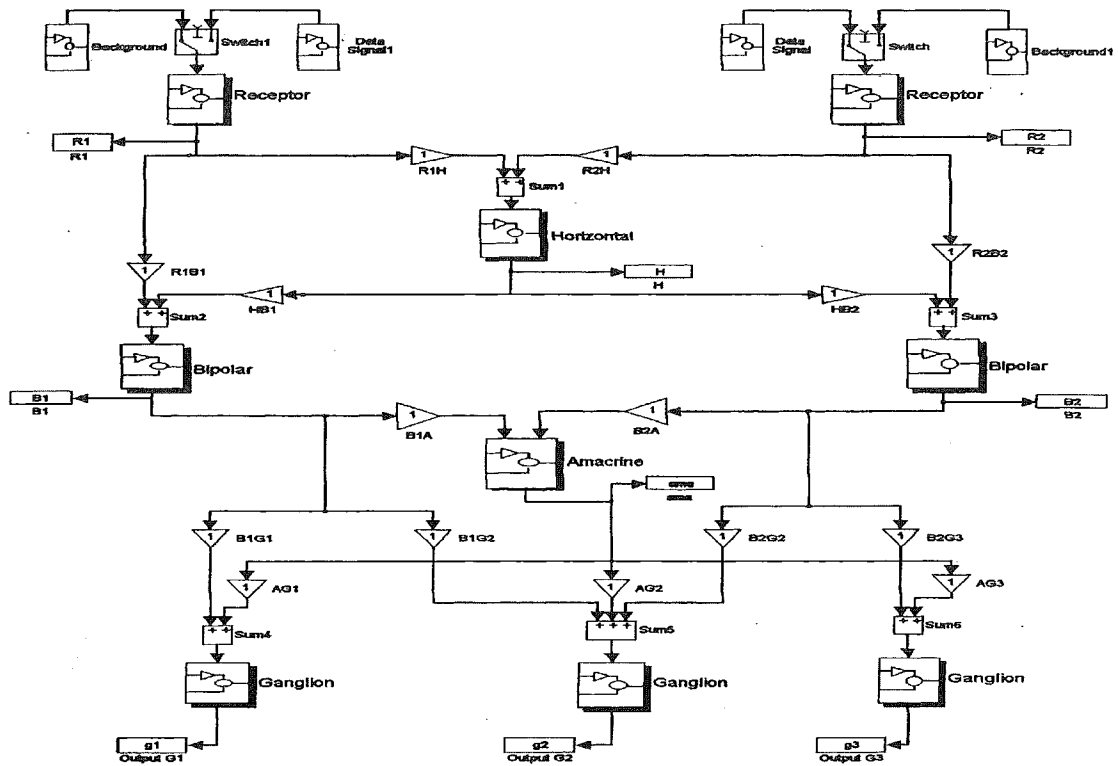


Figure 5.- Working scheme of the computer simulation of the retina as basic element for the processing system.

