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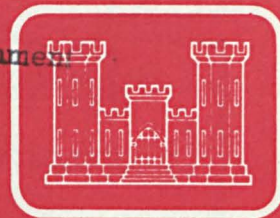
A study of the human visual system in support of automated feature extraction

Frederick W. Rohde

OCTOBER 1981

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PREFACE

This study was conducted under DA Project 4A161101A91D, Task 01, Work Unit 0065, "Research of Artificial Intelligence for Image Data Extraction."

The study was done during the period October 1978 to September 1979 under the supervision of Mr. M. Crowell, Jr., Director, Research Institute.

COL Daniel L. Lycan, and COL Edward K. Wintz, CE were Commanders and Directors and Mr. Robert P. Macchia was Technical Director of the Engineer Topographic Laboratories during the study and report preparation.

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A STUDY OF THE HUMAN VISUAL SYSTEM IN SUPPORT OF AUTOMATED FEATURE EXTRACTION

INTRODUCTION

The purpose of this study is to analyze the architecture and functions of the human visual system and to apply the results to the problem of automated feature extraction. Most tasks performed by man require processing of visual input. Two examples are sorting letters and interpreting aerial photographs. In both cases, a huge amount of material, letters, or images has to be processed. If the tasks are to be performed by machines, visual feature extraction must be carried out automatically. So far, the success of automation has been limited. The study of the human visual system and its unmatched capability may provide new leads to the problem of automated feature extraction and machine intelligence.

The analysis of the architecture and functions of the human visual system is based on an in-depth examination and evaluation of literature concerning the anatomy, neurology, and sensory perception of the human visual system. In recent years, new anatomical staining methods, radioactive tracing techniques, and measurements of neural responses using microelectrodes have greatly contributed to a better understanding of the human visual system.

A brief description of the anatomy of the visual system is presented. The information-processing functions of the components of the visual system are analyzed and discussed. The architecture of the visual system is compared with the architecture of a computer. Some ideas of translating functions of the visual system into artificial intelligence are investigated.

ANATOMICAL ARCHITECTURE OF THE VISUAL SYSTEM

Block Diagram of the Visual System • The visual system consists of the following major components: retina, optic nerve, optic chiasma, optic tract, lateral geniculate nucleus, visual radiation, and visual cortex. In figure 1, a schematic diagram of the visual system is shown. The optical image that is projected onto the retina is converted by the retina into a pattern of neural signals. The signals are transmitted to the lateral geniculate nucleus by nerve fibers that originate in the retina. These fibers form the optic nerve, the chiasma, and the optic tract. The lateral geniculate nucleus, visual radiation, and visual cortex are integral parts of the brain. The visual systems of all mammals, including man, are organized in the same manner. Differences between species are seen in the complexity and detailed structure of the major components. The functional building blocks of the visual systems are neurons (nerve cells).

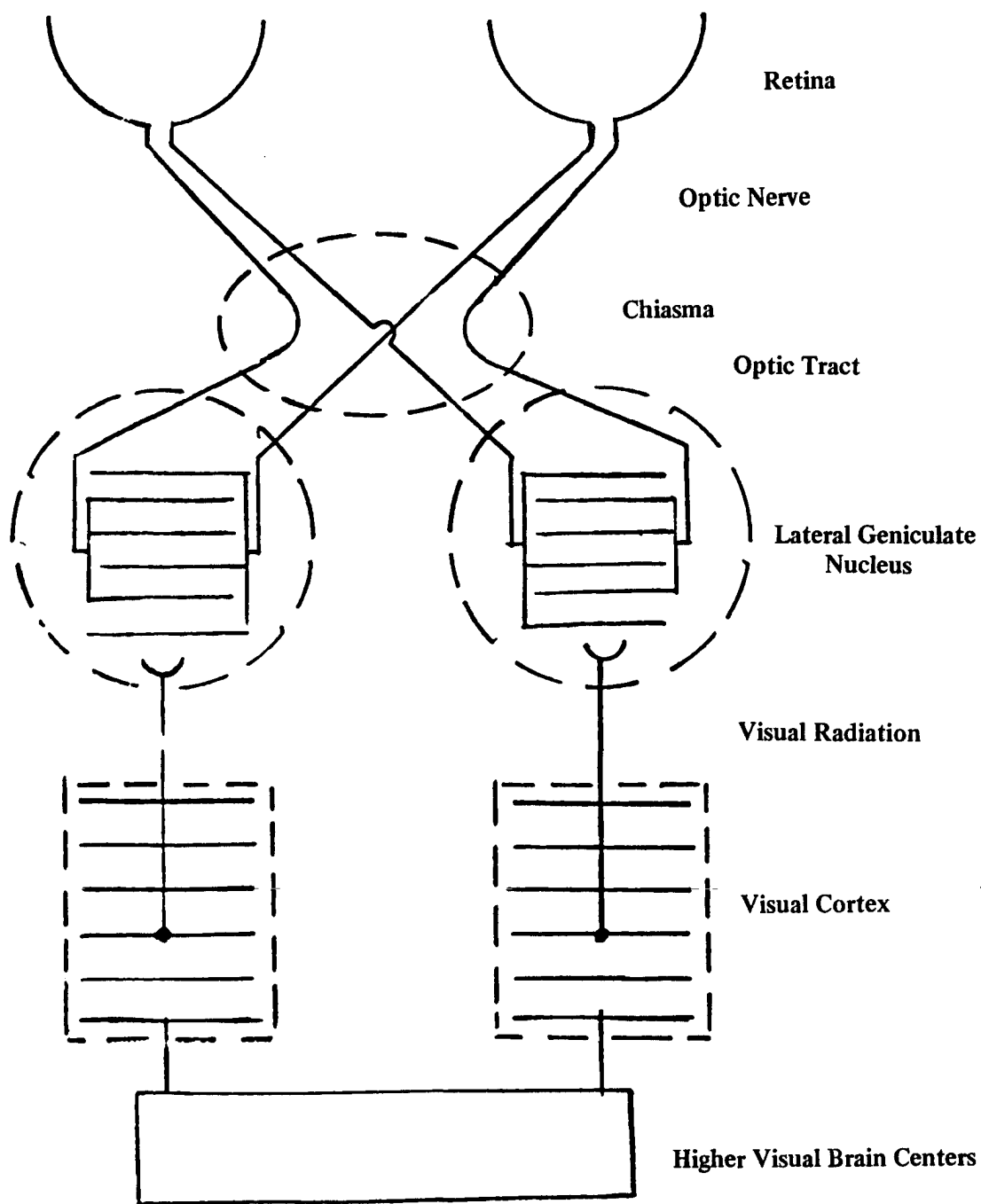


FIGURE 1. Schematic Diagram of Visual System.

Neurons • A neuron consists of a cell body, dendrites, and an axon. The cell body is compact and usually spherical. The dendrites are extensions that branch out and form tree-like clusters around the cell body. The axon is an extension much longer than the dendrites and tends away from the cell body (see figure 2).

