A NEURAL SUBASSEMBLY MODEL OF HUMAN LEARNING AND MEMORY

by
Jeffrey Robert Sampson

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ADDENDA

Page(s)	Comment
37-38	In equations (10) and (11), it is to be understood that when values outside the zero-one interval occur, the g_i or h_i is automatically reset to the (nearer) bound.
49	In the first paragraph of section F, it should be stressed that the informational aspects and set-like attributes of attention are subsumed under the priming concepts of the present model, much as in Hebb's (1949) original theory.
87	It should be mentioned that Postman and Phillips (1965) employed an arithmetic task during delays before recall, as is implied by the parenthetical remark in line 17 on page 97.
123-124	In a paper published after the completion of this dissertation, Atkinson and Schriffen [Storage and Retrieval Processes in Long-term Memory, *Psychological Review*, *76* (2): 179-193, 1969] say that their system is consistent "with the view that the short-term store is simply a temporary activation of information permenantly stored in the long-term store." Although such an interpretation may create some new difficulties for the AS machinery, it considerably reduces the conceptual difference between the AS and SA models in this area.
130-131	Most of the comparisons based on rehearsal should be disregarded, since the writer failed to understand that the short-term buffer in the AS model is viewed as a rehearsal system. This fact was briefly noted in the 1965 Atkinson and Shiffrin reference, but was first noticed by the writer in a later paper, not available during the preparation of this dissertation [Human Memory: a Proposed System and its Control Processes, in K.W. Spence and J.T. Spence (eds.), *The Psychology of Learning and Motivation*, Vol. 2, Academic Press, New York, 1968]. It would now seem reasonable for the AS model to claim that non-set subjects do not use such a rehearsal buffer (although Atkinson and Shiffrin do not, to the writer's knowledge, provide alternative machinery), thus accounting for the lowered primacy in a manner similar to the wirter's explanation in the SA model.

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TABLE OF CONTENTS

Page

Acknowledgements..................................ii

List of Tables....................................iv

List of Figures...................................iv

Abstract..v

Introduction......................................1

Chapter I: Background and Context.................5

Chapter II: The Model Developed...................15

A. The SC Sub-unit................................22
B. The IS Sub-unit................................31
C. The CC Sub-unit................................33
D. The Input Alphabets............................40
E. Networks of SA Units...........................44
F. Attention and Encoding.........................49
G. Retrieval, Rehearsal, and Recall...............61
H. Summary..73

Glossary of Symbols Used in Chapter II............80

Chapter III: The Model Applied....................82

A. Analysis of Free-recall Serial-position Data......83
B. Analysis of Verbal and Non-verbal Recall Data....100
C. Analysis of Delayed Recall and Set Phenomena.....109
D. Comparison with the Atkinson and Shiffrin Model..115
E. Comparison with the Sperling Model...............131

Chapter IV: Conclusions and Prospects.............140

Appendix: Experimental Methods and Raw Data......147

References..156

LIST OF TABLES

Table — Page

III-1 Summary of Serial Position Findings..............92

III-2 Word-Picture Recall Percentages.................101

III-3 Ducharme-Fraisse Mean Recall Data...............103

LIST OF FIGURES

Figure — Page

II-1 The Prototype SA Unit............................23

II-2 State-transition Relations.......................24

II-3 A Simple Example of Input-alphabet Dynamics......42

II-4 A Schematic Example of Multiple Encoding.........53

II-5 Definition of Coherency..........................57

II-6 A Schematic Example of Retrieval.................70

II-7 The Model and its Peripheral Equipment...........74

III-1 Serial Position - Set Subjects..................90

III-2 Serial Position - Non-set Subjects..............90

III-3 Composite Data from Word vs. Picture/Object Recall Studies.................................106

ABSTRACT

The primary objective of this study is the development and application of an automata-theoretic neural model of human learning and memory, using the subassembly (a small, tightly interconnected set of neurons) as the primitive unit of analysis. In a larger context, the research reported here is viewed as a contribution to an understanding of the biological bases of adaptive behavior, particularly language behavior.

The first chapter reviews the historical background of the area of research, beginning with the cell-assembly theory of Hebb; simulation projects are considered along with theoretical advances. The type of neural network model employed is then put in its appropriate context with respect to neural models in general.