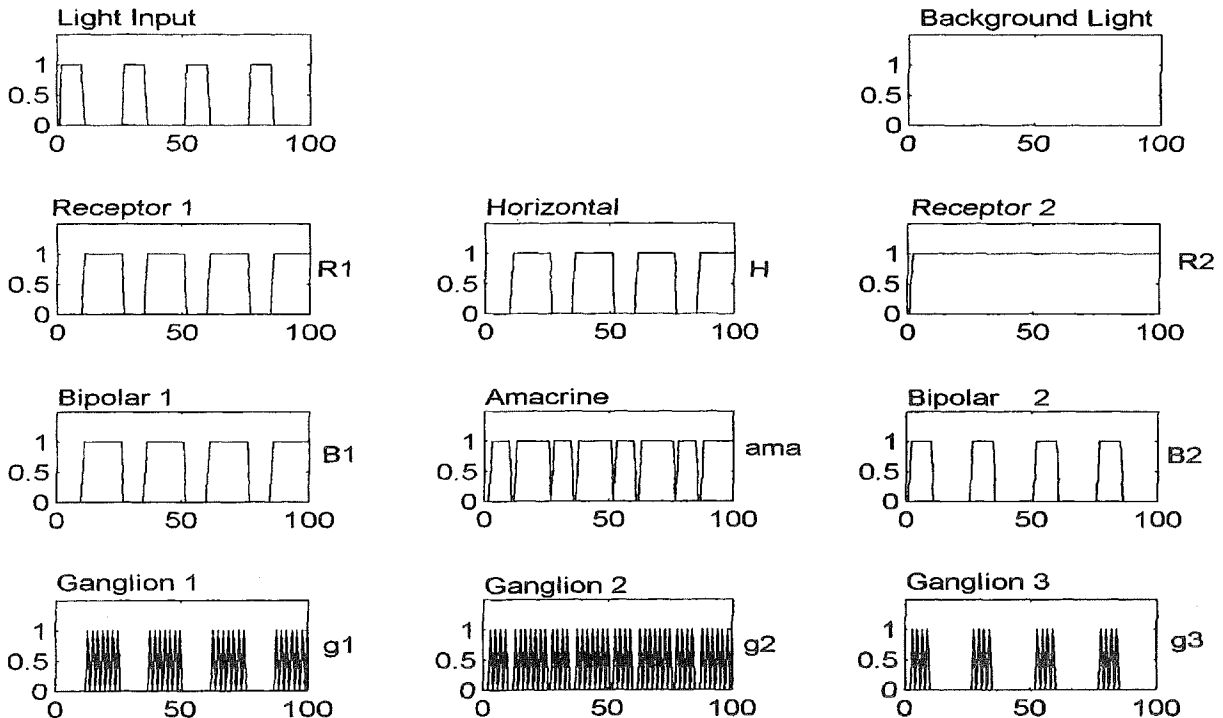


Figure 6.- Output signals from the ganglion cells at the retina adopted model and signals in the other different previous cells (photoreceptor, vertical, horizontal and amacrine cells).

The above indicated model has been computer by simulated by the scheme shown in Fig. 5. Results appear at Fig. 6.

Several possibilities appear from this structure. Fig. 6 shows just a part of them. This configuration, as it can be seen, has as its outputs three different types of signals. At ganglion 1 output is a train of pulses during the time there is no light impinging onto the photoreceptor. Ganglion 2 gives a continuous train of pulses except at the moment when there is a change from light to darkness and viceversa. Finally, output of ganglion 3 is a train of pulses during the time interval there is light going into the receptor. If light changes its position form receptor on the left to receptor on the right, outputs are very different. They are shown in Fig. 7 (a). Ganglion cell corresponding to the channel with light has no output signal. On the contrary, other two ganglion cells offer a continuous train of pulses. A first conclusion from the above results is that this configuration is able to give, as well as information about the time duration of the input light, from where it comes to the receptors. Hence this configuration is an asymmetrical configuration.

