

MEMORY: THE GIFT OF THE MUSES' MOTHER

by

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## PART I: INTRODUCTION

The brain has been the impetus of a tremendous amount of research in the last three decades. Workers in numerous disciplines have attempted to describe mental phenomena, and they have produced a sizable literature on the subject. Three major approaches of these workers to the study of the nervous system are (1) Neurophysiology and neuroanatomy, (2) Pure psychology, and (3) Cybernetics. Of these three approaches, workers in the first two serve primarily to obtain information, while cyberneticists endeavor to utilize this information in an effective manner. F. H. George describes the aims of cybernetics as

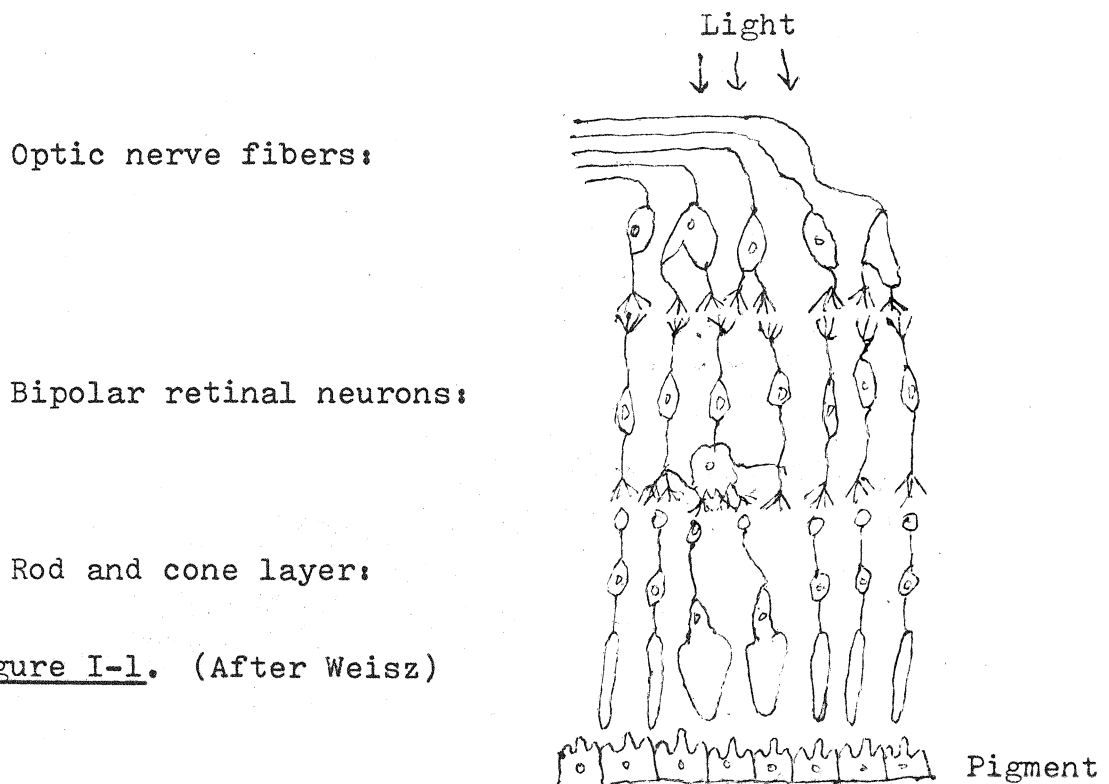
- (1) To construct an effective theory, with or without actual hardware models, such that the principal functions of the human organism can be realized;
- (2) To produce the models and theory in a manner that realizes the functions of human behavior by the same logical means as in human beings. This implies the simulation of human operations by machines, whether in hardware or with pencil and paper; and,
- (3) To produce models which are constructed from the same colloidal chemical fabrics as are used in human beings, (George, 1961).

The present study remains within the realm of the first two of these cybernetic goals. More specifically, a holographic theory of memory is constructed which functions in such a manner as to closely resemble that of the mammalian system, and this theory is realized by computer simulation.

## PART II: VISUAL INFORMATION PROCESSING IN THE NERVOUS SYSTEM

In general, information is processed by means of three main divisions of the nervous system. The peripheral nervous system (PNS) is responsible for transducing sensory stimuli and conveying its information content to the next and most important part, the central nervous system (CNS). The CNS further organizes and analyzes the information it receives, and determines some response on the part of the organism. This action involves a motor response on the part of the PNS and may elicit activity in the autonomic nervous system (ANS), the third part of the nervous system. The ANS handles involuntary nervous functions, including unconditioned reflexes, visceral responses, etc. Of utmost concern, however, is that part of the nervous system involved in visual information processing.

Visual information is available to the CNS in the form of light and is encoded by the retina (Figure I-1).



It should be noted that by observing the anatomical relations of input to the striate cortex, it can be deduced that the cortical representation of the perceptual experience is a coded abstraction of the retinal image, (Kolers, 1968). The method of information processing is probably not a passive thing, but, as Wertheimer suggests, an active organization of stimuli, (Wertheimer, 1912). The receptors, rods, and cones transduce visual stimuli into a form usable by the bipolar cells. These cells synapse on retinal ganglion cells which form the optic nerve. There are approximately 125 million primary receptors in the retina, and of these about 100,000 are to be found in the macula or fovea (Figure I-2).

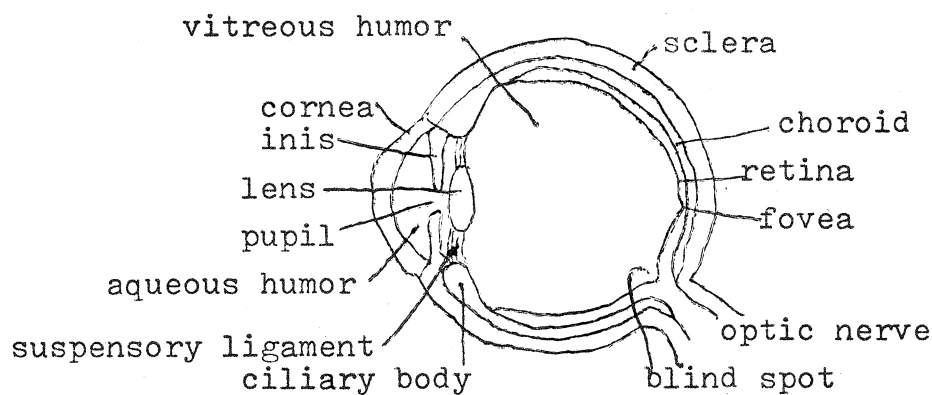


Figure I-2.

Amazingly enough, of the one million nerve fibers which carry information from the retina to the brain, 100,000 are allocated to the 100,000 receptors in the fovea and the remaining 900,000 are mapped onto the other 124,000,000 retinal fibers. Thus, some information coding or analysis has already been achieved



by the time the visual information reaches the optic nerve. This information is then separated as to its relation to the visual field. At the optic chiasma, a crossover of information occurs which sends all information from the left visual field to the right hemisphere of the brain, and vice-versa for the right visual field. (Figure I-3), that is, a decussation takes place.

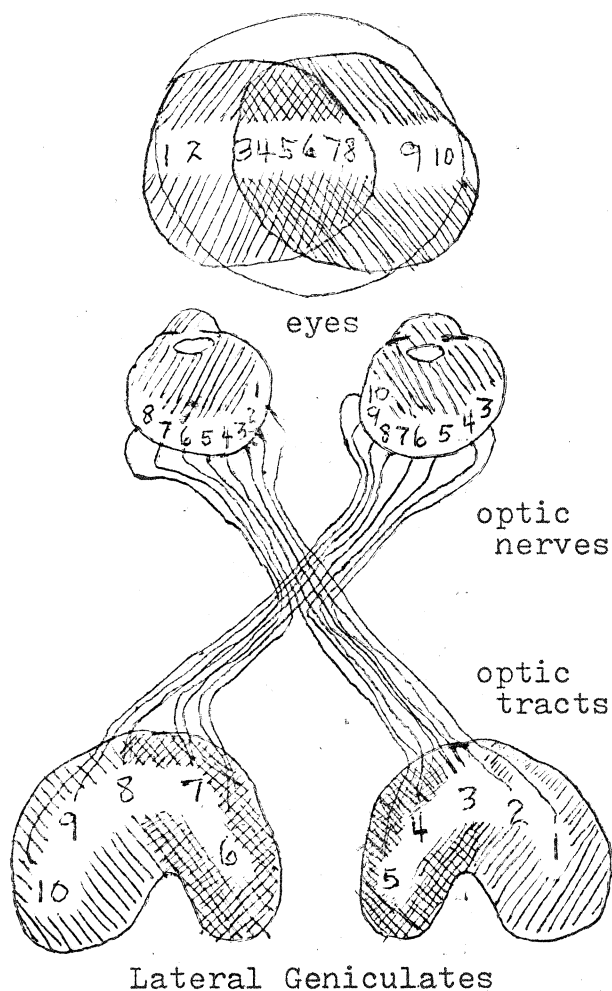


Figure I-3. (After Krieg)

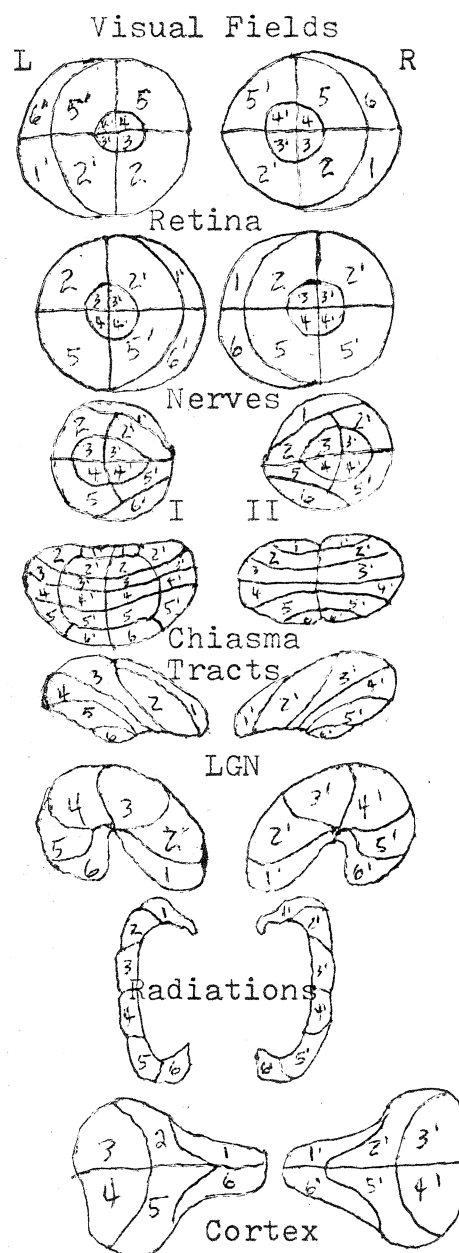


Figure I-4. (After Krieg)

The information is then conveyed as neural impulses to the thalamus where the optic tracts terminate in the lateral geniculate nucleus. From there fibers project to the striate cortex (Area 17) which in turn sends projections to Area 18 and Area 19. The visual field is conformally mapped to Area 17, as all sensory modalities are mapped to their respective cortical areas (Figure I-4). Both ablation and microelectrode studies have substantiated that such conformal mapping occurs from the retina to the cortex. Moreover, it has been shown that receptive fields, areas located on the retina which when stimulated either excite or inhibit a visual cell, exist at each level, traversed by the visual impulses. Ganglion and lateral geniculate cells are particularly responsive to circular spots of light which completely fill the center of a donut-shaped receptive area on the retina. In contrast to that, cells in the striate cortex respond to patterns having linear properties. In addition, cortical cells respond to a stimulus presented to both eyes, while geniculate cells are stimulated by excitation of one eye only. More complex visual patterns elicit responses from Areas 18 and 19. These cells are arranged in vertical columns as is Area 17, (Handler, 1970). Essentially, the cortex is a sheet-like structure consisting of six differentiable layers of cells through which information moves in a vertical direction. This arrangement of the cortex is extremely uniform throughout the brain. It is this property upon which Kabrisky bases his visual information processing model, (Kabrisky, 1966).