The development of the model is undertaken in the second chapter, where the primitive SA (subassembly) unit is seen to consist of connection control, input summation, and state control units. The nature of the sub-components of each of these units is described mathematically and interpreted behaviorally. The representation of stimulus items in hierarchically organized networks is then considered, with emphasis on mechanisms mediating attention, encoding, retrieval, rehearsal, and recall.

The third chapter applies the model to experimental data and compares it with other models of learning and memory. The data, both from the literature and from the writer's own experimental studies, focus on the issues of serial position effects in free recall, on better memory for figural than verbal stimuli, and, to a lesser extent, on the effects of a recall set and of a delay before recall test. The model is also viewed in comparison with the mathematical approach of Atkinson and Shiffrin to free recall data, and with the auditory-rehearsal approach of Sperling to short-term visual memory.

The last chapter considers the degree of rigor in the model, outlines the major claims made for the study, and looks at the prospects for future avenues of research, which include experimental studies, neurophysiological explorations, and computer simulation.

INTRODUCTION

In a recent issue of Scientific American, Stanford Biology Professor Donald M. Wilson (1968)* concluded his article on "The Flight Control System of the Locust" as follows: "What we are striving for . . . is a way of understanding the functioning of networks of nerve cells that control animal behavior. Neurophysiologists have already acquired wide knowledge about single nerve cells--how their impulses code messages and how the synapses transmit and integrate the messages. Much is also known about the electrical behavior and chemistry of large masses of nerve cells in the brains of animals. The intermediate level, involving networks of tens or hundreds of nerve cells, remains little explored. . . . I suspect that it is an area in which important problems are ripe for solution."

While Dr. Wilson and his fellow biologists explore such neural networks in the locust and seek extrapolations to human behavior, other types of investigation, less directly physiological but dealing with more sophisticated behavior, should proceed apace. With the publication of The Organization of Behavior (1949), D. O. Hebb initiated a theoretical approach to the study of neural networks of "tens or hundreds of nerve

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*The author's name and the year of publication are used to cite entries in the list of references at the end of this study.

cells," an approach based in large part on behavioral data. Subsequent contributions to cell-assembly theory have kept it an active part of the more general discipline of neuropsychology. Cell-assembly theory will be further explored in the present dissertation.

One problem in the investigation of the neural bases of behavior is the issue of language. Experimental studies and theoretical positions which draw an explicit contrast between verbal and non-verbal information processing in the nervous system are relatively rare. Furthermore, since many existing neurophysiological theories are rather informal, it is often difficult to derive definite predictions about language behavior from them. The present research has been motivated, then, by the desire for a formal cell-assembly-type neuropsychological theory which is based, at least in part, on data involving an explicit linguistic component. It is the writer's belief that this approach offers the best hope for progress toward an understanding of the complicated processes by which information, and particularly language information, is encoded, stored, and retrieved in the brain. This is surely one of the most challenging research problems in the study of adaptive systems, where one goal is to discover and model the theoretical foundations of biological success.

Four types of research can contribute to an understanding of complex, adaptive behavior. The first type is physiological experimentation, as exemplified by the work of Wilson mentioned above. A second area is behavioral experimentation, like that done by Levonian (1966) on attention and consolidation factors in retention. The third research category is model building or formal theorizing, an example of which is Kaplan's (1968) model of synaptic change during learning. Finally, there is computer simulation of the kind done by Finley (1967) to investigate cell-assembly formation in neural networks. The contribution of this study is based primarily on research in the third area (model building) and, to a lesser extent, on behaviorial experimentation. The framework is also laid for computer simulation.

The organization of this study will now be outlined. The first chapter reviews the historical background of the area of research, beginning with the cell-assembly theory of Hebb (1949); simulation projects are considered along with theoretical advances. The type of neural network model employed is then put in its appropriate context with respect to neural models in general.

The development of the model is undertaken in the second chapter, where the primitive SA (subassembly) unit is seen to consist of connection control, input summation, and state control units. The nature of the sub-components of each of these units is described mathematically and interpreted behaviorally. The representation of stimulus items in hierarchically organized networks is then considered, with emphasis on mechanisms mediating attention, encoding, retrieval, rehearsal, and recall.