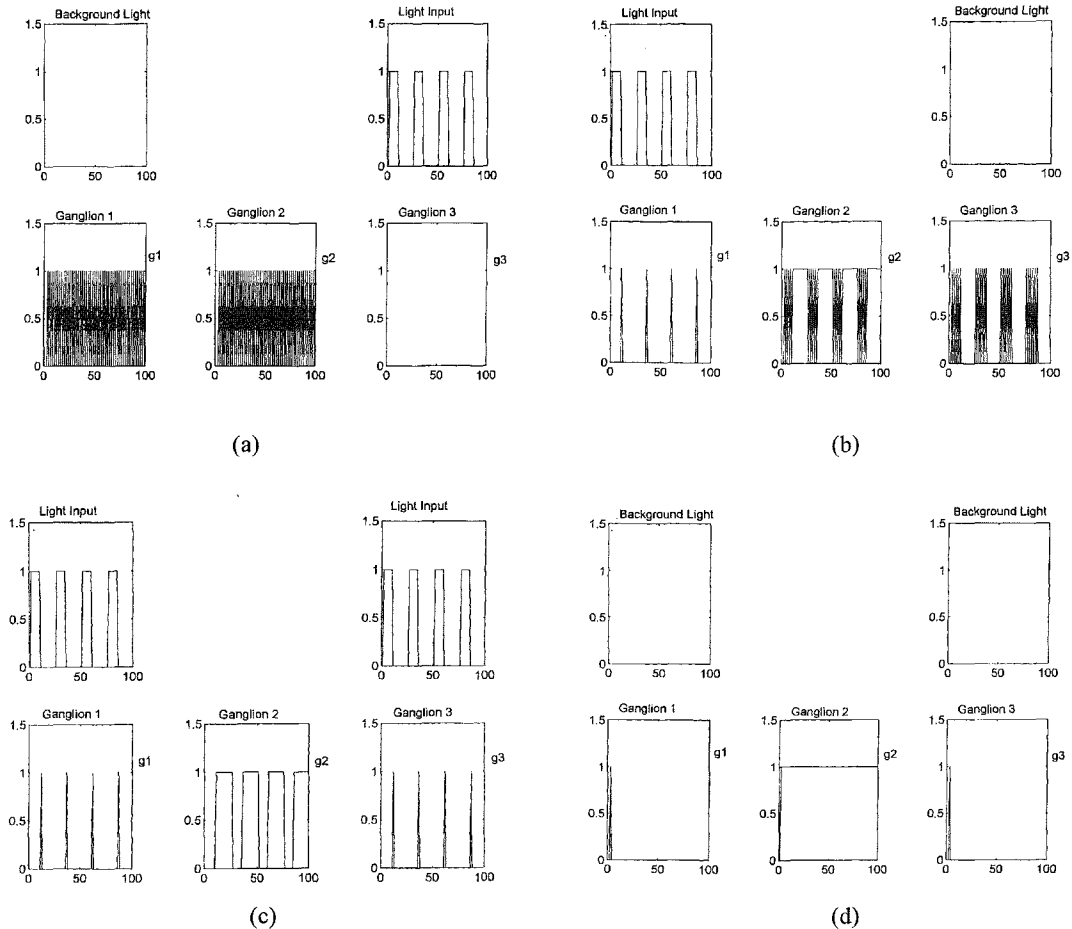


Figure 7.- Outputs from the ganglion cells corresponding to the situations indicated at the text.

If some of the internal connections to the scheme shown in Fig. 4 are changes, this structure may be converted to another one with a symmetrical behaviour. Results are shown in Fig. 7 (b)-(c)-(d). Figs 7 (b) corresponds to a similar situation as the previously studied. This result is the same one without regarding where is the light. Figs. 7 (c) – (d) offer the result when there is light impinging on both receptors and when there is no light onto them.

A last result is shown in Fig. 8. It corresponds to the case when there is a periodic lighting to both receptors, but the signals have some differences with respect to the arriving time. The three analyzed ganglion cells give a similar train of

pulses. But they offer some differences corresponding to the points where they have the beginning and the end. From the obtained information is possible to extract almost any information corresponding to the arriving light.

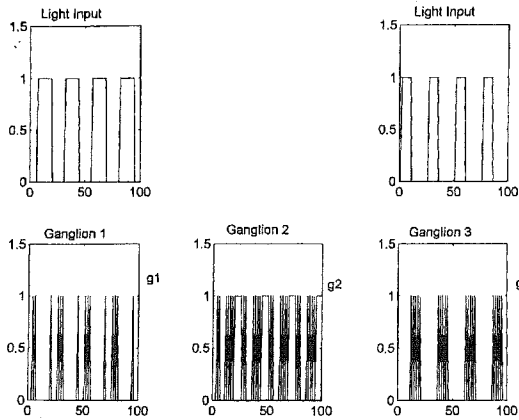


Figure 8.- Outputs corresponding to different time inputs at the receptors.

5. EXTENSION OF THE MODEL TO THE PRIMARY VISUAL CORTEX

As it has been pointed out at the beginning of this paper, any information captured at the retina goes to higher levels of the visual cortex. A very complex process occurs at each one of the successive layers. It is a well known scheme presented by several authors in several places (see, for example, [16]).

Our present objective is to emulate a part of this behaviour, more in those aspects related with subjective or qualitative properties than with objective or quantitative. We think that these aspects need a more careful attention than the last ones because they have been the object of much less attention. In order

to initiate our emulation we have started from a model as the one represented in Fig. 9. It is a very simplified model of the existing structure in the vertebrate visual system, going from the retina to the lower part of the visual cortex, but it may help us for understanding some possible mechanisms in capturing image information.

Our main task will be to construct a model as the above indicated one with main units the previously employed optical programmable logic cell. Hence, each one of the indicated block in Fig. 9 will be structures similar to the one shown in Fig. 3. An even more simplified model is the shown in Fig. 10. It is the basis for constructing the primary visual cortex. It is composed by six layers of cells interconnected in the way shown. Each one has two inputs, corresponding to the previous layer, and one output going to the following layer. The blocks are again of the same type, OPLCs, than before. The logic functions to be performed by them depend on the type of interpretation

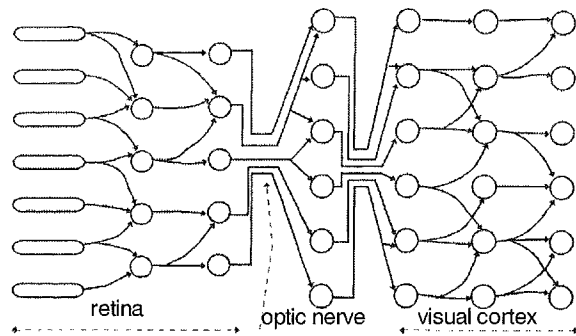


Figure 9.- Initial model of the visual system.