Kabrisky postulates that some sort of cross-correlation takes place in the cortex. In general, the retina receives a two-dimensional

array of intensities which is mapped conformally to the cortex where it is correlated with another two-dimensional array. This second two-dimensional array is equivalent to a short-term memory against which the first is contrasted. A cross-correlation is a function of the form:

$$\varphi_{12} = \int_{-\infty}^{\infty} f_1(t) f_2^*(t+\tau) dt. \quad (1)$$

In this case the cross-correlation evaluates two functions describing planar regions and determines the amount of similarity of shape between the two regions (Figure I-5).

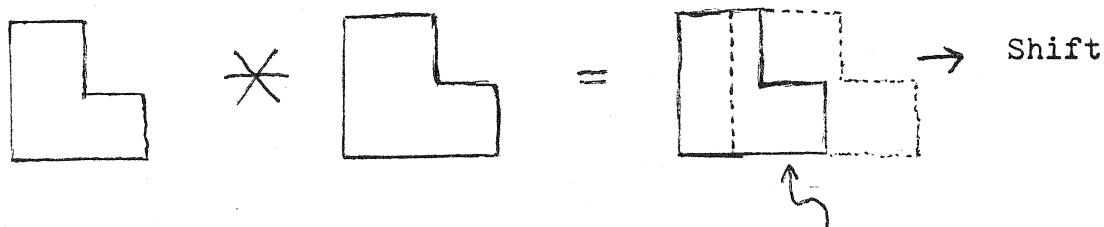


Figure I-5. Cross-correlation Function. Integrate where \* represents the cross-correlation function, and  $\square = f_1$  and  $\square = f_2$ . In this case it so happens that  $f_1 = f_2$  and so \* is an auto-correlation.

Pattern recognition is achieved through a determination made point to point between the input and the memory. For an auto-correlation, one between a figure and itself, the value of  $\varphi_{11}$  achieves a maximum in the general case. However, Kabrisky has redefined the product under the integral to be the absolute value of the difference of the functions  $f_1$  and  $f_2$ , thus yielding a value of zero for an auto-correlation. It is possible to describe the situation formally. A figure,  $A(uv)$ , in the plane is such that its internal points maintain a constant relation to one another. This can be used to determine if the relative nature of another figure is the same by:

$$A(uv) = \frac{1}{ab} \int_0^a \int_0^b p(x,y)p'(xu,yv)dx dy \quad (2)$$

where  $p$  and  $p'$  are functions expressing some central feature of  $A$  and the other figure respectively, as the magnitude of some property of  $x$  and  $y$  in the figure, (McLachlan, 1965).

The physiological basis for the model is found in the previously mentioned plane-like layered structure of the cortex and vertical flow of information. Kabrisky claims that the hierarchical arrangement of the six cortical layers facilitates cross-correlation by allowing a compacting of neighborhood influence. That is, at successive levels some sort of summation of neighboring neural stimuli occurs. This, coupled with the fact that projections from Area 17 to Area 18 are many to one, could allow a comparison of these computed neighborhood values with a memory. It is at this point that Kabrisky postulates a "basic computational element" which correlates the memory to the input at every point and computes an error function,  $Q$ . The errors,  $q_i$ , at individual points are summed to  $Q$  for the entire array, and if the value is lower than some pre-established threshold, then the two patterns are considered functionally to be the same, and the input array is considered to be recognized (Figure I-6).

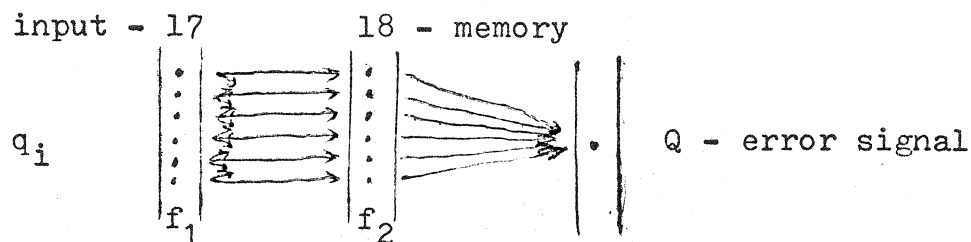


Figure I-6. One-dimensional cross-correlation input in Area 17 is compared to memory in Area 18 and summed to error signal  $Q$ .

The memory array is initially set to zero and changes values as a direct result of the input. This input is defined for a single b.c.e. to be  $P(\alpha)$ , where  $\alpha$  designates the coordinates. Physiologically,  $P$  could be represented by a coded pulse rate which indicates a measure of the light intensities arising in the visual field. An output  $X(\alpha)$  from each of the b.c.e.'s is produced and  $X(\alpha)$  is a function of previous inputs, and  $SF(\alpha)$ , internal storage:

$$X(\alpha) = F_{\alpha} [P(\alpha), SF(\alpha)] \quad (3)$$

where  $F_{\alpha}$  is a computation dependent on  $P$  and  $SF$ . Thus, the output at time  $t_i$  is

$$X(\alpha, t_i) = F_{\alpha} [P(\alpha, t_i), SF(\alpha, t_i)] \quad (4)$$

Now the internal storage at time  $t_i$  is dependent on the internal storage and the input at each earlier time, or:

$$SF(\alpha, t_i) = G_{\alpha} [SF(\alpha, t_{i-1}), SF(\alpha, t_{i-2}) \dots P(\alpha, t_{i-1}), P(\alpha, t_{i-2}) \dots] \quad (5)$$

where  $G_{\alpha}$  is the computation of  $SF$ . There also exists a slow storage,  $SS$ , which is a function of the internal storage at all earlier times:

$$SS(\alpha, t_i) = H_{\alpha} [SF(\alpha, t_i), SF(\alpha, t_{i-1}) \dots] \quad (6)$$

This implies, however, that the internal storage at each  $t_i$  is dependent on  $SS$ , also:

$$SF(\alpha, t_i) = G_{\alpha} [SF(\alpha, t_{i-1}) \dots, SS(\alpha, t_{i-1}) \dots P(\alpha, t_{i-1}) \dots] \quad (7)$$

Then we see that the output of each b.c.e. at time  $t_i$  is:

$$X(\alpha, t_i) = F_{\alpha} [P(\alpha, t_i), SF(\alpha, t_i), SS(\alpha, t_i)] \quad (8)$$

Neighborhood influence on the input to each b.c.e. is computed by:

$$\text{Input} = \gamma_0 P(J, K) + \gamma_1 P(J, K-1) + \gamma_2 P(J, K+1) + \gamma_3 P(J-1, K) + \gamma_4 P(J+1, K) \quad (9)$$

where  $\gamma_i$  is a weighting factor. (For example, if  $\gamma_1 = \gamma_2 = 0$ , and  $\gamma_3 = \gamma_4 = .4$ , then an emphasis is placed on the vertical influence of b.c.e.  $(J, K)$ 's neighbors.) Therefore, (7) becomes:

$$\begin{aligned}
SF(\alpha, t_i) = G_\alpha [ & SF(\alpha, t_{i-1}) \dots \\
& \delta_1 SF((J, K-1), t_{i-1}) \dots \\
& \vdots \\
& \delta_4 SF((J-1, K), t_{i-1}) \dots \\
& SS(\alpha, t_{i-1}) \dots \\
& \beta_1 SS((J, K-1), t_{i-1}) \dots \\
& \vdots \\
& \beta_4 SS((J-1, K), t_{i-1}) \dots \\
& P(\alpha, t_{i-1}) \dots \\
& \gamma_1 P((J, K-1), t_{i-1}) \dots \\
& \vdots \\
& \gamma_4 P((J-1, K), t_{i-1}) \dots \quad (10)
\end{aligned}$$

Thus (6) becomes:

$$SS(J, K, t_i) = H_{J, K} [SF(J, K, t_i), SF(J, K, t_{i-1}) \dots] \quad (11)$$

which changes (8) to:

$$X(J, K, t_i) = F_{J, K} \{ [b.c.e. \text{ input}], SF(J, K, t_i), SS(J, K, t_i) \}. \quad (12)$$

Then, in Figure I-6

$$\text{Input}_{\textcircled{1}} = P(i), i=1, \dots, n \quad (13)$$

in the linear case, and

$$\text{Input}_{\textcircled{2}} = F_{\textcircled{1}}[P(i)] \quad (14), \text{ and } \text{Output}_{\textcircled{2}} = F_2\{F_{\textcircled{1}}[P(i)]\} \quad (15),$$

finally yielding

$$\begin{aligned}
\text{Input } q_i &= \sum_{i=1}^n F_{\textcircled{2}}\{F_{\textcircled{1}}[P(i)]\} \\
&= \int_x F_{\textcircled{2}}\{F_{\textcircled{1}}[P(x)]\} dx. \quad (16)
\end{aligned}$$

For two dimensions,

$$\begin{aligned}
\text{Input } q_i &= \int_x \int_y F_{\textcircled{2}}\{F_{\textcircled{1}}[P(x, y)]\} dx dy \\
&= \int_x \int_y F_{\textcircled{2}}(x, y) \circ F_{\textcircled{1}}(x, y) dx dy, \quad (17)
\end{aligned}$$

which is the cross-correlation function with no translation.

Kabrisky finds it more useful to define this operation  $\circ$  as the magnitude of the difference of two functions:

$$\text{Input } q_i = \int_x \int_y |F_2(x,y) - F_1(x,y)| dx dy. \quad (18)$$

In (18) the value of  $q_i$  goes to zero as the two functions approach similarity. A means of automatically computing the complete cross-correlation function,

$$\text{Input } q(\lambda, \gamma) = \int_x \int_y F_2 \{ \xi F_1 [P(x-\lambda, y-\gamma)] \} dx dy, \quad (19)$$

where  $\xi$  is a scaling factor, is proposed by Kabrisky to lie in the many to one connections of Area 17 to Area 18. Thus, Kabrisky presents a pattern recognition model which suits the properties of the b.c.e.'s computations as given in equations 10-12; by (19) is possible the two-dimensional cross-correlation function. The model includes a recognition process, and it demonstrates some of the aspects of memory.

This model was extended and greatly modified in order to adapt it to a discrimination task. Not only was the program called upon to recognize two patterns, but it was to also learn to discriminate between the two. The two patterns were presented in the program as two sixteen by sixteen input arrays. These differ significantly in that the positively reinforced one has horizontal rows of non-zero input, and the negatively reinforced one has vertical rows (Appendix 1). A trial consists of the presentation of the two input arrays and the consequent experience of one or the other. The two are considered to be aligned horizontally, one left and one right. After every second trial, the patterns are switched, resulting in a new stimulus situation for the program. The program randomly takes a look at one or the other of the input arrays. Immediately following this choice of a direction to look, a number of tests are made (Figure I-7).