The third chapter applies the model to experimental data and compares it with other models of learning and memory. The data, both from the literature and from the writer's own experimental studies, focus on the issues of serial position effects in free recall, on better memory for figural than for verbal stimuli, and, to a lesser extent, on the effects of a recall set and of a delay before recall test. The model is also viewed in comparison with the mathematical approach of Atkinson and Shiffrin (1965, 1968) to free recall, and with the auditory-rehearsal approach of Sperling (1963, 1967) to short-term visual memory.

The last chapter considers the degree of rigor in the model, outlines the major claims made for the study, and looks at the prospects for future avenues of research, which include experimental studies, neurophysiological explorations, and computer simulation.

CHAPTER I: BACKGROUND AND CONTEXT

Theoretical models like the one to be developed and discussed in subsequent chapters are of relatively recent origin. The short but lively history of this research will be briefly sketched in this chapter. An attempt will also be made to place these kinds of theories within the general context of models of the neural bases of behavior.

The 1949 publication of D. O. Hebb's The Organization of Behavior was primarily responsible for initiating a school of thought that has evolved in the two decades since. Hebb introduced the concept of the cell-assembly into neural theory. The cell-assembly was a particularization of the notion of the neural trace (or engram) and, as such, represented the fundamental neural unit of perception and thought. A group of neurons could be organized into such an assembly under conditions of repeated common excitation, usually during the early experience of the organism.

Hebb postulated that if the firing of one neuron was repeatedly influential in the firing of a second neuron, the first would become increasingly important as a determinant of the firing of the second. The mechanism underlying such a change was presumed to be some kind of metabolic or growth change, which increased the efficiency of the synapse between the two neurons; but Hebb did not commit himself to any specific machinery.

In any case, a small group of neurons with only slight mutual interconnection strength could well be subjected to repeated periods of simultaneous activity, as the result of some recurring or persistent external stimulus. Under the influence of the process postulated by Hebb, the group would come to be much more strongly interconnected and capable of circulating activity, through re-entrant paths or closed neural loops, for some time after the evoking stimulus was no longer present. Such a group of neurons was called a cell-assembly; and the post-stimulus circulation of activity was known as reverberation.

For Hebb, reverberation was the means by which something could be remembered for at least the first few minutes--a holding mechanism which gave rise to the slower structural or metabolic changes forming more permanent memory records. Such a fixing of information in long-term storage has come to be known as consolidation. Although some authorities deny the need for any such construct, and while there is considerable dispute about its nature and temporal parameters (see Kimble, 1967, for debate on both these points), consolidation is nevertheless a widely accepted term.

The cell-assembly, which Hebb viewed as perhaps representing one angle of a triangle, was not the ultimate level of organization in his system. As the organism learned to recognize the triangle as a whole, the three constituent assemblies began to establish relations among themselves and with other, previously uninvolved, neurons. The triangle could thus eventually come to evoke an ongoing sequence of activity among the constituent cell-assemblies and an additional "superordinate" assembly. Hebb called such activity a phase sequence.

Hebb was not very specific about the nature of inter-assembly relations; and the manner in which one assembly might influence which other assembly would next be predominantly active has been subject to a number of interpretations. This problem is especially important because it is central to the question of how thought is directed in the absence of guiding external stimulation; the whole issue of the neural bases of association is involved.

The first suggestion in this area originated with Milner (1957). He introduced inhibition into the Hebb scheme, primarily to keep the cortex from "blowing up" as a result of snowballing excitation. Milner then proposed that, although the currently active assembly was broadcasting non-specific inhibition throughout the cortex, it might also have facilitory connections with some other assembly. Although these connections would carry insufficient weight to arouse the other assembly to concurrent life (in the face of the general inhibition), they could "prime" it for subsequent activity. Milner believed that this priming was accomplished because sub-threshold excitation of a neuron made it easier to fire later (a view which does not seem to have much physiological support). As soon as the first assembly died out and its inhibition of others disappeared, the primed second assembly would be most ready to go and therefore most likely to succeed in competition for dominance of the cortex.