The dendrites receive incoming signals, the cell body integrates the signals, and the axon transports the outgoing signal to the axon terminals, which distribute the information to a new set of neurons. Information is transferred from one neuron to another at specialized points, which are called synapses. At a synapse, an axon terminal is separated from the end of a dendrite only by a very narrow gap. The transfer of information from the axon to the dendrite is accomplished by chemical transmitters. Chemical transmitters are the substances that are ejected by the axon into the synaptic gap, diffuse across the gap, and are received by the dendrite. The reception of transmitter molecules produces an electrical signal in the surface membrane of the dendrite, which is conducted to the cell body. The signals arriving from the various dendrites are combined by the cell body into a frequency coded pulse signal that is transmitted along the axon to other synapses. The pulse amplitude is for all neurons about 70 millivolts, the pulse duration is about 1 millisecond, and the frequency or firing rate does not exceed approximately 800 pulses per second. The electrical impulses are generated and transmitted by a process within the surface membrane that is called the potassium-sodium ion pump.

There are two types of synapses. The first type is called the excitatory synapse and it increases the firing rate of the neurons upon receiving signals across the synapses. The second type is called the inhibitory synapse and it reduces the firing rate in the follow-on neuron. Most neurons receive input through many synapses (up to several thousands), some of which are excitatory and some inhibitory. The sum of the excitatory and inhibitory effects will determine the firing rate of the neuron. Because the flow of information within a neuron is always from the dendrite terminals to the axon terminals, the neuron may be considered as a directional information processing element.

Retina • The retina is a layer of nerve cells of approximately spherical shape. It is approximately one-tenth of a millimeter thick and comprises an area of approximately 9 square centimeters. The retina is composed of three major layers of cells, receptors, bipolars, and ganglion cells, with lateral cross-connections accomplished by amacrine and horizontal cells. The peripheral cells of the first layer are photo-receptors – cones and rods. The center of the retina is called the fovea. It is roughly circular, and covers approximately 2 square millimeters. The number of

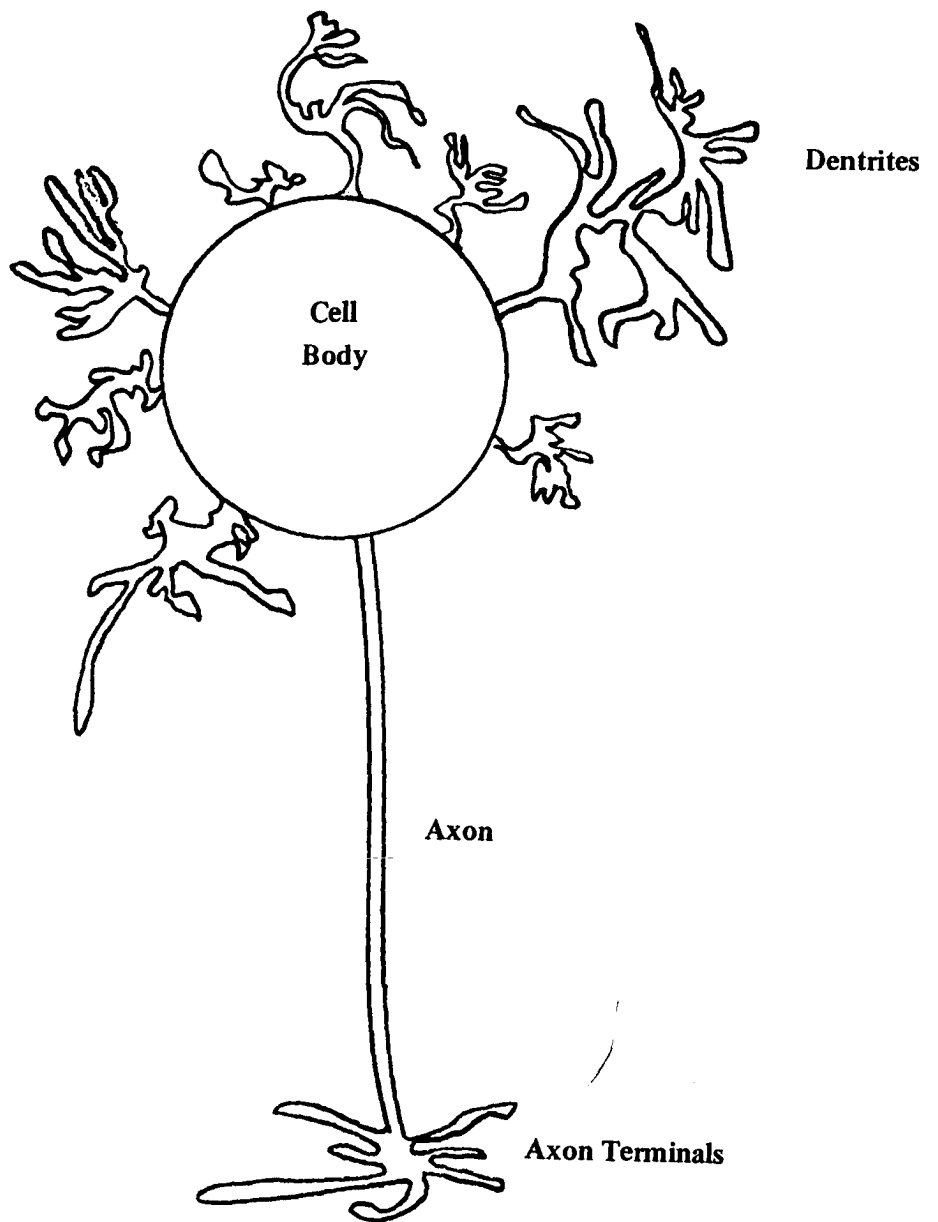


FIGURE 2. Diagram of Typical Neuron.

cones per square millimeter is approximately 7000 over most of the retina, except in the area within 2 mm from the center in which the fovea is located. The number of cones decreases rapidly from the center.

The central fovea has a diameter of 0.5 mm and contains about 20,000 cones. The overall fovea has a diameter of 1.6 mm and contains about 100,000 cones. The cones at the center of the fovea are longer and thinner than those at the periphery. The distance between the centers of two adjacent foveal cones is between 2.0 and 2.5 μm (micrometers). The total number of cones is approximately 6.5 million. There are no rods at the central fovea, but the rods increase away from the fovea to reach a maximum of 160,000 per square millimeter at a distance of 5 to 6 mm from the center. In the more peripheral areas, the number of rods decreases, but remains higher than the number of cones. The total number of rods is approximately 120 million.