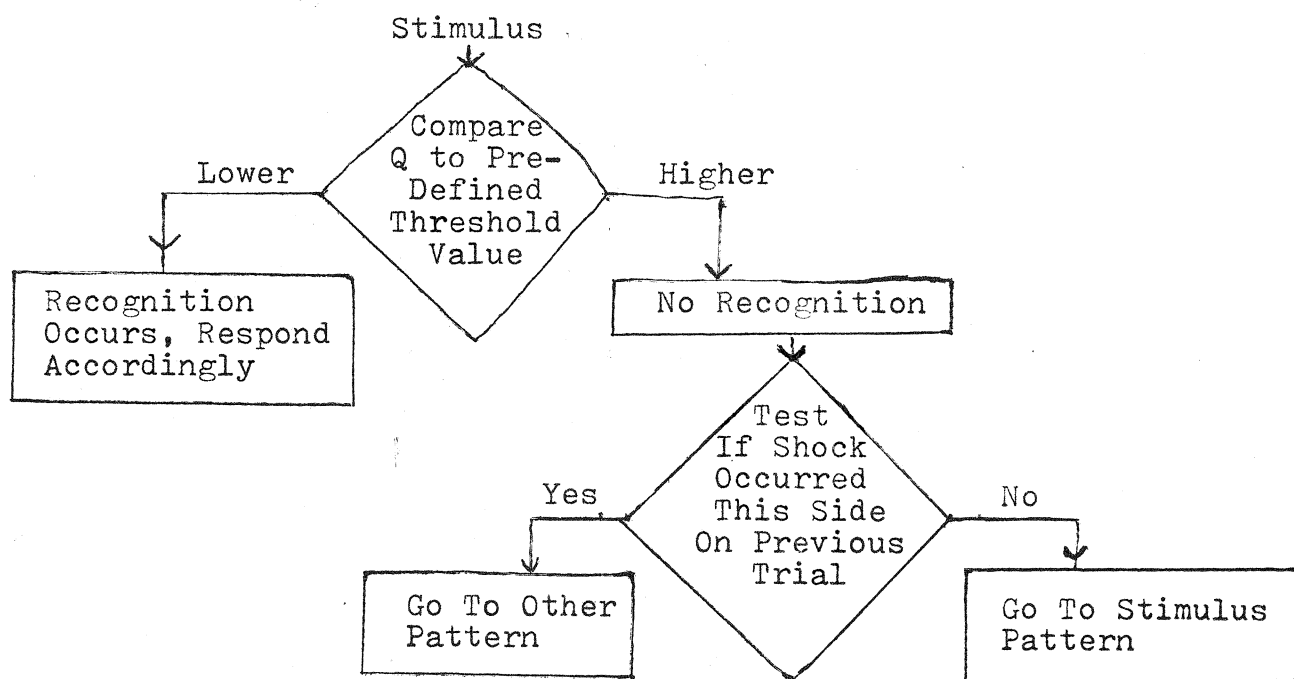


Figure I-7.

First,  $Q$  is compared to a previously defined threshold value. When  $Q$  falls below this value, a prewired response takes place (i.e., the vertical pattern is avoided). Since  $Q$  will not have a value until one or the other pattern is experienced (it is dependent on  $P$ , the input pattern), it is initialized to a value higher than the threshold value in order to make the first trial workable. If after  $Q$  is tested no recognition occurs, then the program is to determine if it received a shock on the previous trial, and if so, whether or not it occurred on the side presently being looked at. If no such shock occurred, then the choice is made to experience this input pattern. The other pattern is chosen if a shock did occur. This is the last test to determine which pattern to experience, and there are two separate memory arrays for accumulating an experiential memory of the two separate patterns. A new value is then calculated for the respective  $Q$  as



to whether a horizontal or vertical pattern was experienced, and a shock is recorded as to which side it occurred on. A distinct  $Q$  exists for each pattern, and is calculated by (18), where  $F_2$  is SS and  $F_1$  is  $P$ .

The program is prewired in that although the two input arrays must be memorized, the response is written into the program, and the program is in no way responsible for the choice of what to do, but only to do it once the input is recognized. While using the ideas of shock, looking, avoidance, etc., it must be remembered that these things derive their significance from their meanings outside of the program, and these meanings are carried naively into the discussion. It is possible to formally establish their meanings in the program, but this would not be very productive. Therefore, these terms are not as quantitative as they could be, but their meanings are generally clear from the context in which they are used.

This model can be said to learn then only in a limited sense of the word. The program already knows what to do for this class of problems and requires merely to see the input enough times in order to develop the ability to respond correctly. Why choose such a model? First, with one such as this, the parameters of learning and memory can be fairly well specified; the model is not so complex as to confuse the issue when the long-term memory process is introduced. Second, the model is functionally defined neurophysiologically, although the arguments for such a scheme are necessary but not sufficient. Third, the model provides a means of obtaining explicit values for the information being handled.

The method of learning is still dependent on the modification of arrays, which is necessary and offers a place from which to expand to a holographic memory method. Thus, the various aspects of the simulation of short-term memory information processing may be summarized as follows.

Environmental information is supplied to the program through the input of horizontal and vertical arrays. These are switched from left to right after every second trial. If they were not switched, the program would make only one mistake as would be expected in a normal learning situation.

The information is transformed into a usable form in the next part of the program. The learning is explicit, but altered circumstances can be handled to a certain extent. If, for example, the cards were not switched for a number of trials and then normal switching resumed, the program would accordingly make only one mistake until the cards were switched and then proceed to "learn" the pattern discrimination. During training the learning curve closely approximates that of experimental animals. The memory here is not long-term, however, and any new input modifies old memory values. Thus, only learning for particular sets of inputs occurs.

The means of response is established a priori in the program. An input pattern is chosen, and the corresponding array values affect the memory array associated with the input. The horizontal array is not experienced every trial, even though in actual learning experiments it is.

The knowledge of the results of a response is implicit in

whichever is experienced (i.e., a shock automatically results from experiencing the vertical array). This means that the program is set to avoid a position unless recognition of the input occurs.

This model has several disadvantages, but for the purposes of this study, they were too minor to have a deleterious affect. Namely, both the horizontal and vertical patterns were utilized in learning, where it would probably be more accurate if only the vertical affected the memory. Also, the general method of determining a storage location for different sets of learned patterns was predetermined by cue names related to the input. However, these things were not overriding factors, and a more satisfactory study which would eliminate these objections will be discussed in the next section.

### PART III: HOLOGRAPHIC MEMORY PROCESSES AND THE VISUAL SYSTEM

In order to better understand how a holographic memory mechanism could work in the brain, the neurophysiological data of the visual memory system has to be considered. Although it has been postulated that the memory may operate by spreading individual memories over a significant portion of the brain, it has been shown that a visual memory system may be localized, at least as far as the white rat is concerned, (Thompson, 1969). In that study it was concluded that the "occipital cortex, posterior diencephalon, and ventral mesencephalon comprise the core of a neural system mediating storage, retrieval, and utilization of all visual engrams formed in the albino rat."

This corresponds well to the centrencephalic theory proposed by Penfield, (Penfield, 1954), which maintains that subcortical processes play an equally important role in the memory system as cortical processes. That is, there exist structures in the brain stem which mediate learning experience. Penfield based his centrencephalic system on clinical observations, but neuroanatomical results as well as animal studies support his proposal as has been pointed out by Thompson, (Thompson, 1965). Further evidence for this theory was provided in a study by Thompson and co-workers, (Thompson, et al, 1966), which tested the possibility that visual discriminative tasks are mediated by a pathway between the occipital cortex and the ventral mesencephalon which includes the pretecto-diencephalic area and showed that such a centrencephalic process may function in the visual memory system. More importantly, this study also showed that the nucleus posterior thalami, a

critical nucleus in the pretecto-diencephalic area for visual behavior responses, did not, upon lesioning, seriously affect a kinesthetic discrimination habit. The kinesthetic problem serves as a standard to point out areas primarily useful to visual discriminations. As far as the present study is concerned, the visual memory system discussed will refer primarily to that of the white rat and will be assumed to consist of the occipital cortex, posterior diencephalon, and ventral mesencephalon.

Visual information will be assumed to proceed in the following fashion: from Area 17, fibers project to the ventral lateral geniculate nucleus which in turn has pathways through the nucleus posterior and on to the red nucleus (Figure III-1). Thus, areas involved other than those specified by Kabrisky include the substantia nigra, red nucleus, and the interpedunculo central tegmental area (Figure III-2). It is possible that portions of the brain stem reticular formation may be involved in memory and learning, (Thompson & Henderson, 1971), but as these areas do not seem specific to visual memory but rather to learning in general, they will not be included in the proposed visual memory system. It has been shown not only that the lesion locus rather than lesion size is of greater importance in disrupting visual behavioral responses, but also that the size of the lesion at a particular locus is directly related to the retention deficit, (Thompson, 1969). Thompson goes on to hypothesize two sets of engrams, one dealing specifically with the visual stimuli and actions related to it and another concerned with the elimination of "error-producing" responses. It is possible that the first

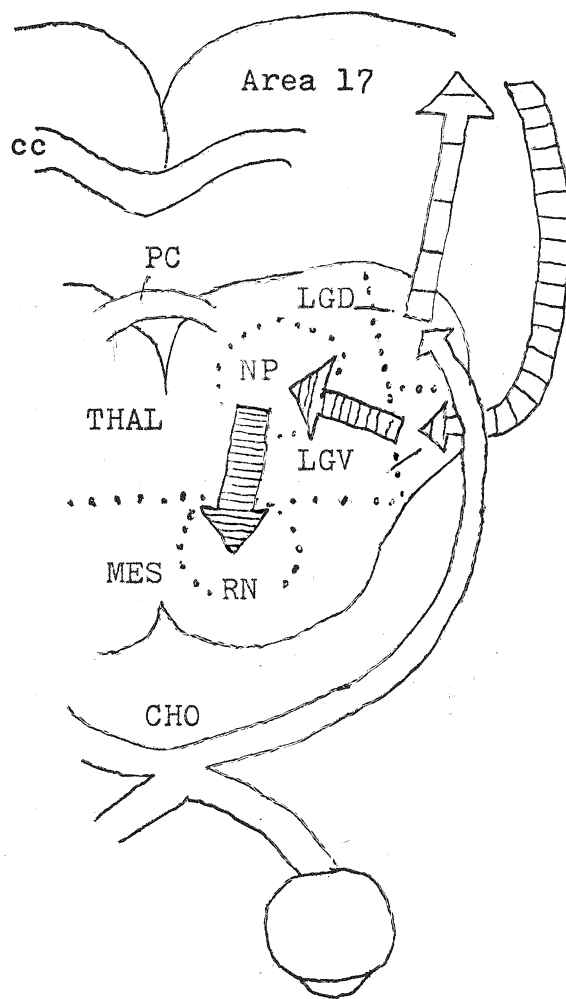


Figure III-1. Structures involved in visual information system. (cc-corporis callosum; CHO-optic chiasma; LSD-dorsal lateral geniculate nucleus; LGV-ventral lateral geniculate nucleus; MES-mesencephalon; NP-nucleus posterior; RN-red nucleus; THAL-thalamus.)