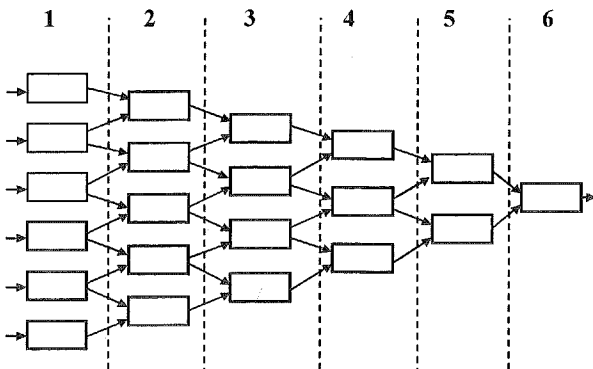


Figure 10.- Simplified model of the primary visual cortex based on the diagram of Fig. 9.

1 0 0 0 0 1	1 1 0 0 1 1
1 0 0 0 1	0 1 0 1 0
1 0 0 1	1 1 1 1
1 0 1	0 0 0
1 1	0 0
0	0

(a) Symmetry: A logic "0" is always obtained at the 6th layer

1 0 0 0 0 0	1 1 1 0 0 1	1 1 0 0 0 1
1 0 0 0 0	0 0 1 0 1	0 1 0 0 1
1 0 0 0	0 1 1 1	1 1 0 1
1 0 0	1 0 0	0 1 1
1 0	1 0	1 0
1	1	1

(b) Asymmetry: A logic "1" is always obtained at the 6th layer

Figure 11. Results obtained from Fig. 10 for different cases of the incident light symmetry.

it is wanted.

As a first example, if the property is desired to know is the symmetry of the light impinging onto the cells, the function to be performed by the OPLCs are simply XOR functions. Some examples are given in Fig 11. Light on a receptor gives logic "1" and no-light gives a "0". In Fig. 11.a, a symmetric light acts on the first row of cells. In this case, the obtained logic digit gives the results in higher levels of the system. As it can be seen, depending on the order of the symmetry, just zeros are obtained from a certain level on, the fifth row in the first case and the third row in the second one. On the contrary, when the light signal is asymmetric, as in Fig. 11.b, logic "1" is always obtained at the fifth level of the processing layers. This study can be extended to obtain some other properties of the incident light. Dimension of the object and number of borders can be obtained in the same way.

From this configuration is easy to go to a higher order structure. The studied architecture we have analyzed is the one shown in Fig. 12. It is composed by four planes of cells arranged in the indicated form. This scheme allows extending previous concepts to a bidimensional image. In this case the employed architecture is a 3D one. It is obvious that an electronic or optical implementation requires some more considerations than just the simple ones presented here. But the same concepts are easy to apply. S corresponds with the sensor element, C is the control system located there in order to

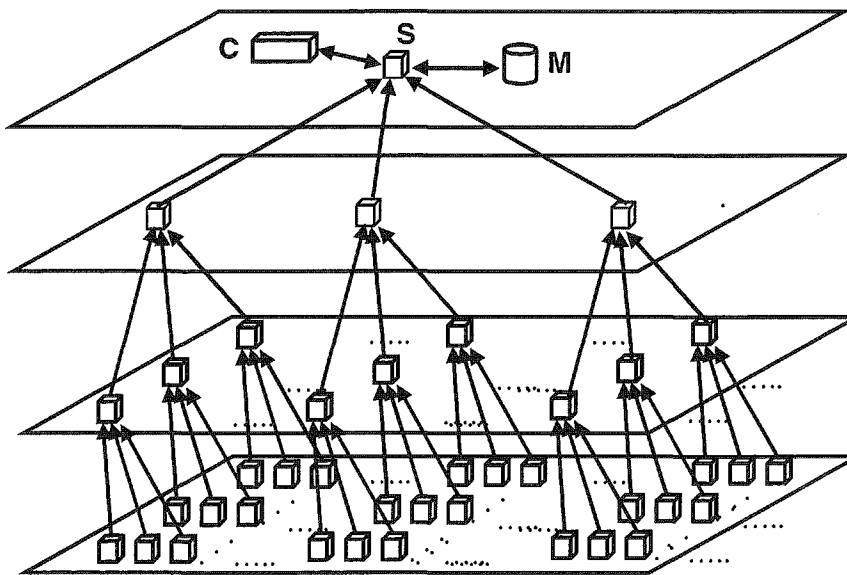


Figure 12.- Proposed 3D-structure designed to analyze higher order tasks in the visual processing.

recognize the type of information arriving to S, and M is some possible memory.