Adjacent to the level of receptors is a layer of complex, reciprocal synaptic interconnections, called the outer plexiform layer, where the horizontal cells are found. These units serve to interconnect the various receptors to each other in the lateral dimension. The second, or inner, nuclear layer consists of bipolar cells that transmit incoming signals from the receptors to the next layer of cells, the amacrine cells. The latter are also found to run in the horizontal dimension among bipolar cells and ganglion cells, which make up the third layer of the retina. The axons of the ganglion cells are the fibers that comprise the optic nerve, chiasma, and optic tract and send visual information to the brain. Thus, information is transmitted vertically and horizontally in the retina, such that there is a widespread interaction between the cells.

The retina may be divided into two parts; the nasal hemi-retina and the temporal hemi-retina.

Optic Nerve, Chiasma, and Optic Tract • The optic nerve fibers leave the eye via the optic disc, an area containing no photoreceptors, thus called the “blind spot,” at approximately 16° of the nasal hemi-retina. From the optic disc, the optic nerve from each eye converges and meets at the chiasma, where the fibers from each nasal hemi-retina cross to the opposite side of the brain. The fibers from each temporal hemi-retina enter the chiasma, but remain on the same side of the brain when they exit the chiasma. Thus, some fibers cross to the side opposite of their origin, others do not. The ratio of crossed to uncrossed fibers is approximately 3:2. The optic

nerve fibers undergo a rearrangement of position along the course of the nerve. The most marked rearrangement occurs with those fibers that serve central vision. These are progressively displaced from the middle third of the temporal side of the nerve toward the center.

The crossed fibers from the nasal hemi-retina and the uncrossed fibers from the temporal hemi-retina form the optic tract on each side of the brain. These fibers then proceed to the lateral geniculate nucleus on each side of the brain. The number of fibers of the optic nerve for several vertebrates is shown below:

Man	:	1,000,000	Dog	:	154,000
Pig	:	681,000	Cat	:	119,000
Chicken	:	414,000	Frog	:	29,000
Rabbit	:	265,000	Hag Fish:	:	1,579

Lateral Geniculate Nucleus and Visual Radiation • The majority of the optic tract fibers terminate in the lateral geniculate nucleus (LGN). The LGN is the first synaptic relay station in the path from the retina to the visual cortex. The LGN has six layers of neurons, which are numbered from 1 to 6. The neurons of layers 1 and 2 are relatively large cell bodies; whereas, the neurons of layers 3 and 6 are small. The large, as well as the small, neurons have long axons that synapse with neurons of the visual cortex. Each layer also contains neurons with short axons that make synaptic connections within the LGN. These cells are specialized for lateral transmission among layers and provide a means for lateral interaction and neural integration between cells at all layers of the LGN. Fibers from the central area of the retina terminate predominantly in the wedge-shaped middle part of the LGN, and fibers from the peripheral area of the retina terminate in the outer portions of the LGN. Thus, the retina is mapped with relatively minor distortion into the LGN.

Each LGN receives fibers from both eyes. Crossed and uncrossed fibers of the optic tract terminate in separate layers of the LGN. Layers 1, 4, and 6 receive their input from the eye on the opposite side via crossed fibers and layers 2, 3, and 5 receive their input from the eye on the same side via uncrossed fibers. Descending

from the cortex are long axons with many synaptic contacts within each layer. These axons establish a neural feedback network and provide for signals from the cortex to be integrated with those signals coming from the retina. The organization of the LGN displays the same kind of lamination and lateral connection observed in the retina, and the microanatomy reveals a kind of columnar organization also found in the cortex.

The main efferent fibers from the LGN form the visual radiations. The fibers fan out and then reassemble in a compact bundle that terminates in the visual cortex.

Visual Cortex • The visual cortex is a laminated structure that is about 2 millimeters thick and covers approximately 15 square centimeters. The number of neurons in the visual cortex is estimated to be 150 million. The neurons are arranged in six parallel layers, numbered from I to VI, and have alternately low and high neuron density. The structure of each layer shows a marked uniformity.

The principal input to the visual cortex is provided by the visual radiation. The fibers of the visual radiation make synaptic connections with neurons of layer IV. Other input is provided by fibers of the corpus callosum, which is a bundle of nerve fibers connecting the two cerebral hemispheres. Fibers of the corpus callosum make synaptic connections with neurons of layers I and II.

The visual cortex, which occupies essentially the Brodmann area 17 of the cerebral cortex, is also connected with other parts of the brain through axons projecting from the visual cortex. Axons from layer VI project mainly back to the LGN. Axons from layer V project into the superior colliculus, which is believed to be a visual interpretive system. Axons from layers II and III project into the Brodmann area 18 and 19, which are known to re-process information that has been processed through the visual cortex.

There are two broad classes of neurons in the visual cortex; pyramidal neurons, having extended dendrite fields and long axonal extensions, and stellate neurons, having dendrite fields distributed uniformly around the cell body.

Most stellate neurons are found in the central layers of the visual cortex, especially in layer IV. Pyramidal neurons are concentrated in the layers II, III, and VI. The stellate neurons of layer IV receive the input signals from the visual radiation, which are then carried to the other layers by pyramidal neurons. The pyramidal neurons establish synaptic contacts with stellate neurons and carry signals vertically (normal to the layer) through the layers of the visual cortex. Different pyramidal cells make specific connections between different layers.

Local horizontal connections along the cortex are established by short axon cells, which have an effective spread of less than one-half of a millimeter. The six layers of the visual cortex are interconnected horizontally. There are local connections along the layers, which are equivalent to a connection between adjacent regions of the visual field. The retina is mapped through the visual pathway into the visual cortex. A significant characteristic of the mapping is nonlinear distortion. For example, the central part of the retina, which includes only 3 percent of the retinal surface, is represented by almost half of the visual cortex. Thus, the retinal area with high acuity is represented unproportionally large in the visual cortex.

INFORMATION PROCESSING OF THE VISUAL SYSTEM

Effect of Eye Motion • The eyes project an image of the external world onto the retina and are constantly in motion. Even during steady fixation of a stationary object, eye movement occurs, which is comprised of three components: flick, drift, and tremor. The flicks occur at irregular intervals of $1/300$ of a second to 5 seconds and have an amplitude of approximately 20 minutes of arc. Between flicks, the eye drifts slowly about 1 degree per second. Superimposed upon these movements is a high frequency tremor of varying amplitudes up to one-half minute of arc and a frequency of up to 150 per second.

The eye movement causes a corresponding motion of the image on the retina. When the image of a pattern is stabilized on the retina, the perceived outline and contrast in the pattern begin, after approximately 1 second, to deteriorate and finally to disappear. The stabilization of an image on the retina is accomplished by an optical arrangement in which one mirror is attached to the eyeball to compensate

for the eye movements. If the image is flickered or caused to move on the retina, it immediately reappears. The flick movements of the eye are most important for maintaining optimal accuracy.