( From Thompson )

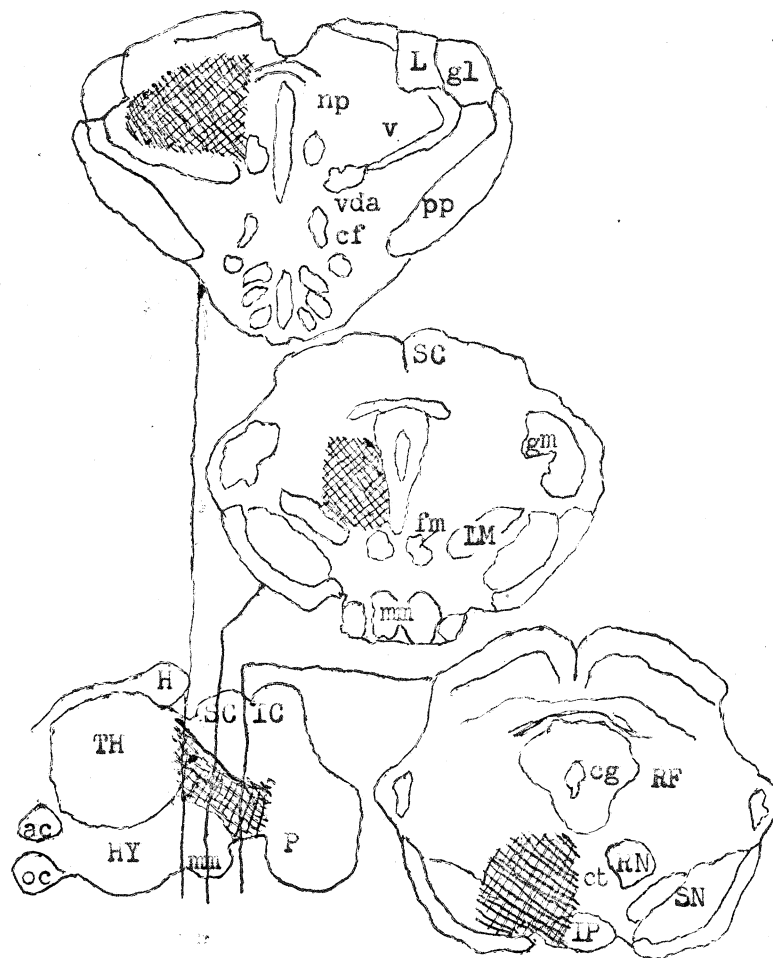


Fig. III-2. Subcortical areas important for visual information processing. ( ac-anterior commissure; cf-column of fornix; cg-central gray; ct-central tegmentum; fm-habenulo-peduncular tract; gl-lateral geniculate nucleus; H-habenula; HY-hypothalamus; IC-inferior colliculus; IP-interpeduncular nucleus; gm-medial geniculate nucleus; L-lateral posterior thalamic nucleus; LM-medial lemniscus; mm-mammillary bodies; np-nucleus posterior; oc-optic chiasma; P-pons; pp-cerebral peduncle; RF-reticular formation; RN-red nucleus; SC-superior colliculus; SN-substantia nigra; TH-thalamus; V-ventral thalamic nucleus; vda-mamillo-thalamic tract.)

could be stored in any combination of the striate cortex, the posterior thalamus, and the ventral mid-brain while it is probable that the second would be located in the ventral midbrain alone, (Thompson, 1969)..

Also of relevance to a holographic memory model based on the visual memory system outlined above are the results of a study which investigated the effects of knife-cuts horizontally and longitudinally through the various structures of the system, (Thompson, et al, 1970). Besides the neuroanatomical data suggested by the work (that is, the existence of an occipitogeniculo-posterior thalamo-rubral pathway), the fact that longitudinal cuts through the central tegmentum, horizontal cuts through the red nucleus, and transverse cuts through the midline tegmental, postrubral, and rubral regions produce significant loss of visual discrimination habits implicates the importance of these areas in the holographic memory model.

The neurophysiological data given above provides an ample basis for theories of memory and learning. Of particular importance, however, are those theories addressing themselves to an associational method of memory. Perhaps the first to approach the problem this way was Lashley. He argues that a memory trace engram could not be demonstrated to be in an isolated locale. He maintained that limited regions are necessary for learning and memory of specific events, but that within these regions, the parts are functionally the same. Each association was assumed to be dependent on time and space, (George, 1961). The cortex was viewed by Lashley as being a set of resonators, and on the



topic of the neuron's relation to memory, he proposed:

The equivalence of different regions of the cortex for retention of memories points to multiple representation. Somehow, equivalent traces are established throughout the functional area. Analysis of the sensory and motor aspects of habits shows that they are reducible among components which have no constant position with respect to structural elements. This means, I believe, that within a functional area the cells throughout the area acquire the capacity to react in certain definite patterns which may have any distribution within the area. I have elsewhere proposed a possible mechanism to account for this multiple representation. Briefly, the characteristics of the nervous network are such that, when it is subjected to any pattern of excitation, it may develop a pattern of activity, reduplicated throughout an entire functional area by spread of excitations, much as the surface of a liquid develops an interference pattern of spreading waves when it is disturbed at several points, (Lashley, 1942).

This early work by Lashley was followed shortly by the McCulloch-Pitts paper which described brain action in terms of "neural nets" and proposed a logical calculus for these nets, (McCulloch & Pitts, 1943). Von Foerster has adequately and succinctly characterized the nature of neural nets:

- (i) There exist parallel networks without loops that are known to compute invariants (abstracts) in a set of stimulus configurations.
- (ii) Cascades of such parallel networks are known to compute abstracts of ascending order of generality.
- (iii) Nets with loops, once excited, may continue their activity around these loops and, under certain conditions may maintain reference to the past for an indefinite period of time.
- (iv) Nets with loops are equivalently represented by indefinite temporal cascades of virtually parallel networks without loops.
- (v) From (ii) and (iv), networks with loops may in time compute abstracts of ascending order of generality.
- (vi) Linear networks with loops, once excited, will continue their activity around these loops, however, eventually without reference to the past whatsoever, save for the fact of having once been excited.

- (vii) No such decay occurs, if linear superpositions are replaced by superpositions defined in non-linear algebraic systems.
- (viii) Reference to algebra only, without specifications of function, suffices to show the possible decomposition of present activity into representations of elements belonging to the remote past, (von Foerster, 1968).

This idea of neural nets has been popular for some time and has had numerous supporters. Beurle maintained that memory could be attributed to neural nets with the following properties:

- (1) They are connected in a non-specific manner which can be described statistically;
- (2) Excited parts can activate unexcited ones by means of immediate connections;
- (3) Summation of excitation occurs over some time interval;
- (4) Once the threshold value of a unit of the net is exceeded, the unit is activated; and
- (5) A brief refractory period followed the firing of each unit, (Beurle, 1954).

Beurle also proposed an associative memory process expressed in terms of these neural nets, (Beurle, 1956). He described the flow of information through the nets as planar waves of activity. He believed that the interaction between the waves and the totality of the net forms the basis of a more complex mechanism. He tried to show that large masses of randomly distributed neurons may support certain relatively simple, well-defined forms of activity: in particular, plane waves and other types such as spherical or cylindrical waves, circular waves, and circular effects. The description of modification of the medium-storage of information and the regeneration of waves is closely correlated to the methodology of holography (Figure III-3). Two waves,  $w_A$  and  $w_B$ , result from the association of two activities, A and B. The occurrence of these two waves travelling together through the net

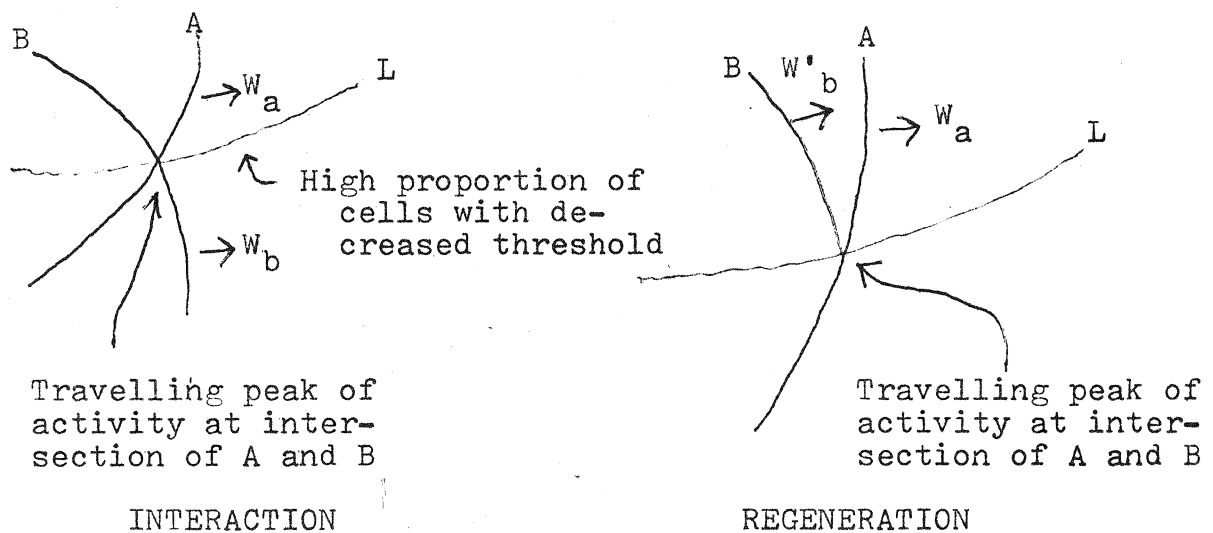


Figure III-3. Beurle's Hypothesis.

tends to modify thresholds of units of the net so that when A alone occurs later, it is sufficient to regenerate  $W'_B$  which in turn results in the activity B. In this case it is clear that  $W_A$  acts as a reference through the net to reconstruct B. In a later study, Beurle reconsidered his model and provided a means of stabilization controlling the activity in the net, and he described the close interrelationship of short-term and long-term memory, (Beurle, 1962).

Other workers in the area of neural nets developed the theory of interaction of nets, threshold logic, pattern recognition by nets, etc. Rosenblatt developed the "Perceptron" which is a self-organizing net capable of handling pattern recognition problems, (Rosenblatt, 19 ). This aspect of neural nets has been extensively explored by Minsky, (Minsky & Papert, 1969). Minsky and Selfridge have also attempted to show the limiting parameters of neural nets and claim that owing to the ability of more advanced forms of learning to discover and use new categories, neural nets with random organization are not capable of complex learning,

(Minsky & Selfridge, 1960). Associative models of memory have been proposed which do not attempt to formally establish the ability of neural nets to perform as models of formalistic logic or to conform to probabilistic or statistical theory. Blum concludes:

A new class of machine is proposed which differs in its basic concept from the present mathematical machines and logical nets. Its basic concept uses a time-domain signal propagation to memory and gets from this a very powerful primitive associative mechanism. The force of such a time memory, even for spatial inputs, has also been shown. It presents an existence theorem (by presenting one example) showing the inadequacy of our present theoretical foundations of cognitive and associative machines, (Blum, 1962).

However, it must be noted that Blum bases this mechanism on wave propagation with emphasis on an association space which handles the information provided by a neurospace. This neurospace depends on neural net actions to produce its output. Another proposed associative memory which basically differs from a straightforward neural net type is a semantically associative memory, (Boydell, 1962). This memory operates on a weighting function between different nodes in the memory and accounts for various phenomena such as the "chain of associations," time-sharing of mental tasks, and free-running cycles of thought; the latter occur in sensory deprivation experiments.

If neural nets are to serve as the basis for a theory of the memory mechanism, then it is important to consider the underlying physical phenomena which provide modification of the nets during learning. Evidence points to a biochemical process of synaptic alteration for memory and learning. Conceptually, this model of

memory involves a chain of interrelated events. (Figure III-4).