At about this same time, Rochester, Holland, Haibt, and Duda (1956) began looking at the cell-assembly theory with an eye to simulation of the formation of assemblies on a digital computer. The original model involved sixty-nine neurons with ten synapses each. The parameters determining whether a given neuron would fire were the number and strength of its inputs, the degree to which it had recovered from its previous firing (refractoriness), and the level of fatigue resulting from the overall intensity of recent activity. The strength of a particular input was determined by Hebb's postulate--whenever "neuron A participated in firing neuron B, the synapse that enabled A to stimulate B was increased in magnitude." With six neurons distinguished as inputs to the network (their firings being under external control), diffuse reverberation was relatively easy to demonstrate, but no combination of input pattern and parameter settings produced cell-assembly-like behavior.

The investigators then conferred with Hebb and Milner and, as a result, introduced Milner's concept of inter-assembly inhibition. They also increased the scope of the simulation to a 512-neuron net with an average of six synapses per neuron. Frequency of firing and synapse magnitude were determined as before. Rather than using a uniformly random interconnection pattern, as in the earlier study, a "distance bias" was put in, so that two nearby neurons were more likely to be connected than two remote neurons. Inputs, or receptors, consisted of four blocks of four neurons each, with pairs of blocks stimulated in alternation. An examination of firing patterns and synaptic magnitudes revealed that cell-assemblies had formed after repeated stimulation; within assemblies most connections were facilitory, while between assemblies most were inhibitory. Although this result provided good confirmation of the Hebb-Milner theory, there was little tendency for the simulated assemblies to arouse or influence each other. Instead of displaying any sort of priming, the assemblies seemed almost entirely input-dependent.

One of Holland's students (Finley, 1967) made progress on this issue of assembly interaction. He worked with nets of up to 900 neurons with an average of up to twenty-four synapses per neuron. Important parameters included the presence and nature of distance biasing, the initial distribution of synapse values, threshold and fatigue curves, and the synapse value function controlling increase and decrease in connection strength.

In a preliminary study of input-free networks, Finley demonstrated the importance of inhibition, distance biasing, and fatigue to the achievement of reasonably stable behavior without the presence of unusual, artificial constraints. He then turned to a study of network behavior under conditions of periodic input. Selecting an input set of from nine to sixty-four neurons, he varied its anatomical compactness, the period and intensity of the input, and (in the most complicated cases) the frequency of alternation between two different patterns.

The most impressive result occurred in Finley's last series of simulation runs. He chose a 400-neuron network with an average of six synapses per neuron, and with distance bias, inhibition, and fatigue. The input set consisted of nine neurons spaced one apart in a five-by-five grid. Stimulation was applied to this set every seventh time step for 100 time steps; each such "on" period was followed by an "off" period of 100 time steps without any stimulation. After about 3000 time steps, overlapping cycles of neurons, containing closed chains of excitation, had formed in the net. In other words, a cell-assembly had developed.

Finley then introduced a new stimulus at another input region. The second stimulation was also periodic, but was applied only every eighth time step during its on period (which coincided with the off period of the first input). Although exhaustion of computer funds dictated an early termination of the experiment, preliminary observations indicated a second assembly in the process of formation, while the first continued undisturbed. Of particular interest was the fact that the connections between the two assemblies tended toward inhibitory values in a manner highly suggestive of specific assembly interaction.

A byproduct of these various simulation studies was a theory of priming quite different from Milner's. The cross inhibition between simulated assemblies led Holland and others to a theory of inhibitory priming, in which the primary function of inhibition was not to keep the cortex stable but variably to depress spontaneous or background activity in the non-dominant assemblies. The most inhibited assembly would be the best candidate for the next active unit, since it would be the most fully "rested," having been prevented by the inhibition from developing much fatigue in its component neurons. It would thus be the one most likely to spring to life following the release of the inhibition.

Thus, between 1956 and 1967, a series of increasingly sophisticated simulation studies, aided by advances in neural theory, provided preliminary validation of a cell-assembly-type model of learning and memory.