A basic property of the visual system is its sensitivity to local contrast. The eye's ability to detect an edge or contour is determined by the change in brightness of the visual field across that contour. Within a wide range, the absolute level of illumination is relatively unimportant. The spatial changes in brightness of the image appear to the photo receptors of the retina as temporal changes of brightness because the involuntary eye movement produces a time-varying input to the receptors. Only the changes of luminance at the photo receptors in the retina signal the pattern of the retinal image to the brain. The visual neurons of the retina, LGN, and visual cortex respond to changes in luminance, whether these are produced in time by light-on or light-off or in space by contrast patterns shining upon their receptive fields. Such stimuli are created under natural conditions by the voluntary and involuntary eye movements so that a continuously changing neural input from the eye is provided to the visual brain.

Receptive and Perceptive Fields • The receptive field concept is important in understanding the visual system. The receptive field of an individual neuron is defined as the area in the external world in which a stimulus elicits activity in that neuron. Receptive fields are determined by electrical recordings from visual neurons, and are organized by exploring localized visual stimuli. Neural signals are recorded by coupling a microelectrode to a neural axon. The microelectrode picks up the signals transmitted along the axon, which are then amplified, recorded, or displayed. Because inserting microelectrodes in the visual system requires surgical operations, most of the recordings have not been performed on human beings, but on rabbits, cats, and monkeys. Receptive fields are also organized by using radioactive tracing methods. The receptive fields are found in the retina, the lateral geniculate nucleus, and the visual cortex. In the same way as stimuli are applied to test animals for receptive field research, stimuli may be also applied to test persons. The experiments lead to the concept of perceptive fields. Perceptive fields are defined as the psychophysiological equivalents of visual receptive field organization in man, and they can be estimated by visual phenomena, including illusions.

Receptive Fields and Information Processing in the Retina • The ganglion cells of the retina are the neurons that determine the retinal receptive fields. The structure of retinal receptive fields shows two regions, an approximately circular center and a ring-shaped surround. If center and surround are equally diffusely illuminated, the cell response is weak. If the illumination is non-uniform, containing e.g. a border between light and dark areas, the cell may respond strongly. A retinal ganglion cell responds best to a roughly circular spot of light of a particular size in a particular part of the visual field. The size is critical because each cell's receptive field is divided into an excitatory center and an inhibitory surround, or into the reverse configuration.

There are retinal ganglion cells with wide dendrite fields and others with small dendrite fields. Because the wide dendrite fields receive a large amount of converging information, and small dendrite fields, small amounts of information, the feature extraction operation is instrumental in distinguishing large objects from small ones. The size of receptive field centers in the fovea varies from 20 to 60 μm in diameter. The dimensions of an entire receptive field, including center and surround, varies between approximately 100 and 200 μm in the central region of the retina. The mean diameter of receptive field centers increases from the center of the retina to its periphery. The receptive field centers of the peripheral retina have diameters of approximately 1 mm. In figures 3 and 4, the schematics are shown of foveal and peripheral receptive fields.

The receptive fields of the retina are divided into two classes. In the first class, the ganglion cells of the receptive fields are called on-center cells. They will increase their firing rate when the center of the field is illuminated and decrease their firing rate when the surround is illuminated. In the second class, the response of the ganglion cells is reversed. That is, illumination of the center decreases the firing rate, and illumination of the surround increases the firing rate. The populations of ganglion cells of both classes are approximately equal in numbers as well as in their distribution over the retina. The ganglion cells of the second class are called off-center cells. On-center cells with their center region located just on the bright side of a border will be most activated; those on the dark side will be most inhibited.

Greatest retinal activity is thus associated with border regions. The retina is particularly responsive to sharp contrast borders. This property of border enhancement is clearly important in the discrimination of the shape of features. The border contrast is coded by a combination of "darkness" signals from off-center cells on the dark side of the border and "brightness" signals from on-centers on the bright side. The

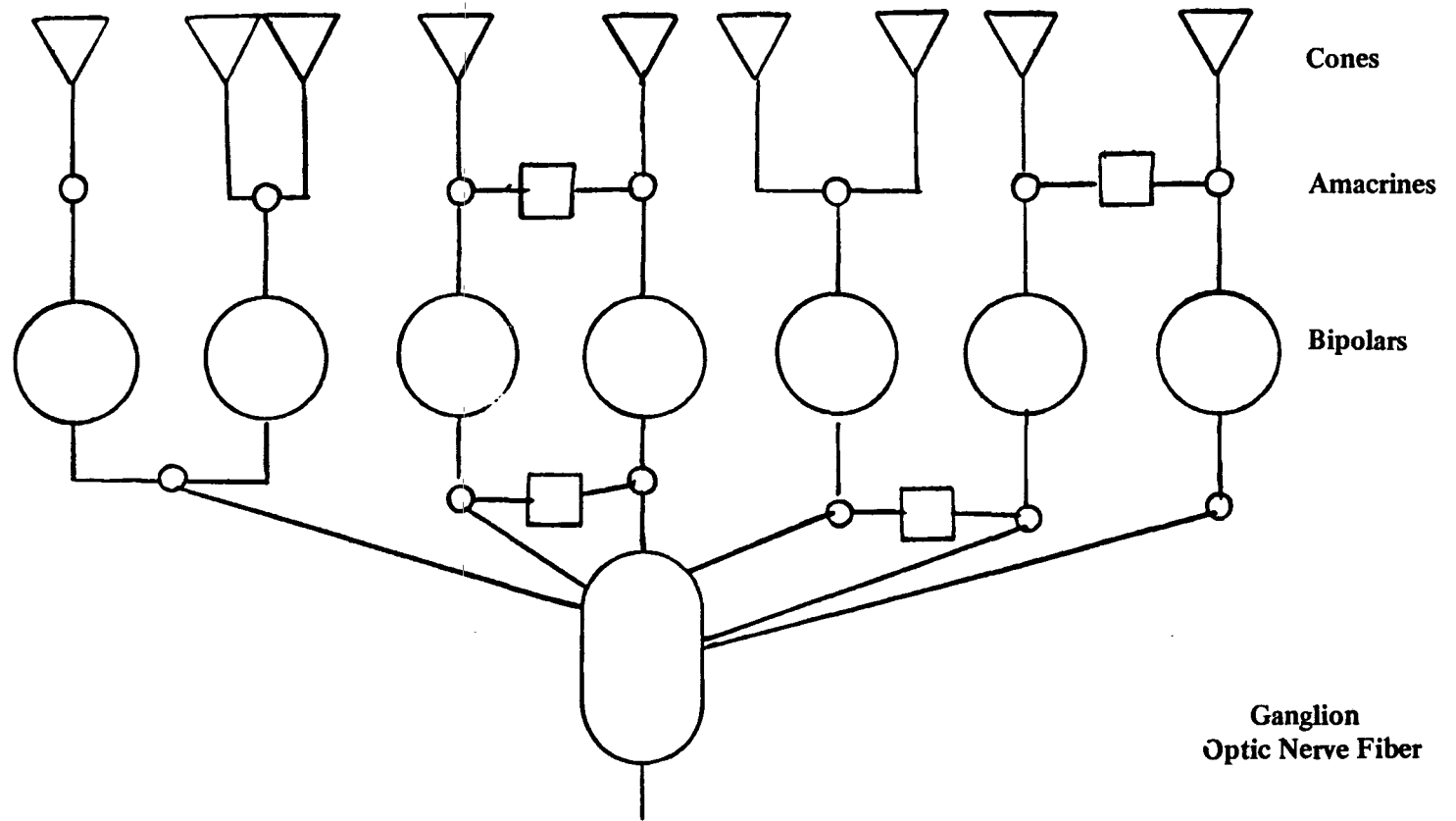


FIGURE 3. Receptive Field Organization in the Fovea.