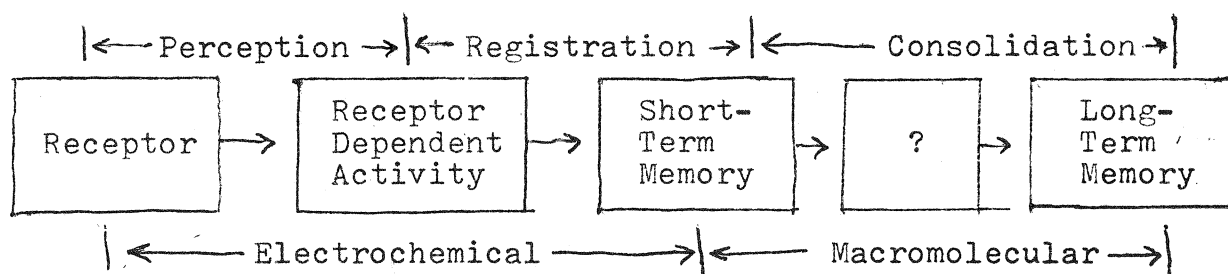


Figure III-4. (After W. L. Byrne) Consolidation and macromolecular memory.

- A. Physical changes (e.g., conformation)
- B. Chemical changes (e.g., new molecules)

1. DNA
2. RNA
3. Protein
4. Lipid
5. Glycoprotein
6. Glycolipid

Molecular basis of memory requires that long-term memory be the result of synaptic modification, that this be the consequence of the synthesis of new molecules, and that the CNS be predominantly prewired, (Byrne, 1970). The entire process of the consolidation and maintenance of a long-term memory is described in Figure III-5, (Halstead & Rucker, 1971). The sensory input is received

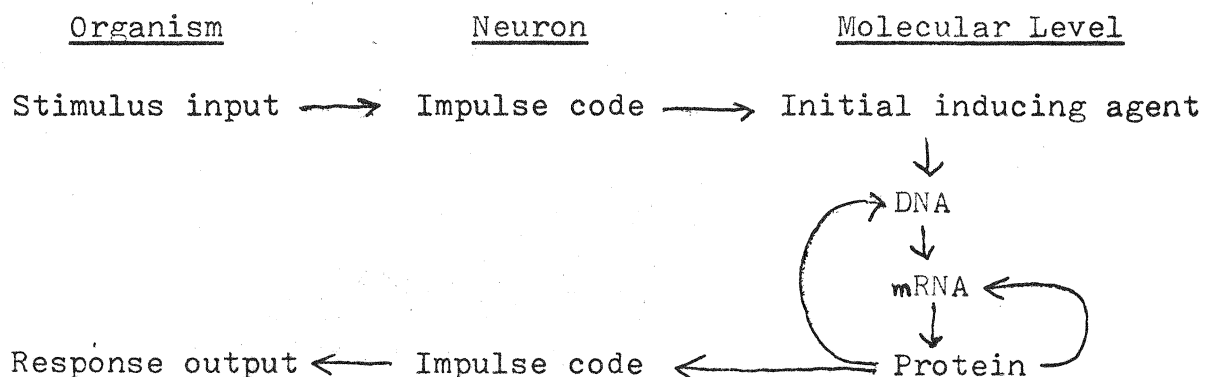


Figure III-5. Consolidation and maintenance of permanent memory.

and encoded for transmission by the transduction from primary sensory modalities to an electrochemical equivalent which is utilized by the nervous system. The next step includes association with previously stored information, pattern recognition, abstraction, or synthesis of new constructs. All of these can occur at the conscious or unconscious level. Storage of information may require further encoding, and it is still not known whether or not the short-term memory process is the same as the long-term, although current indications are that a different process exists in humans, (George, 1961). Retrieval of information must be accounted for by the model, including both remembering and forgetting. Lastly, effector consequences of information retrieval, motor and affective accompaniments must somehow be explained.

Some of the methods used to study biochemical mechanisms of these problems include (1) immunological systems in which one molecule must "recognize" another, (2) tissue cultures, (3) single nerve cells and synapses in situ, (4) whole ganglia in primitive organisms, (5) relatively intact nervous systems, (6) intact organisms, and (7) non-biological systems such as computers, (Bogoch, 1968). The methods involved in researching these systems include surgical (lesion), electrical (electroconvulsive shock and electrode implantation), and pharmacological studies. From these studies have arisen several different molecular interpretations.

There are eleven major molecular theories of memory: (1) memory is mediated by certain distinct brain regions (lobes,

nuclei, tracts) and memory functions are maintained by a group of areas or organ subsystems, (2) memory traces are to be found in neurons, (3) memory traces are contained in one specific population of neurons, (4) memory is mediated by axonal changes, (5) new growth of nerve cell processes provides memory mechanism, (6) new cells arise as a function of experience and associations, (7) memory traces are a result of activity at the synapse, (8) glial cells subserve memory functions, (9) memory traces are coded in DNA and/or RNA, (10) proteins provide the basis for memory, and (11) brain mucoids (molecules formed from carbohydrates, protein, or lipids) are responsible for the memory trace, (Bogoch, 1968). All of these are hard to verify and substantiate in any event, and the problem may be that of dealing with different parts of the elephant, as it were.

A good deal of the biochemical work has been performed on humans suffering various kinds of brain damage. In contrast to work with rats, (Thompson, 1969), it has been shown for humans that deficits marked by good immediate retention of visual material but very rapid forgetting are associated with bilateral lesions of Papez's circuit, (Barbizet & Cany, 1969), and the hippocampus is thought to play a part in short-term memory in humans, (George, 1961). Barondes has proposed a biochemical model for short- versus long-term memory processes, (Barondes, 1969). He speculates that two kinds of biochemical changes occur for memory storage; that is, a rapid reversible change for short-term, and a stable, possibly self-replicating change for long-term memory exist. Next he believes that both effect changes in synaptic transmission at

some critical synapses in the nervous system, and that short-term memory results from a structural change in proteins while the long-term memory occurs by way of protein synthesis. His suggested mechanisms for transient and permanent memory more specifically call for structural changes in proteins in the post-synaptic membrane. These changes render it more permeable for transient memory and biosynthesis of proteins at either the pre- or post-synapse. They also alter the permeability of transmitter substances at the membrane or its proclivity to reaccumulate transmitters or to degrade transmitters. In his studies Barondes analyzes the effects of cerebral protein synthesis inhibitors on memory and transport of proteins to nerve endings and synthesis and structural changes of protein at nerve endings. Others have expounded more abstract theories, including Broadbent's communication model which calls for retrieval of information by specific tags or labels, (Broadbent, 1969). This method runs into the difficulty of overlap due to tag similarity, and his model is rather vague. He claims short-term memory may be organized by simple sensory dimensions such as sound or time of arrival whereas long-term memory is dependent on meaning and association. A model similar to this one, proposed by Bruner, has some experiences tagged while others are converted into skills or generic modes, (Bruner, 1969). Tulving shifts the emphasis to the retrieval process, and holds that the storage mechanism is the same for both short- and long-term memory, (Tulving, 1970). Some data on the subject has shown that semantic similarity affects long- but not short-term whereas acoustic similarity



affects short- but not long-term memory, (Murdock, 1970). Aside from short- versus long-term memory research, a great deal of work has been done concerning the transfer of learning through biochemical means, (McConnell, et al, 1970). Ungar claims to have localized a molecule specific to an avoidance habit, and Gaito has produced much in the way of changes of RNA content of the brain during learning. However, most of these efforts have not been conclusive. What is reasonably well established is that puromycin, an inhibitor of gross protein synthesis, when injected into the hippocampus and entorhinal cortex within two days of learning, will abolish memory. If puromycin is injected into the hippocampus, entorhinal cortex, front, and middle parts of the brain for up to five weeks after learning, retention is abolished. Another inhibitor, acetoxycycloheximide, which does not interfere with protein in the same manner as puromycin, fails to produce losses and therefore no conclusions can be drawn from these results until further study has been completed.

It is interesting that one of the original articles that termed memory "holographic" also mentioned the results of RNA studies in the brain, (New Scientist, 1967). It stated that increased amounts of RNA in the brain after learning were restricted to the area involved in the specific kind of learning. It went on to explain that a hologram could (1) reconstruct a three-dimensional picture of the original, (2) store several images on one plate and retrieve them separately, and (3) reconstruct the original from any smaller part. Holographic methods of information storage as analogies of human memory had been forwarded as early

as 1963 when P. J. van Heerden suggested the importance of storage by interference patterns because it allowed simultaneous search for a specific piece of information through the whole memory, (van Heerden, 1963(a)). His three-dimensional storage mechanism is associational in function (Figure III-6). A situation  $S_i$  is

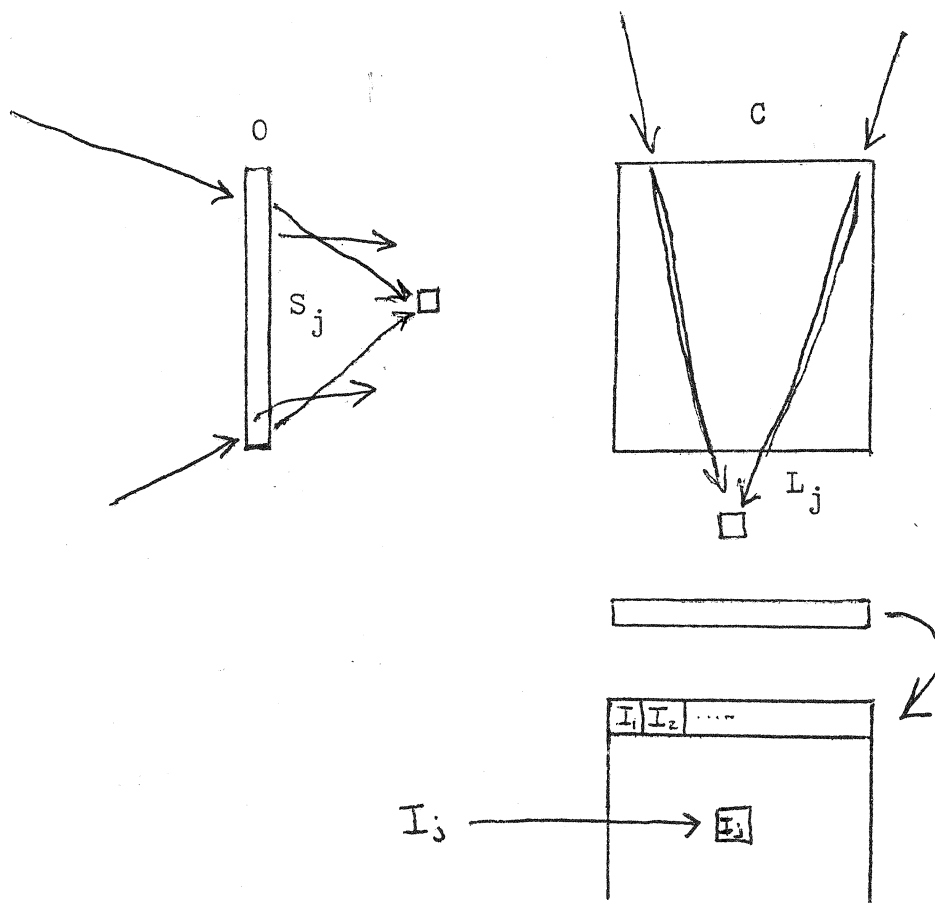


Figure III-6.

coded as a transparency in  $O$ . The transparency is illuminated by a converging light beam  $L_0$  in  $F$ , where the direct light of the beam is blocked off. The diffracted light containing the intensity as information will illuminate the crystal. A second convergent light beam  $L_i$ , coherent with  $L_0$ , is made to illuminate the crystal simultaneously.  $L_i$  converges to a point directly above a

transparency  $I$ , which is divided into squares in each of which some information  $I_i$  is written.  $L_i$  is focused in such a position as to illuminate  $I_i$ . Suppose all situations  $S_i$  are stored, each with its own light source  $L_i$  illuminating  $I_i$ . When an arbitrary  $S_j$  is put in the object plane, a ghost image of  $L_j$  will appear which designates the associated  $I_j$ , (van Heerden, 1963(b)). Van Heerden describes an analogy with information storage in the brain. Three-dimensional storage holds for any wave phenomena, satisfying Huygens principle. (Neural nets have already been described which satisfy this principle.) Large amounts of information could be stored with this method, and if the frequency of the waves is high enough, then the amount it is possible to store is on the order of the number of brain cells. This work provides some support for Beurle's system.