Meanwhile, yet a third approach to the priming issue had appeared. Good (1965) introduced the notion of subassemblies, small subclumps of especially high connectivity within the larger cell-assembly. He viewed the priming process as a transfer of activity from the currently active assembly to the next one in line by means of the subassemblies they had in common. In Good's scheme, then, assembly A and assembly B would share some group of neurons, a group which could contain one or more subassemblies. As activity in A began to die out, the shared subassemblies would (because of their high internal connectivity) tend to remain active the longest and hence, in their roles as members of B, arouse the second assembly. The result would be a transfer of activity from A to B via common subassemblies. In addition to providing an alternative to the Milner and Holland theories of priming, the notion of subassemblies has been employed by Good and others as an important tool in theorizing about other aspects of neural models (e.g., see Kaplan, 1968). The subassembly has also been recently acknowledged as a useful tool by Hebb (1968).

This concludes a brief survey of a field which might best be termed "neo-Hebbian neural modeling." No attempt has been made to be exhaustive, either with respect to the investigators mentioned or with respect to the details of their investigations. Rather, this discussion has been designed to provide a general picture of the context in which the writer's work has been carried out.

Since there are many others who deal with neural models of one kind or another, what remains to be done in this chapter is to identify the larger context. That is, where does neo-Hebbian neural modeling fit into the general scheme of theories about and research into the neural bases of behavior?

Initially, it is important to distinguish neural-net models from other types of models or theoretical approaches to the neural bases of behavior. There are, for example, a number of models of the function of the single nerve cell, ranging from abstract mathematical formulations to actual electronic implementations. While the contributions to modern neurophysiology of such models cannot be denied, it seems unlikely at present that much can be learned about perception, learning, and memory except from studies of the dynamic interactions among large numbers of neurons.

At the other end of the continuum from such very molecular, single-unit, models are the very molar approaches which form a subset of what is sometimes called "artificial intelligence." Here can be found models of pattern recognition, problem solving, and the like, which often show only remote concern with the underlying physiological substrates of the behavior in question. Once again, the importance of such studies is not being questioned; but their contribution is usually more to an understanding of behavior, _per se_, than to a grasp of its neural bases. It would seem, then, that the most productive interface between behavior and physiology lies at the neural network level, with models which deal with the interactions among large numbers of neural primitives (neurons or small groups of neurons).

A useful means of further categorizing these neural-net models themselves has recently been developed; it is summarized by Kaplan (1968). Neo-Hebbian models can apparently be distinguished from most other varieties of network models by the presence of two independent characteristics.

The first of these characteristics is a learning rule, by which is meant any algorithm or mechanism, internal to the model, which provides for the adjustment of parameters (notably synapse strength) on the basis of experience. A model lacking such a rule can seldom exhibit true adaptive behavior. The classic McCulloch-Pitts (1943) neural networks, for example, made possible the realization of arbitrary behavior; but once a network was designed, there was little provision for modification of its behavior. And the networks of Farley (1962), despite their more random nature, were each limited to modeling one particular class of EEG phenomena.

The second characteristic which serves to distinguish neo-Hebbian models is the largely random nature of their connection schemes and the resultant possibility for closed neural circuits. Instances of non-random net models would again include the McCulloch-Pitts approach, as well as Rosenblatt's (1958) perceptrons. In the latter case, closed neural circuits are precluded by the "straight-through" design of the connection patterns.

Kaplan concludes that, among the handful of models which have both a learning rule and sufficiently random interconnection patterns to guarantee multiple closed loops, "the Hebb-Milner model is the best known and most influential."

In the chapters to follow, a new neo-Hebbian model, based on the subassembly as a primitive element, will be developed and applied to (among other things) some new experimental data.

CHAPTER II: THE MODEL DEVELOPED

The primitive unit in the model to follow will be the formal counterpart of a subassembly, a concept originated by Good (1965). As outlined in Chapter I, Good viewed subassemblies as smaller, more strongly interconnected, groups of nerve cells within the larger cell-assembly. These small units were capable of self-sustained activity which endured longer than that of the cell-assembly as a whole and were thus good candidates for the means of transferring activity from one cell-assembly to another, among other functions.

The notion of the subassembly that will be employed here is much in the spirit of Good's conceptualization, but differs from it in a few important respects. First, Good's suggestion that there might be sub-sub-assemblies, etc., is fully employed; a large neural circuit is here understood to be a hierarchical collection of many subassemblies, organized into larger and fewer subgroups at successively higher levels. Note that the term subassembly is reserved for the smallest, bottom-level, units, however. There is reason to believe that some such hierarchy exists, since the processes envisioned by Hebb (1949) as responsible for the formation of a larger trace could be just as operative on its own internal structure. So, while the hierarchy is thought of as built up of subassemblies, its development might well proceed by progressive downward differentiation.