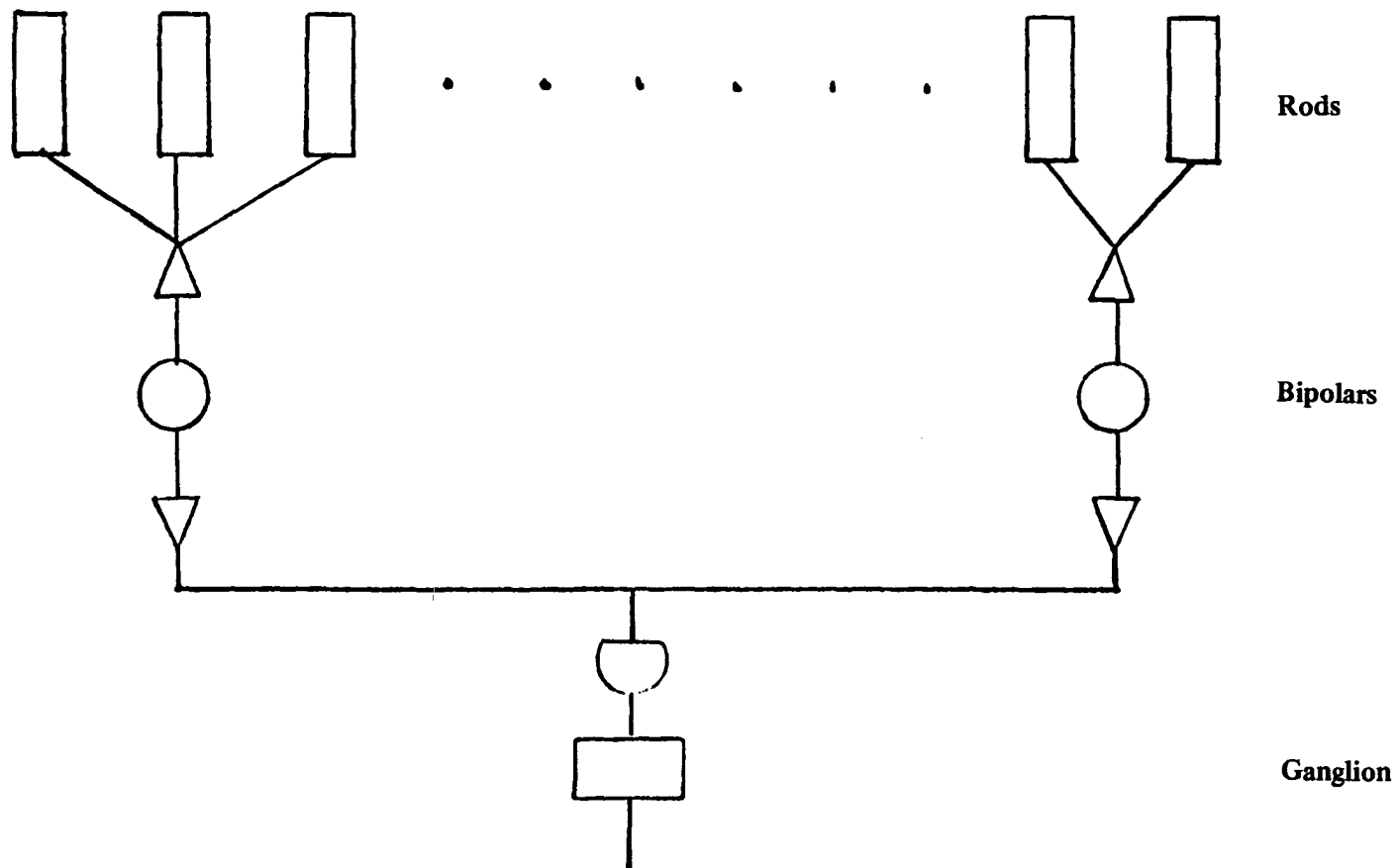


FIGURE 4. Schematics of Peripheral Receptive Field.

fact that the retina is coding changes in brightness rather than absolute brightness of each small segment of the pattern may be considered as a first step of signal processing to economize the flow of visual information. The visual system might then interpret the comparative brightness of two areas in terms of the luminance gradient at the border between them.

The reciprocal system organization of the two classes of receptive fields has advantages for information transmission and perception because it sends signals of opposing visual qualities via specific channels from the eye to the brain and, hence, doubles the sensory range of contrast vision.

In summary, the receptive fields of the retina are less concerned with evaluating absolute levels of brightness than they are with detecting contrast of brightness within receptive fields.

Signal Flow and Processing in the LGN • The LGN receives inputs from the retinas of both eyes and the visual cortex. The LGN is made up of six layers of neurons arranged in a shell-like manner. Each layer receives an ordered two-dimensional map of the retina. The projection of the retina into the different layers of the LGN are in register, that is, a single corresponding point on the two retinas projects to points on the six neural layers of the LGN that lie one above the other. Thus, projection lines can be drawn through the six layers corresponding to a single retinal projection point. Hence, corresponding small areas of each retina, approximately the size of a receptive field, are represented as a column of cells in the LGN. The column systems are a solution to the problem of portraying more than two dimensions on a two-dimensional surface. There are two principal classes of neurons in the LGN: (1) relay cells that pass signals received from the retina onwards to the visual cortex, and (2) short axon neurons that transmit inhibitory signals within the different layers of the LGN. The fibers carrying signals from the visual cortex back to the LGN influence all six layers. Thus, signals from one eye arriving at the LGN via the cortex can suppress direct neuronal signals arriving in the LGN from the other eye.

The transformation of visual coding taking place in the LGN is best approached in terms of receptive field organization. LGN fields are concentric in organization, with antagonistic center and surround regions. Like retinal fields they respond less to diffuse illumination, which activates both center and surround simultaneously, but

are strongly excited by spot stimuli that stimulate just the center region. The principle difference from retinal fields is the greater suppressive effect of stimulation of the surround on responses evoked from the center. LGN cells receive excitatory influence from one or a few retinal cells and therefore resemble ganglion cell fields in many ways, but they also receive inhibitory retinal input that modifies their receptive field properties. The modifications seem to make the LGN fields more selective for stimulus features than retinal fields. Most LGN cells reveal increases in rates of firing to stimuli whose diameters are up to about half the area of the center of the receptive field.