Not long after van Heerden's work was published, Longuet-Higgins proposed a temporal analog of optical holography, (Longuet-Higgins, 1968). His model described a signal  $f(t)$  as being arbitrarily partitioned into an earlier part  $f_1$  and a later part  $f_2$ .  $f_1$  acts as the reference for  $f_2$  so that after the whole signal has been memorized, the input of  $f_1$  will reconstruct a  $g_2$  proportional to  $f_2$ . Thus, the signal could be divided into any number of parts  $f_n$ , each  $f_i$  acting as the reference for  $f_{i+1}$ . Not only that, but numerous signals  $f^{(n)}$ ,  $n=1,2,3,\dots$  could be retained, and an input of some  $f^{(n_0)}$  will evoke a  $g_2^{(n_0)}$  without being affected by the other stored signals.

Gabor, the founder of holography, followed with a model of a holographic memory mechanism based on convolutions, (Gabor, 1968(a)).

This model is realizable with McCulloch-Pitts' neural nets by taking sums over lattice points, and it simulates human memory which is able to recognize and recall long sequences of which only a small fraction is consciously remembered. However, he elaborated on the model and pointed out that even with new corrections, it still allowed one to remember a sequence backwards, (Gabor, 1968(b)). This problem did not occur in Longuet-Higgins' model because it was dynamic.

Thus, holographic devices have been realized that exhibit properties comparable to that of memory in animals. Namely, the recording of each object point is uniformly distributed throughout the recording film, and each point of the hologram contributes to the reconstructed image. It is significant that damages to the hologram are directly related to the loss of resolution in the reconstructed image; however, the loss must be fairly large before the reconstruction becomes unrecognizable. Pribram has begun work on providing a neurophysiological basis for a holographic memory process, (Pribram, 1969). R. W. Rodieck has demonstrated that the relations between excited cells in the visual system can be described as "convolutional integrals." In other words, the visual input can be described as a planar wavefront. It is possible that this wavefront may interact with some reference wave in the brain (or with itself, as suggested by Longuet-Higgins) and actively modify the synapses in particular structures as a consequence of molecular synthesis. The holographic memory process can be adapted to the macromolecular theory of long-term memory and learning in the following manner.

At the synapses of neurons influenced by a wave and its reference there are produced structurally modified proteins which provide a short-term memory by acting as a diffraction grating when the reference or stimulus occurs again. A long-term memory occurs when these altered proteins are coded for and synthesized by either the neuron or glial cells. These ideas do not preclude specificity of the location of engrams, but instead make it more plausible that if the memory trace is localized to a particular structure or group of structures, then it is spread over the whole structure or group, respectively.

This study was conducted in the general framework of the following model. Neuroanatomically, the visual memory system as proposed by Thompson serves as the group of structures involved in storage and retrieval of visual information. This system forms a holographic information processing device of visual information. A stimulus in the visual field encodes a reference which is dependent upon the properties of the stimulus, and the stimulus and this reference produce a "neural hologram" by modifying the synapses of the neurons of the system. Two very similar stimuli will encode the same reference which provides a basis for generalization of learning. The visual system can be supposed to correlate with the three-dimensionality of a photographic plate: that is, the reference wave must pass through each level of the system in order to be properly diffracted. Ablation of a sizable portion of the visual system at any depth will result in the loss of the response.

While the preceding discussion is concerned primarily with

the visual system of the rat, Penfield's work throws some light on the human subject, (Penfield, 1954). He found upon stimulation of the occipito-temporal region that a sharply demarcated boundary exists between the temporal and occipital lobes. Hallucinations were elicited by exciting the temporal area, while brightness, color, outline, etc. were visualized upon stimulation of the occipital region. The electrical stimulation could have served to create reference waves which passed through the visual memory system and reconstructed the particular experiences or sensations. These reference waves were probably not completely arbitrary, but depended upon the threshold values of the entire system. These results indicate that the cortex is the structure primarily involved in producing reference waves. In humans, the temporal lobe appears to function in long-term memory formation, and bilateral lesions to this area may disrupt the ability to form new reference waves.

#### PART IV: COMPUTER SIMULATION

For a simulation study of visual information processing to be comprehensive, it must account for four discrete areas of information handling: (a) receiving information in a usable form, (b) dealing with that information and arriving at a decision of what response to make, (c) carrying out the response decided upon, and (d) having some means of acquiring knowledge of the result of the response, (Hilgard & Bower, 1966). The main emphasis of this study is the second of these, or more precisely, dealing with information storage by means of a long-term holographic memory process. The rest of the simulation is structured around Kabrisky's "basic computational element," (Kabrisky, 1966). The cross-correlation model and the associated learning process have been described previously; now the computer generation of holograms and the reconstruction of stored wavefronts will be discussed.

Optical holograms had been predicted and physically achieved through the efforts of Gabor by 1949, (Gabor, 1949). With the advent of large scale computing systems and precise plotter devices, it was possible for holograms to be generated by computation instead of being made physically. One of the first successful works in this area was completed by Brown and Lohmann, (Brown & Lohmann, 1966). They used a computer driven plotter to record an interference pattern on paper. This pattern was then photo-reduced onto film and contained only ~~contained only~~ binary transmittance values. They demonstrated that by inserting a Fourier hologram into the Fraunhofer plane of a coherent image-forming

system, it acts as a special type of spatial filter. This binary matched filter is suitable for optical character recognition.

In a later work, Lohmann and Paris demonstrate the usefulness of computer generated binary holograms, (Lohmann & Paris, 1967). The binary hologram is illuminated with a tilted plane wave, and a lens between the hologram and the image performs a two-dimensional Fourier transformation of the complex amplitude (Figure IV-1). For hologram synthesis in general, it is necessary

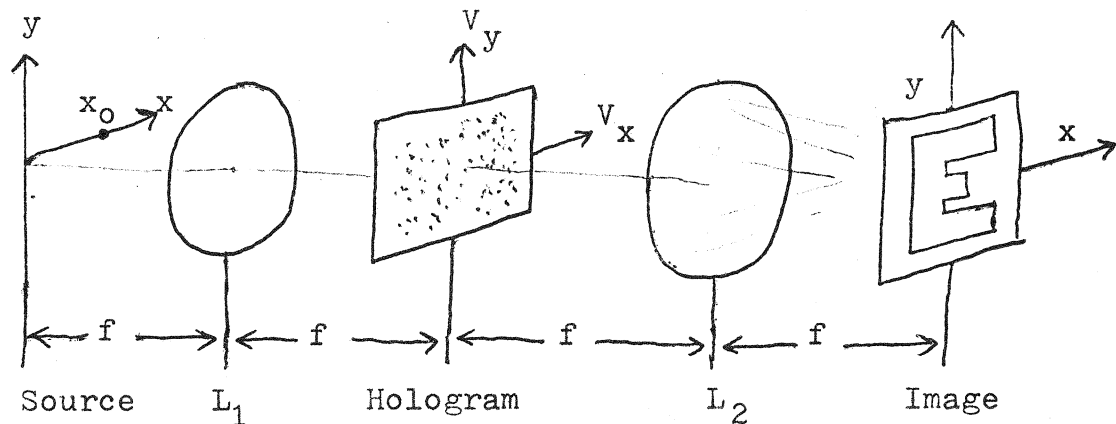


Figure IV-1. Reconstruction from computer generated binary hologram. Lenses  $L_1$  and  $L_2$  have focal length  $f$ .

to compute the propagation of the complex amplitude of the image to the hologram plane. The system (cell assembly or neural network or whatever) is treated as if it consists of a hologram plane. The complex amplitude must then be encoded as a real, non-negative function (e.g., the simulation of the interference fringes caused by interaction of the image wavefront with the reference beam, (Brown & Lohmann, 1970)).

One objective of this study is to take the information pro-



vided by Part II, represent it as a complex wavefront, store it holographically, and be able to reconstruct the stored wavefront. To convert the memory array provided by Part II into a complex wave form requires that the memory array has both a magnitude and phase. The general equation of a wavefront is:

$$W(a,b) = A_0 e^{(i\pi/\lambda z)((x-a)^2 + (y-b)^2)} \quad (20)$$

where  $A_0$  is the magnitude and  $e^{i\theta}$  is the representation of the phase. This is the Fresnel approximation to the Kirchoff diffraction theory for a plane wave illumination of a single aperture (Figure IV-2). If an array of point apertures,  $T(x,y,z)$ ,

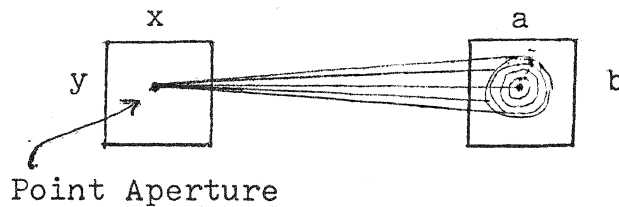


Figure IV-2. Plane wave from a single point aperture.

is achieved by superposition, then the wavefront is expressed as:

$$W(a,b) = \sum_{A(x,y,z)} T(x,y,z) F(x-a, y-b, z) \quad (21)$$

and

$$F(x,y,z) = e^{(i\pi/\lambda z)(x^2+y^2)}.$$

But since

$$e^{(i\pi/\lambda z)\{(x-a)^2 + (y-b)^2\}} = e^{(i\pi/\lambda z)(x^2+y^2)} e^{-2\pi i(xa+yb)},$$

then

$$W(a,b) = \sum_z F(a,b,z) \sum_{A(x,y)} T(x,y,z) F(x,y,z) e^{-2\pi i(xa+yb)/\lambda z}. \quad (22)$$

(See Figure IV-3.) If this function is quantitized into regular intervals (Figure IV-4), where  $x=k\Delta x$ ,  $y=l\Delta y$ ,  $a=m\Delta a$ ,  $b=n\Delta b$ , and  $\Delta a=\lambda z/M\Delta x$ ,  $\Delta b=\lambda z/N\Delta y$  holds for all  $z$ , and  $M,N$  are the number of evaluations of

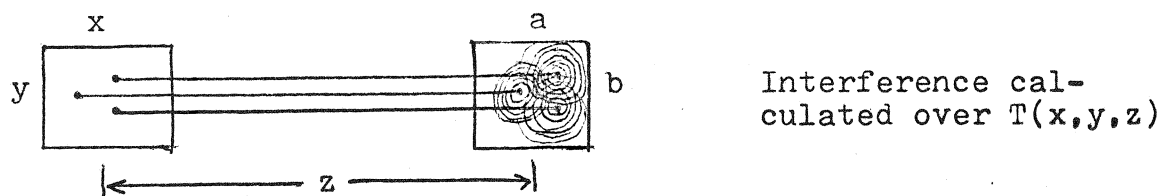


Figure IV-3. Plane wave from an array of point apertures.