A second difference between the present approach and Good's is that subassemblies are here assumed to provide a non-overlapping, exhaustive decomposition of any higher-order trace. There are no "free neurons" in the portion of neural space under study; and a given neuron is not considered a member of more than a single subassembly. This too is not unreasonable, since in the highly-interconnected structure of a mature cell-assembly there would not likely be a neuron which is not connected to many others. Each neuron then has "allegiance" (in the sense of connection strength) to at least one subassembly. If it has allegiance to many subassemblies, it can be considered a member of that one to which it is most strongly connected and a means of interconnection between its "own" subassembly and those others with which it makes significant contact.

(Individual neurons actually play no role in the model to follow. The subassembly is the primitive element, in the sense that there is no attempt to model its internal physiology.)

Another addition to Good's approach concerns the stability of subassemblies. Since the organism principally under consideration is the human adult, it is assumed that most subassemblies are permanent cerebral fixtures. Two considerations prompt this hypothesis. First, the amount and variety of prior experience should have been sufficient to allow fractionation and recruitment (Hebb's terms for loss and gain of member neurons as a result of experience) to run their courses. And second, since subassemblies are perceptual and conceptual building blocks, the stability of adult percepts and concepts suggests that subassemblies do not change much.

Although Good occasionally suggests that subassemblies represent specific stimulus components, like phonemes, no such commitment is made here. Rather, it is assumed that sensory input consists of familiar entities (or of entities with familiar components) which have stable neural counterparts in collections of subassemblies.

Although all of the above differences from Good's conceptualization are important, the term subassembly is retained here because the similarities are even more important, because credit is due Good for the innovation, and because other choices of label (like "primitive trace component") are cumbersome. One final point must be emphasized. The size of the primitive unit in the present model, while it could be about the same as what Good had in mind (on the order of ten to a hundred neurons), is not critical to the operation of the model. Thus the term subassembly should not be construed as placing an upper bound on the flexibility (number of states) of the primitive unit. In fact, the minimal-primitive nature of an isolated subassembly makes it an entity not behaviorally accessible and therefore not subject to arbitrary interpretations concerning size or behavioral aspect.

In the present context, then, the subassembly is the primitive component in the neural circuit hierarchy and may be thought of as a group of neurons, smaller than the complete representation of a simple stimulus or concept, but capable of self-sustained activity as a unit following some appropriate and adequate stimulation. And, since the concern in this model is more with neural dynamics in the adult organism than with the development of neural circuits, an extensive history (which led to such permanent subassemblies and their current patterns of interconnection) is assumed.

Although no commitment is made here to the region of the brain in which the portion of neural space being modeled exists, the area usually termed association cortex (perhaps combined with some higher sub-cortical centers) seems a likely candidate. This means that peripheral input-output matters are not within the scope of the model. The following two assumptions embody this understanding: (1) preliminary encoding of input stimulation, possibly through approximately the level of the more complex receptive-field pattern detectors, is taken for granted; (2) the issue of motor control is sidestepped by assuming that, when an item has been successfully retrieved from memory, there are appropriate subroutines available to program its expression in spoken or written form.

Also, while processes like rehearsal and retrieval will be described in terms of the model, the circuitry responsible for the initiation of such processes is presumably located elsewhere. No attempt is made to account for volition or planning. More generally, the present model has as its principal objective the limited goal of explaining the mechanisms mediating, and some of the variables influencing, the ability of subjects to remember various kinds of stimuli in one type of experimental situation (free recall). The extent to which this goal is realized will be considered in Chapter IV. The statement of goal, however, is not meant to imply that the model has no explanatory capacities outside the limited area of study; but such additional capacities are not often considered here.