Signal Processing in the Visual Cortex • Visual information is carried from the lateral geniculate nucleus to the visual cortex by fibers of the visual radiation. The fibers terminate in the layer IV of the visual cortex. The neurons in layer IV that receive the signals directly from the lateral geniculate nucleus have circular receptive fields with center and antagonistic surround. They respond best to spot light stimuli and are monocular (respond only to signals from one eye). Layer IV contains another group of neurons that do not have circular receptive fields. These fields are called “simple receptive fields” and the neurons are called “simple cells.” Simple cells respond to an optimally oriented line stimuli in a narrowly defined location. Like retinal fields, many simple fields have antagonistic “on” and “off” areas, which are arranged in parallel strips and not concentrically.

Layers II, III, V, and VI are populated by neurons that are called “complex cells” and have receptive fields that are called “complex fields.” Complex receptive fields respond to moving bar stimuli and are selective for the orientation of the bar. Complex fields are larger than simple fields and are selective for the contrast and width of bar stimuli.

Layers II and III also contain neurons that have “hypercomplex fields.” Hypercomplex fields have a higher stimulus sensitivity than that of simple and complex fields, and they select the orientation, width, contrast, length, and direction of the stimulus.

One of the properties of the visual cortex is its sub-organization into functional columns. Each receptive field has a certain preferred orientation. Cells with the same orientation preference are grouped together into columns. Each small area of the

retina is represented by a considerable population of cortical receptive field. Features of a stimulus appear to be coded in terms of differential activity among functional subgroups of that population. Cortical cells generally have small receptive fields, especially those cells representing the fovea. The retinal position of a stimulus feature can be coded in terms of which sub-population of cells is activated. Contours with different orientations will excite different subgroups of cortical fields, even though they are imaged on the same small area of the retina. The positions of the ends of a contour will determine which group of hypercomplex fields is excited.

There is a great increase between the retina and the visual cortex in the number of cells involved in visual coding. For every retinal ganglion cell, there are some hundreds of cells in the visual cortex. Cortical cells that are excited from the same small area of the retina are selectively responsive to different orientations of the contrast edge, to position of its ends, and to differences in the visual depth relative to the fixation point. A change in any of these parameters or in retinal position results in a change of population of excited cells.

The coding of features of a stimulus pattern does not appear to converge on a single or several neurons, at least not in the cortex. Rather considerable populations of cortical cells are involved in the representation of a small area of the retina. Stimulus features determine which subgroup of that population are excited, unaffected, or inhibited. The activity of these populations is presumably sampled or integrated by the higher visual areas of the cortex to provide for the perception of complex forms. Generally, there is a process of increasing abstraction of the visual input along the neural pathway of the visual system. The abstraction must be independent of retinal position, size, brightness, and small distortions. It must take into account the recognition of shape independent of contrast, the ability to abstract outlines of filled shapes, and the ability to consider segments of a pattern separately. Virtually all tasks that might be termed "form discrimination" involve visual memory. For example, the recognition of a pattern as belonging to some previously learned class, or the discrimination between two patterns in learning tasks, both clearly involve interaction between visual input and memory.

Higher Level Processing • The visual information is processed along the visual pathway by neurons that have characteristic receptive fields. The information processing neurons of the retina, LGN, and layer IV of the visual cortex have receptive fields of circular shape. The receptive fields are like area elements, and the

neurons respond to point features such as spatial and temporal contrast. Simple, complex, and hypercomplex neurons of the cortex respond to line segments of specific orientation, length, width, and contrast. The receptive fields of these neurons are more complex in shape and structure than the receptive fields of the retina and LGN. In figure 5, the antagonistic structure is shown of the receptive fields of the visual system. At higher levels of visual processing, the neurons may respond to increasingly complex features that eventually will lead to the visual perception of the external world. The concept has not yet been confirmed by neurological research.

Three experiments are discussed that deal with the concept of trigger features and their perception. Thirty persons, including 20 adults and 10 children, participated in the experiments. Most of the adults were college graduates. Five of the children were older and five were younger than 10 years old.

In the first experiment, figures 6a through 6d were shown to all persons independently and at different times. Figures 7a through 7d were shown in the second experiment. In both experiments, each person was asked what he or she saw when looking at one of the figures. The answers in both experiments were divided into two categories, namely "yes, I recognize something" or "no, I recognize nothing." Concentric circles were recognized in the first experiment and a dog in the second. The results of the two experiments are shown in table 1.

In the third experiment, in which 22 people participated, a person was given a page to read. During the reading, the page was rotated until reading became impossible. Rotating the paper up to about 60° slowed down the reading only slightly. Between 70° and 90° , a marked slow down was observed. At approximately 100° to 110° , reading became impossible. However, one test person was able to read continuously without being noticeable affected as the page was turned one complete revolution (360°).

In all experiments, a feature (concentric circles, dog, or text) was changed until the test person was unable to recognize the feature. A random rotation of 30° destroyed the impression of concentric circles, a relocation of 30 percent of elements made the presentation of the dog unrecognizable, and a rotation of 110° made reading of the text impossible.