6. SYNTHESIS OF MAIN FACTORS TO BE CONSIDERED

Although many other factors should be considered, in order to summarize some of the vertebrate nervous system characteristics, we present now some of the main factors to considerer in present work. These points, in a much synthesized form are the following¹⁷:

- a. Different aspects of the visual scene, as seen by living beings, are perceived in a parallel way.
- b. Each portion of the visual scene goes through the different layers of the retina by different paths.
- c. Information about the relation between the information obtained from a particular area and information from adjacent areas is transferred to following layers, by a particular frequency coding in adjacent neuronal paths.

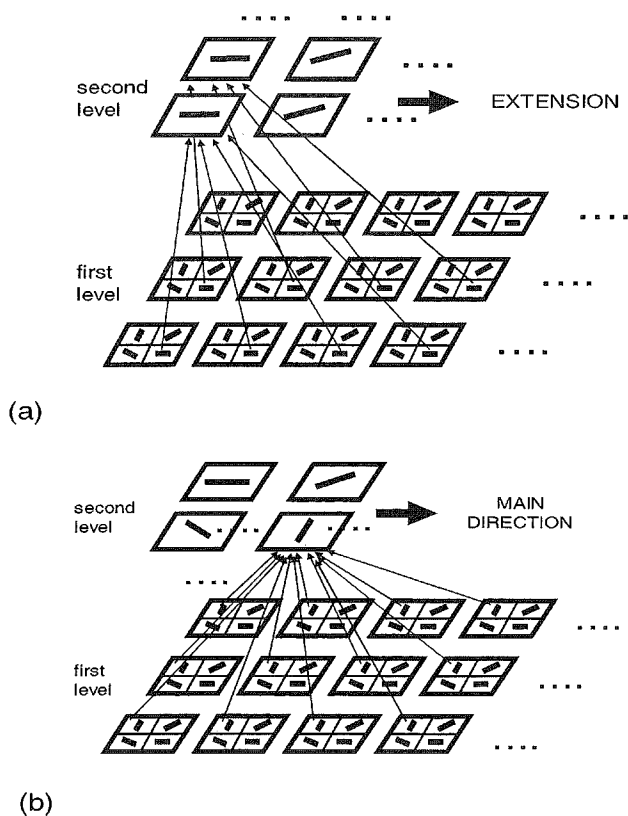


Figure 13.- Proposed structure for detecting line direction and extension

- linear effects.
- k. Although different types of information processing appear in the retina and visual cortex this processing is the result of interchange of information among neurons in the same level. No feedback processes appears in the neural network.
- l. The number of levels needed to go from receptor neurons in the retina to V1 layer in the cortex is lower than 15.

7. APPLICATIONS AND CONCLUSIONS

The above reported model is able to process a special type of qualitative information better than a quantitative one. The obtained result gives, without any kind of doubt, too much simplified information. It is just binaries "ones" and "zeros", depending on some characteristics of the object. But this type of signal may be able to trigger some type of system connected with the presently reported architecture. For example, as we have shown¹⁰, under certain circumstances, a set of new frequencies, and no present previously may appear. These frequencies give information about the type of signal impinging on the system. This is because the optical bistable properties of the involved devices are strongly dependent on a large number of their parameters and how they related with external signals. Some of them have been shown by us previously¹⁸.