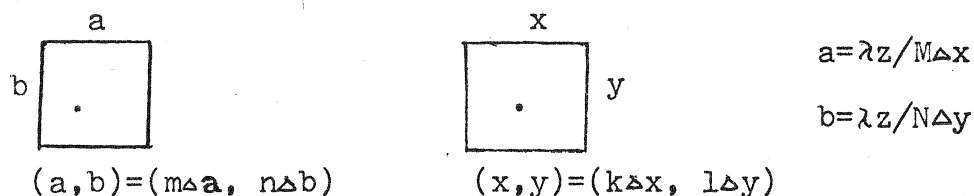


Figure IV-4. Quantization of aperture and illumination planes.

the sum in the  $x$  and  $y$  directions, then

$$W(a,b) = \sum_z F(a,b,z) \overline{TF}(a,b,z) \quad (23)$$

where

$$\overline{TF}(a,b,z) = \sum_{k=-M/2}^{(M/2)-1} \sum_{l=-N/2}^{(N/2)-1} T(x,y,z) e^{-2\pi i(km/M + ln/N)}. \quad (24)$$

$\overline{TF}$  is a two-dimensional Fourier transform of  $T(x,y,z)F(x,y,z)$  and is periodic of periods  $M,N$ , but only one period must be calculated. In the actual programming, the subroutine HARM which is part of the SSP of subroutines was used to calculate  $\overline{TF}$ . In other words, the Fourier transform of  $T(x,y,z)$  was taken.

In order to get good spreading of the object wave over the recording plane, it is necessary to choose  $T(x,y,z) = SS(x,y,z)e^{i\phi(x,y,z)}$  (25) where  $SS(x,y,z)$  equals the intensity of the point apertures, and  $\phi(x,y,z)$  equals the phase of the point apertures. These phases of the point apertures were chosen randomly which closely simulates the manner in which light is reflected from physical objects.

Using all these results, the wavefront can be explicitly defined as:

$$W(a,b) = \sum_z (e^{i\pi a^2/\lambda z}) (e^{i\pi b^2/\lambda z}) \sum_{k=0}^{M-1} \sum_{l=0}^{N-1} SS(x,y,z) (e^{i\pi \phi(x,y,z)}) \dots \\ \times (e^{-2\pi i(km/M + ln/N)}). \quad (26)$$

Once the wavefront is explicitly defined, it is necessary to establish a suitable reference wavefront. It is the interference of the two which saves the phase information of the object wave and makes holography possible. The reference wave,  $R(a,b)$ , is chosen as:

$$R(a,b) = (e^i) \left( \frac{\pi}{\lambda z} \right) \{ (x_0 - a)^2 + b^2 \},$$

where  $\pi/\lambda z = \alpha$ , a constant,  $x_0$  equals the distance from the origin that the point source is in the x-y plane, and the amplitude is set to 1. Thus, the holographic representation of the wave interference is:

$$H(a,b) = |W(a,b) + R(a,b)|^2 \quad (27) \\ = |W|^2 + |R|^2 + W^*R + R^*W.$$

It is the latter half of this equation which allows the reconstruction of the image and its conjugate (Figure IV-5).

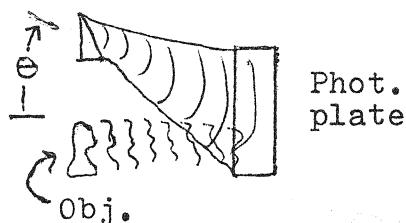


Figure IV-5. Hologram construction.

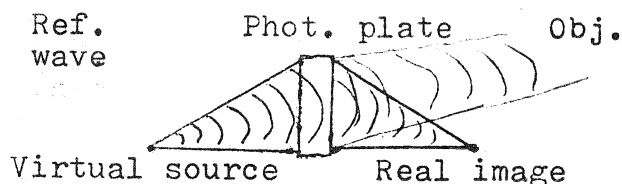


Figure IV-6. Hologram reconstruction.

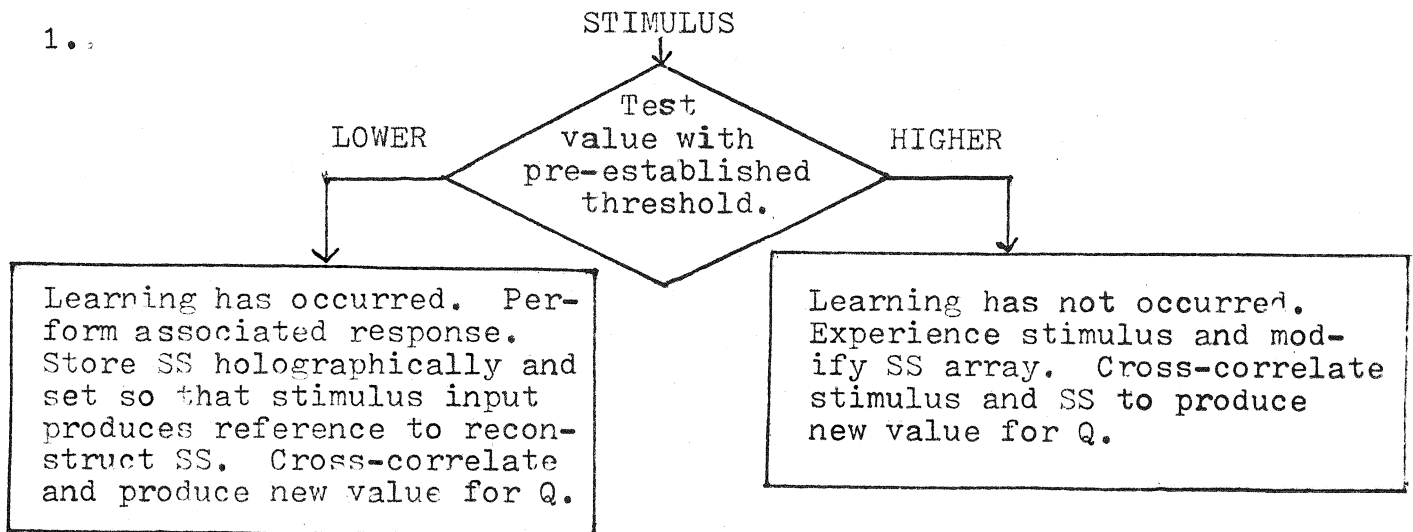
The reconstruction of the original wave from the object (in this case a two-dimensional array) follows simply by the multiplication of  $R(a,b)$  by  $H(a,b)$ , as illustrated by Figure IV-6. This produces a virtual source and a real image, one forward in time and the other backward. Another Fourier transform is needed here to compute the image from the hologram. A plane wave reference is used in the reconstruction, and its affect upon each point in the hologram array is used in the Fourier transform.

This is the method of representation of a two-dimensional array as a wave, and it forms the basis for memory storage and retrieval. The development of the mathematical representation of the wave from equation (20) to (27) is after Hirsch, Lesern, and Jordan. Figures IV-5 and IV-6 are after Stroke.

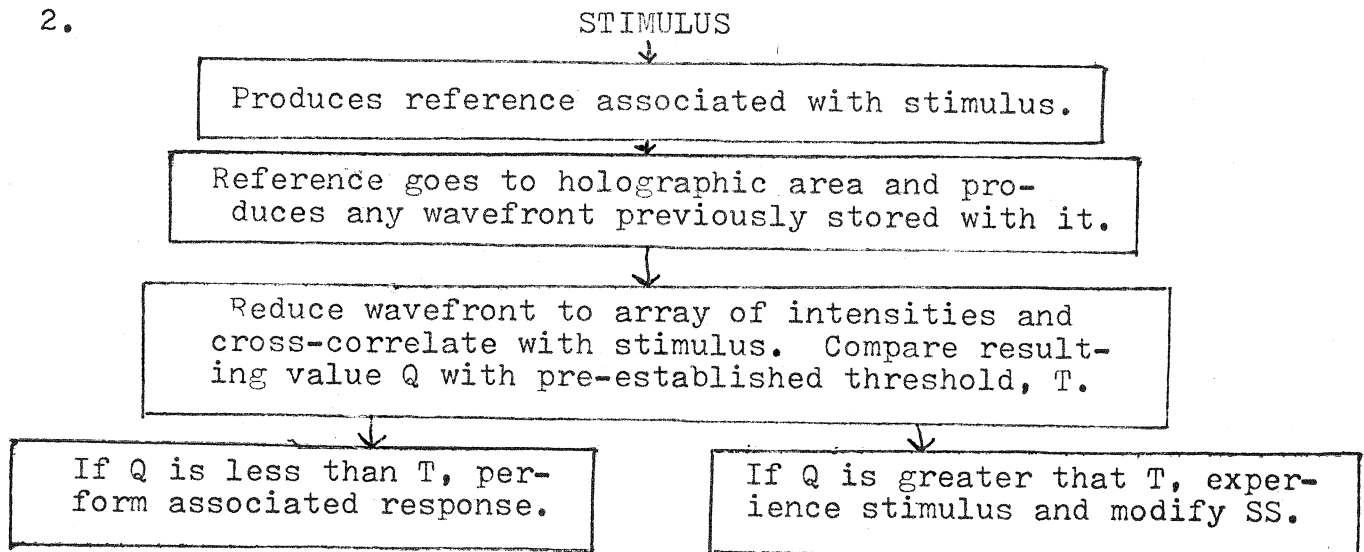
Three methods present themselves as means of incorporating the holographic storage mechanism with the learning model proposed earlier in the paper (Figure IV-7). Method one was chosen as it more aptly separated the learning process into two parts:

- (1) The initial procedures associated with learning (i.e., the modification of SS) simulate the function of short-term memory, and
- (2) After learning is completed, the memory array SS is stored holographically and will provide information whenever stimulated by the appropriate input, thus performing comparably to a long-term memory process.

1.



2.



3.

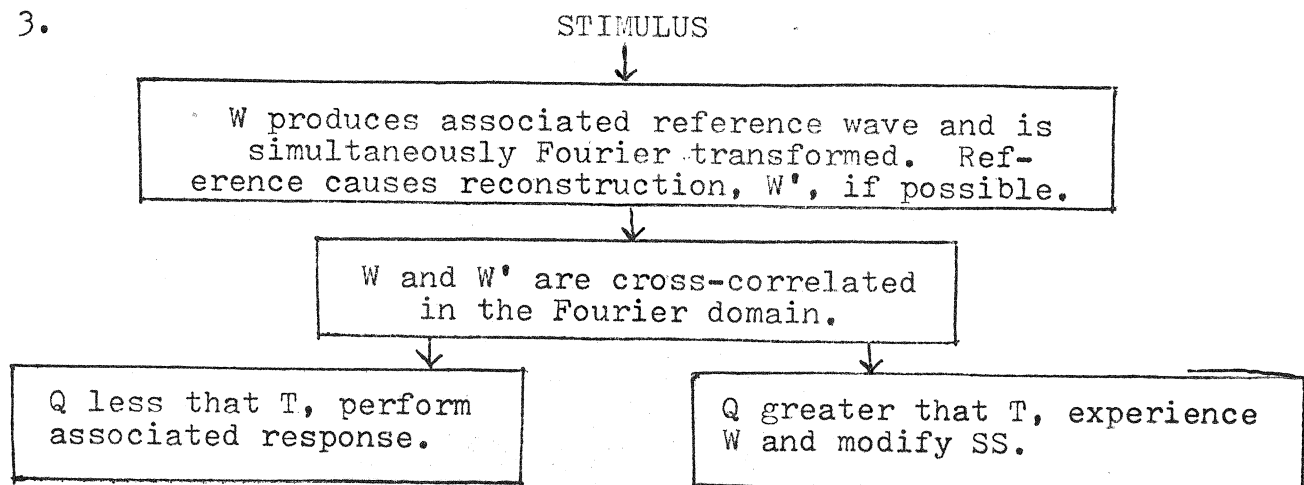


Figure IV-7.