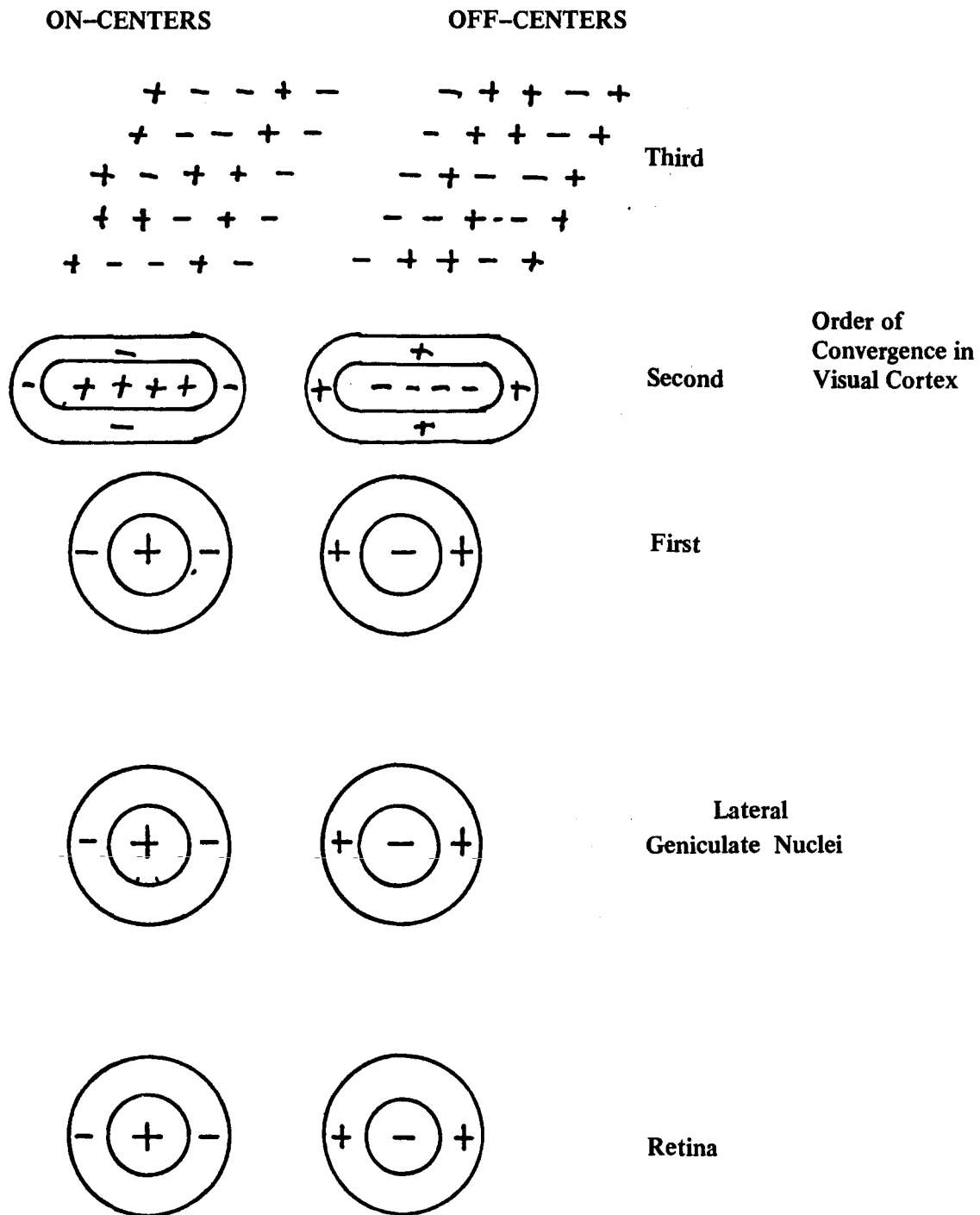
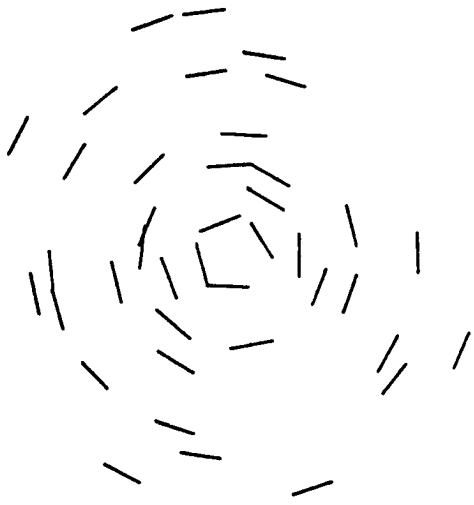
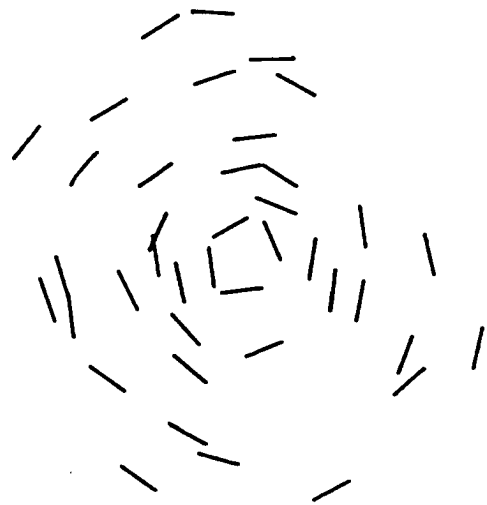


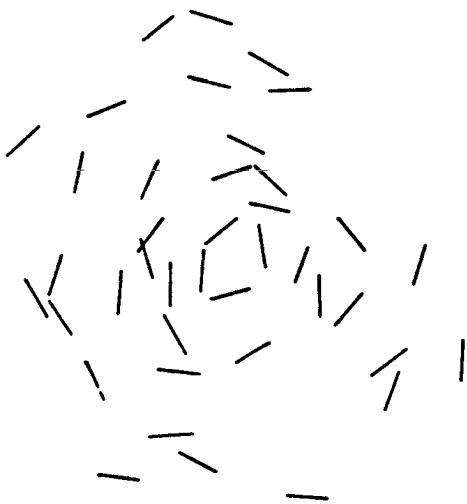
FIGURE 5. Antagonistic Field Structures in Visual System.



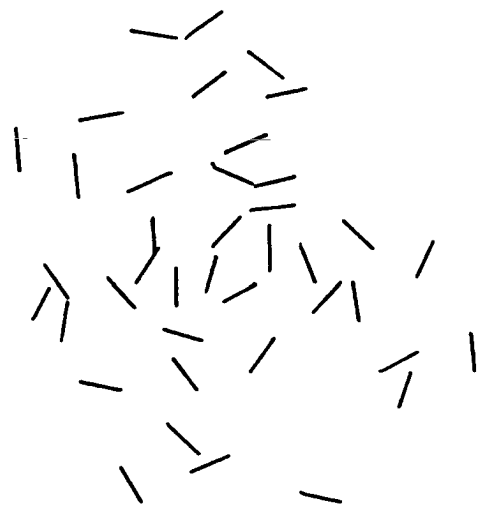
A. Segments of Tangents on Concentric Circles



B. Segments Rotated by $\pm 10^\circ$



C. Segments Rotated by $\pm 20^\circ$



D. Segments Rotated by $\pm 30^\circ$

FIGURE 6. Segments of Targets on Concentric Circles.



A.



B.



C.



D.

FIGURE 7. Gradual Distortion of an Image of a Dog.

TABLE 1. Perception Experiment

Experiment 1

Group Figure	A		B		C		D	
	Yes	No	Yes	No	Yes	No	Yes	No
6a	15		4	1	4	1	2	3
6b	11	4	2	3	1	4		5
6c		15		5		5		5
6d		15		5		5		5

Experiment 2

Group Figure	A		B		C		D	
	Yes	No	Yes	No	Yes	No	Yes	No
7a	15		5		5		5	
7b	15		5		5		5	
7c	7	8	1	4	3	2		5
7d		15		5		5		5

Note: A: Adults with college background.
 B: Adults without college background.
 C: Children above ten years of age.
 D: Children below ten years of age.

The columns show the number of yes and no answers.

The process of visual recognition is apparently analogous to the process of signal detection. Both in visual recognition and signal detection, there are thresholds beyond which the features cannot be recognized and the signals cannot be detected. The thresholds in both processes depend on the signal-to-noise ratio. A signal that has been corrupted by the transmission channel can still be detected by a matched filter. A visual feature that has been corrupted, as shown in the experiments, can still be recognized. There appears to be "feature detectors" at higher levels of visual information processing in the brain that show threshold behavior and that function like matched filters.