- d. Information about the intensity of each one of the scene details are transferred from the third retina layer to following levels after a conversion from intensity level to frequency. Lower intensities correspond with lower frequencies.
- e. Information about different line orientations is transferred to selected areas at the visual cortex. These areas become excited by this information and living beings get a stimulus concerning that orientation in the visual scene.
- f. Each particular orientation, or each particular shape, goes to a precise area in the V1 area of the visual cortex.
- g. Information is always transferred in a parallel way.
- h. Visual cortex, at area V1, gets a "virtual image" of the real image appearing in the scene as "seen" by the living beings.
- i. No "biological" software appears at the visual cortex. Any type of information is processed by hardware interconnections among different neurons.
- j. Any biological information processing is performed by non

The possibility to detect particular characteristics of objects as motion, symmetries, shapes or directions, from an independent point of view, allows the possibility to implement specific systems designed to detect them without special high level requirements. Configurations as the one shown in Fig. 13 allow, for example, the extraction of properties as line direction or its dimension. Although this model is still very straightforward, it gives a first idea about the advantages of taking some ideas from the living bodies and the way they interact with their environment. Some more details about these aspects are given in [17].

ACKNOWLEDGEMENTS

This work was partly supported by CICYT, grant TIC2003-04309.

REFERENCES

1. Shepherd, Gordon M, *Neurobiology*. Oxford University Press. New York. 1994.
2. "Neuro-vision Systems. Principles and Applications". Eds.: Madam M. Gupta and George K. Knopf. IEEE Press. New York. 1993.
3. "Neurocomputing. Foundations of Research". Eds. J.A. Anderson and E. Rosenfeld. The MIT Press. Cambridge. 1990.
4. "Neurocomputing 2. Directions for Research". Eds. J.A. Anderson, A. Pellionisz and E. Rosenfeld. The MIT Press. Cambridge. 1990.
5. Hubel, D.H. and Wiesel, T.N. "Receptive fields, binocular interaction and functional architecture in the cat's visual cortex", *J. Physiol. (London)* 160, pp. 106-154. 1962.
6. Martín-Pereda, J.A. and González-Marcos, A.: "Some Connections between Neurophysiology and Optical Computing based on the Theory of Complexity". In "Fluctuation phenomena: disorder and nonlinearity". Eds.: J. Bishop & L. Vázquez. pp. 107-113. World Scientific Press. Singapore. 1995.
7. González-Marcos, A. and Martín-Pereda, J.A.. "A Model of Amacrine and Ganglion Cells for Optical Information Processing". IEEE Lasers and Electro-Optics Society, LEOS'94. Boston, 31 October - 3 November, 1994.
8. Martín-Pereda, J.A.; González-Marcos, A. and Sánchez-Guillén, C. "A model of the Mammalian Retina and the Visual Cortex. Disorders of vision". IEEE Conf. on Engineering in Medicine and Biology. Amsterdam. November, 1996.
9. Martín-Pereda, J.A. and González-Marcos, A. "Image processing based on a model of the mammalian retina". In "Applications of Photonics Technology 3. Closing the Gap between Theory, Development, and Application". Edited by G.A.Lampropoulos and R.A. Lessard. SPIE Volume 3491, 1185-1190, 1998.
10. Gonzalez-Marcos, A. and Martín-Pereda, J.A. "Digital Chaotic Output from an Optically-Processing Element". *Optical Engineering*, 35, pp. 525-535 (1996).
11. Martín-Pereda, J.A. and González-Marcos, A. "Optical Programmable Processing Element using Optical Fibers". IEEE Lasers and Electro-Optics Society, LEOS'92. Boston, 15-20 November, 1992.
12. Gonzalez-Marcos, A. and Martín-Pereda, J.A., "Sequences of bifurcations and transitions to Chaos in an Optical-Processing Element". In "Optical computing". Ed.: B.S. Wherrett. pp. 621-624. *Inst. Phys. Conf. Series*. No. 139 Part IV. 1995.
13. Nicholls, J.G.; Robert, A. M. and Wallace, B.G. "From Neuron to Brain", Sinauer Associates, Inc. Sunderland, MA. 1992.
14. Shepherd, G.M., *Neurobiology*, Oxford University Press. New York. 1994
15. Dowling, J. E. "The Retina: An Approachable Part of the Brain". The Belknap Press of Harvard University Press. Cambridge, MA (1987).
16. *The Cognitive Neurosciences*, Ed. Michael S. Gazzaniga. The MIT Press. Cambridge. 1995.
17. Martín-Pereda, J.A. "Learning from the living bodies: New Principles and Techniques for Photonic Sensing" (Invited). SPIE Volume 5502. Second European Workshop on Optical Fibre Sensors. pp. 1-8 (2004)
18. Hurtado, A.; González-Marcos, A. and Martín-Pereda, J.A. "Wavelength Monitoring with Semiconductor Laser Amplifiers". SPIE Volume 5502. Second European Workshop on Optical Fibre Sensors. pp. 508-511 (2004)