## PART V: COMPUTER SIMULATION

The computer simulation of the visual information processing and memory storage is divided into two parts. The first is the learning program, and the second is the holographic memory program. The first provides an  $n$  by  $n$  memory array,  $SS(n,n)$ , which is formed during the learning of a discrimination problem. The values in this array serve as the magnitudes of the complex wave,  $W(n,n)$ , which is generated by the second part of the program. The second part also computes a spherical reference wave,  $Ref(n,n)$ . This spherical reference wave (28) is used to store  $SS$ , and it is related to the stimulus by (29), (Figure IV-8).

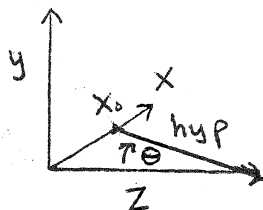


Figure IV-8.

$$Ref(A,B) = e^{(i\pi/\lambda z)\{(x_0-a)^2+b^2\}} \quad (28)$$

where  $x_0 = \sin(\theta) \cdot \text{hyp}$ , and  $\text{hyp} = z/\cos(\theta)$ , and  $\theta = f(SS)$ , where  $f$  is defined by:

$$f(SS) = \sum_{i=1}^{n-1} \sum_{j=1}^{n-1} \left( \sum_{l=j+1}^n a_{jl} - \sum_{k=i+1}^n b_{ik} \right) \quad (29)$$

such that

$$\left. \begin{array}{l} a_{jl} = l-j \\ b_{ik} = k-i \end{array} \right\} \text{ If } SS(i,j), SS(k,l) \text{ have non-zero entries;} \\ 0 \text{ otherwise.}$$

Finally, it finds the hologram that results from the interference of the two waves. This is the  $H(n,n)$  array. The reconstruction is achieved by illuminating the hologram with a planar reference wave,  $\text{Ref}(n,n)$  (30);

$$\text{Ref}(a,b) = e^{i2\pi\theta a/\lambda}. \quad (30)$$

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## Part VI: Computer Simulation-II

Stroke has shown that the intensities in the hologram plane in Fig.VI-1 can be mathematically computed as:

$$\begin{aligned}
 hg(x) = & |A_0|^2 + |A_S|^2 + A_0 \int_{\xi_1}^{\xi_2} SL1(\xi) \exp[-i(k/f)x\xi] d\xi \\
 & + A_0 \int_{\xi_1}^{\xi_2} SL1(\xi)^* \exp[+i(k/f)x\xi] d\xi \quad (28)
 \end{aligned}$$

where  $A_r = A_0 \exp[i(k/2f)x^2]$  is a spherical reference at R, and  $SL1(\xi) \exp[i(k/2f)(x-\xi)^2] d\xi$  describes the influence of a particular point in the object on the hologram. As the first two terms of (28) are constant, and the fourth term is the complex conjugate of the third, (28) reduces to:

$hg(x) = 2TR(\xi)$ , where  $TR(\xi)$  represents the sum of the real parts of the third term of (28). But this is merely the Fourier transform of  $SL1(\xi)$ , and it is easily computed by the subroutine HARM which is found in the Scientific and Statistical Package.

Reconstruction of the object is accomplished by multiplying the hologram by a planar wave and then taking the Fourier transform of the resulting complex array. (Fig.VI-1) This reconstruction results in the appearance of the object and the conjugate image of the object at equal distances from and on opposite sides of the central order. For example, a point source would result in the reconstruction of two point sources symmetric about the central order. (Fig.VI-2)

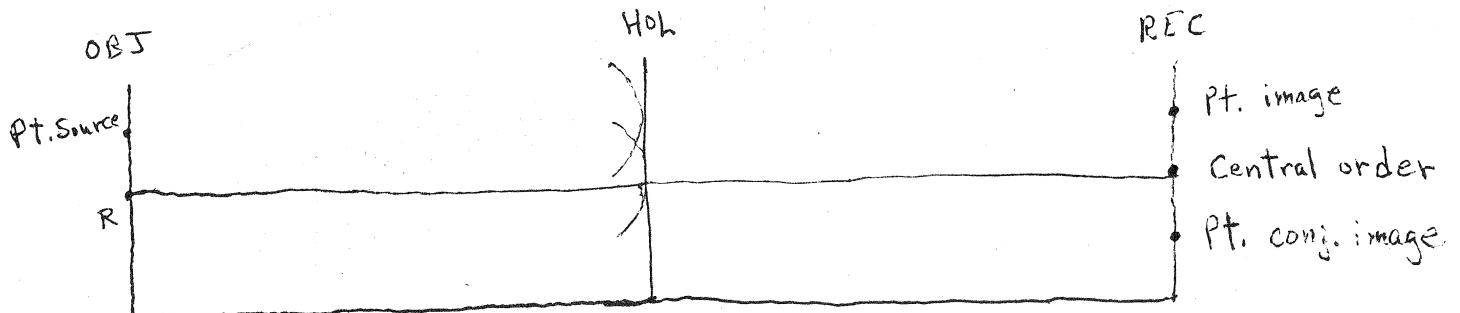
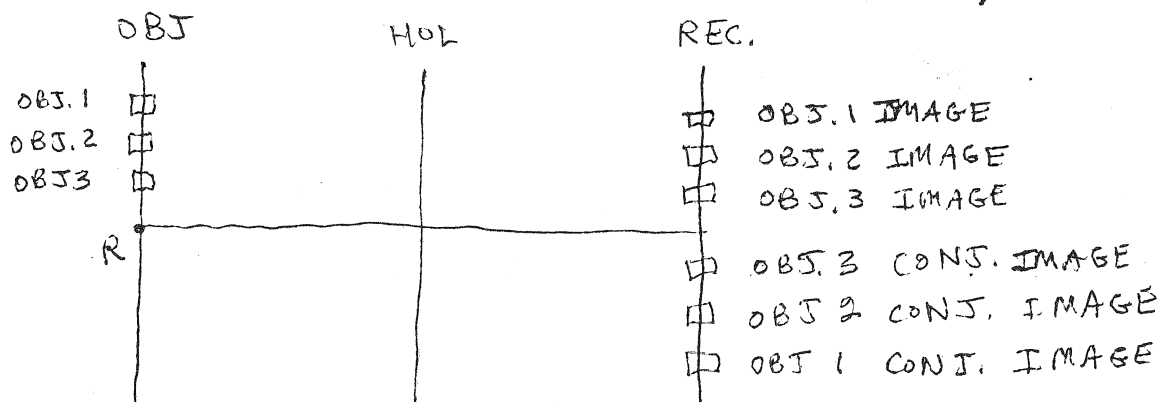


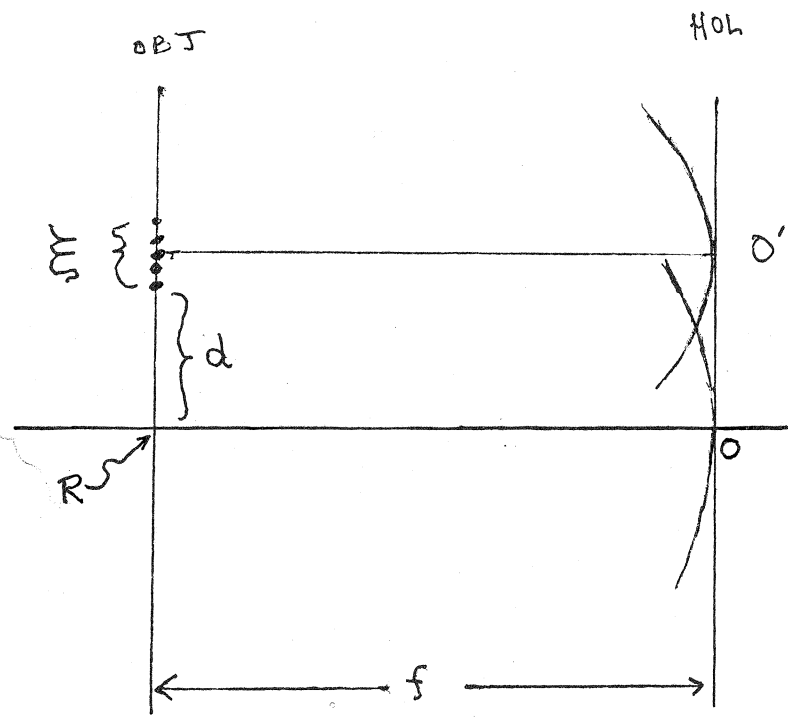
Fig. VI-2. Pt. Source Hologram and Reconstruction

The memory array which was stored was the array of vertical bars, a two-dimensional array of real numbers. These are stored in a complex array, SL1. This is the object from which the hologram is made. HARM is capable of handling three-dimensional arrays, but this study only utilized the transform up to two dimensions. By using the Fourier transform as described above, the hologram can be achieved in six seconds of CPU time as compared to five minutes using methods outlined in Part V.

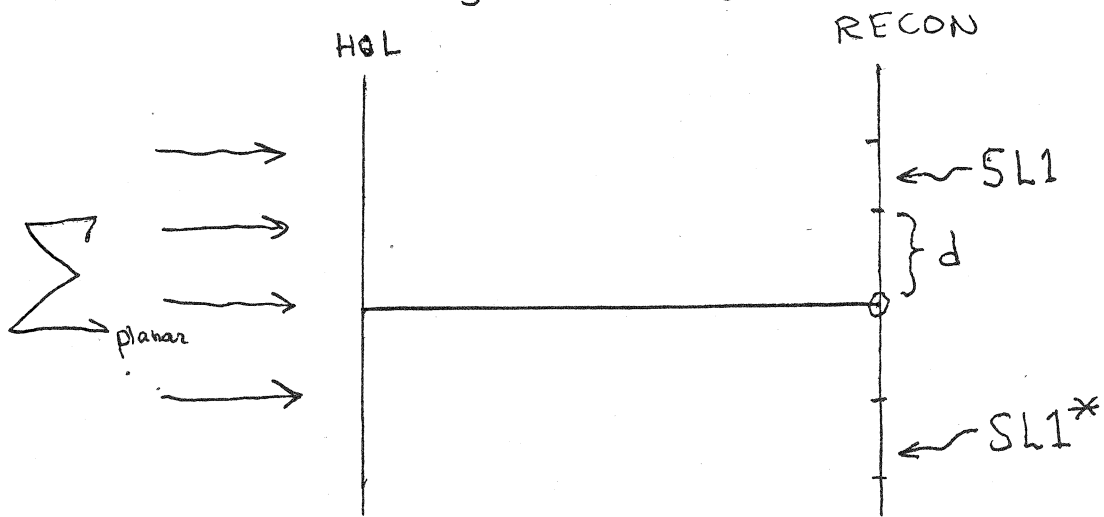
The reconstruction from the Fourier hologram yields a central order, and an array in which the numbers of any one column are equal, while the columns' values vary in magnitude. This is essentially the input object. Thus, a cross-correlation could occur between the original and the reconstruction. However, this could be more easily accomplished in the Fourier domain (i.e., multiply the two functions.)

The storage of several memories can be accomplished with the Fourier transform by the arrangement of these objects in the object plane as is suggested by Fig.VI-3. Upon reconstruction, an object would appear at some particular site in the reconstruction plane. In the brain this might be equivalent to the appearance of the reconstruction ( or something equivalent to it ) in a specific locus of cells.





(a) Recording the hologram



(b) Reconstruction from hologram

Fig. IV-1. Lensless Fourier transform holography.

[illegible][illegible]

### Vertical Rows

# Flow Chart