COMPARING THE VISUAL SYSTEM AND THE COMPUTER

Both the visual system and the computer have developed in an evolutionary manner. However, the driving force for each evolution has been quite different. The successful visual system has to solve problems, such as recognizing danger, food and cartographic features. The successful computer has to solve mathematical problems.

All computers consist of an input/output (IO) system, a central processing unit (CPU), and a memory. Large computers may contain several million components. The human visual system consists of a sensor system containing about 130 million individual sensors and three sets of information processors: retina, LGN, and visual cortex. These processors are connected by long nerve fibers. In a computer, information is processed at a high speed and serially. Typical processing times in computers, such as operating gates or shift-registers, are approximately 1 microsecond or less. The components of modern computers are highly reliable. Because of the serial computer architecture, the failure of one or few components may interrupt the entire computation process.

The information processing rate of the visual system is approximately tens of milliseconds, which is about 1,000 to 10,000 times slower than that of a computer. Also, the performance of neurons is less reliable than the performance of computer components. However, the deletion of quite a few neurons is unlikely to lead to any appreciable difference in performance of the visual system.

A computer operates on a short binary code. The visual system seems to rely on less precise methods of signaling, probably adjusting the number and efficiency of its synapses in a complex way to adapt its operation to experience. To execute a specific mathematical process, one must program the computer. The visual system does not depend on anything like a linear sequential program. Its architecture is more likely to be thousands of circuits primarily in parallel and richly interconnected. The visual system seems to rely on a strategy of relatively hard wired complex circuitry with elements working at low speed.

Human beings are rather unreliable and slow in executing accurately complex and long arithmetical calculations, which can be done by a computer in a small fraction of a second. Human beings, however, can recognize pattern in ways no contemporary computer has ever been programmed to do. To translate the intelligence of the human visual system into machine intelligence, one must be able to hybridize the predominantly parallel architecture of the visual system with the high speed serial architecture of computers. Relatively short serial circuitry operating on very high speed may offer trade-offs for large numbers of components in parallel circuitry.

TECHNICAL APPROACH TO VISUAL FEATURE EXTRACTION

The human visual system is capable of extracting and recognizing from its environment an enormous number of features, e.g. faces of human beings, animals, vegetation, houses, cartographic features on images, and so forth. Only about 100,000 to 150,000 photoreceptors of the central region of the retina are used for pattern recognition. This includes color vision.

Correspondingly, about 100,000 fibers of the optic nerve are involved in the transmission of feature information. Because of the highly distorted mapping of the retina onto the visual cortex (the central part of the retina has a representation about 35 times more detailed than the peripheral part), the number of neurons participating in the feature extraction process is estimated to be about 60 million. The number of cartographic features to be extracted from images is very small compared to the number of all visual features that the human visual system has to process. Thus, a visual system with the sole purpose of extracting cartographic features would require much less processing capability, say only a tenth of a percent of that of the human visual system.

A machine for automated cartographic feature extraction that is designed according to the architecture of the human visual system would require an estimated 100,000 components for information processing. There are essentially two types of imagery to be evaluated: photographic imagery having normally a width of 9 inches (229 mm), and radar imagery having normally a width of 2 inches (50 mm). The noise resolution of fine-grained film is about $1\text{ }\mu\text{m}$. To obtain a reasonable signal-to-noise ratio, one should integrate the sensor dimension over a linear distance that is about 10 times the noise distance.

There are now linear and area-sensing arrays on the market having linear resolutions of 15 to $100\text{ }\mu\text{m}$. For example, there are sensing arrays with about 1700 sensor elements arranged over 1 inch (25 mm) length or arrays with 1024 elements arranged in a square of 3.2 mm side length. At 40 MHz, the content of these two types of arrays can be transferred to a temporary memory in 25 or 42 microseconds, respectively. Sensing arrays can be arranged in bar-shaped windows across the image-carrying film. A calculation has shown that it is possible to move the film with a speed of about 1 inch per second over the window containing the arrays. The film could be illuminated homogeneously by a strobe light. Strobe light, speed of film transport, and information transfer can be synchronized by a high precision clock, e.g. a rubidium clock. The information content of the sensing arrays can be transferred into a set of tapped delay lines that represent the area of the window. The information contained in the first set of delay lines can be further processed for texture and statistics, and developed for contrast and contours. The contours can be encoded in terms of their normalized curvatures, which are invariant to size, location, and orientation. The coded signals developed in this way have to be processed into signals that represent trigger features of specific cartographic features. Once unique signatures of cartographic features in terms of coded trigger feature are developed, a reference memory of these codes can be designed, and incoming signals can be correlated against them for recognition.

Another approach to feature extraction is to derive characteristic signal signatures of features using functional transforms, statistical and texture analysis, and other analytical methods. The signal signatures derived from a feature must be measurable and represent the components of a feature vector that is uniquely associated to the feature. The recognition can then be accomplished by an autocorrelation with a replica of the feature vector or by a response of a specially designed matched filter. For each feature, a special recognition strategy has to be developed that will include a mix of the various operations.

An automated visual feature extractor may conceptually consist of a sensor unit, an information distribution unit, a central processing and recognition unit, and an output unit. The sensor unit may include various types of sensing arrays and “smart sensors,” which will perform screening and initial classification. The information distribution unit will include a temporary memory and a transmission network to conduct the signal. The central processing and recognition unit may consist of a number of parallel channels. Each channel is dedicated to extracting a single feature and includes the necessary signal processing and recognition circuitry. The output unit will provide the feature extraction information in a format as required by the user. The channels are arranged essentially in a parallel architecture. This architecture enables the extractor to grow organically from few channels to many channels as extraction and recognition methods are developed.

CONCLUSIONS

It is concluded that

1. The success of the visual system is due to its architecture, which prefers parallel processing.
2. The optical image is transformed by the visual system into a spatial and temporal pattern of neural signals.
3. The neural signals are processed progressively to trigger the feature of increasing abstraction.
4. The trigger features of specific visual features, represented by spatial and temporal patterns of neural signals, interact with the visual memory.
5. The visual memory of human beings is expanded during a lifetime by experience and visual learning.
6. The architecture of contemporary computers is not suited for automated feature extraction.

7. Development trends for Vary Large Scale Integration (VLSI) electronic circuitry, temporary memories (RAM, ROM), micro-processors, and sensing devices indicate that components for automated feature extraction systems will be available in the future.
8. The first step towards automated feature extraction is an in-depth analysis of the individual feature and the derivation of measurable, unique parameters, such as feature codes or feature vectors that determine the feature unambiguously.
9. A machine feature extractor has to employ a predominantly parallel processing architecture in order to be efficient.

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