Before explication of the model is begun, a few final comments are needed. The first concerns time. Time is quantized in the model; a single time step might be thought of as corresponding to some small fraction of a second of real time (the exact value is not critical). Also, there are three overlapping time periods to which frequent reference will be made. Very-short-term (VST) processes last at least several seconds and up to a couple of minutes following termination of input stimulation (they are also co-occurrent with such stimulation); their strength and duration are direct consequences of the strength and duration of the input, although other factors can be influential. Short-term (ST) processes begin a few minutes after input-termination and have effects up to several hours later; their strength and duration are based on activity during a time period in the recent past. Long-term (LT) processes begin after a few hours and have effects up through at least a few days later, and possibly much longer; their strength and duration are based on activity in a past time period more remote than that for short-term processes. The selection of this three-time-period approach and the approximate boundaries of the time periods are based on ideas in Kaplan (1968) and Halstead and Rucker (1968) and particularly on John's (1967) summary and interpretation of the work of Albert.

The terms priming and memory will become important. To avoid confusion, they will be generally defined at this time; a number of specific forms of each will eventually be introduced in terms of particular parameters of the model. Priming refers to any process by which one subassembly (or group thereof) increases the probable future response to a given level of input of either itself or another subassembly (or group thereof). The subassembly or neural circuit that is more likely to have a higher future level of response is called primed.

A brief digression concerning terminology is necessary. Both Milner (1957) and Herzog (1968) employ the term priming in the context of Hebb-like neural models. Milner's physiological interpretation of priming (the "excitatory priming" described in Chapter I) led him to identify a "primed state" with an "excited state." In the present model, current excitation will be only one form of priming.

Herzog has a nice treatment of priming which is similar to (and in fact influenced) the present approach. Herzog calls a trace primed if it is easier to activate than usual; he distinguishes three major types of priming--prior, concurrent from within, and concurrent from without. The types of priming to be introduced in the following development, although they employ temporal and external-internal distinctions, cannot be identified with Herzog's types in any straightforward manner. This is true first of all because concurrent priming is only available from within in the present model. Furthermore, the writer acknowledges an unusual use of the term priming with respect to LT processes, since Herzog and other users generally restrict the term to fairly short-term ("pump-priming") kinds of processes.

In contrast to priming (although once again in a contrast perhaps least significant in the long-term situation), memory refers to any state of a subassembly or neural circuit that contributes to an improved capacity for correct response in a recall task (see Adams, 1967, for a similar definition). In the subsequent analysis, memory states will always be the results of priming processes; the better primed a neural circuit is (in the relevant time period), the better the chances for recall. The two terms are kept separate not only because one refers to a process and the other to a state, but also because at least one kind of priming mediates more than its analogous form of memory and at least one kind of memory is based on more than a single form of priming.

In the development which follows, the mechanics of the model will be described in detail, beginning with the primitive subassembly unit and then turning to networks of such units. In addition to the formal development, terminology and concepts to be used in subsequent applications of the model are introduced at the points in the discussion when the most relevant underlying parameters are being described. Such interwoven interpretation is identified in the first five sections of this chapter by an (I) at the beginning of each paragraph. This should reduce confusion about where the model stops and the interpretation begins. Finally, a glossary of all symbols used in this chapter is included at the end.

A prototype primitive component of the model, the SA (subassembly) unit, is diagrammed in Fig. II-1 on the following page. It has 2N-2 binary input lines and a single binary output line (branching into 2N-2 equivalent lines). N relates to the size of a network of such units and will be used later. The SA unit can be seen to contain rather elaborate machinery, which is divided among three major sub-units, SC (state control), IS (input summation), and CC (connection control). These three sub-units will be discussed in turn in the first three sections to follow.

It should again be emphasized that the behavior (output) of such an SA box, as a function of its inputs from other such units and/or the "outside world," is a model of the behavior of a physiological subassembly as a function of <u>its</u> inputs. Since the behavior of a physiological subassembly has never been measured, the model is based on the writer's own theory (as influenced by Hebb, Good, single-neuron physiology, intuition, and other sources) of how a subassembly behaves. The internal componentry of the SA box is built to produce such behavior and does not reflect the neural contents of a physiological subassembly.

A. <u>The SC Sub-unit</u>. This component has two parts, FSD (finite state device) and STP (short-term primer). FSD is the usual finite automaton quintuple, (I^6, O, S, q, o). S is the set of (internal) states of FSD and consists of a subset of the

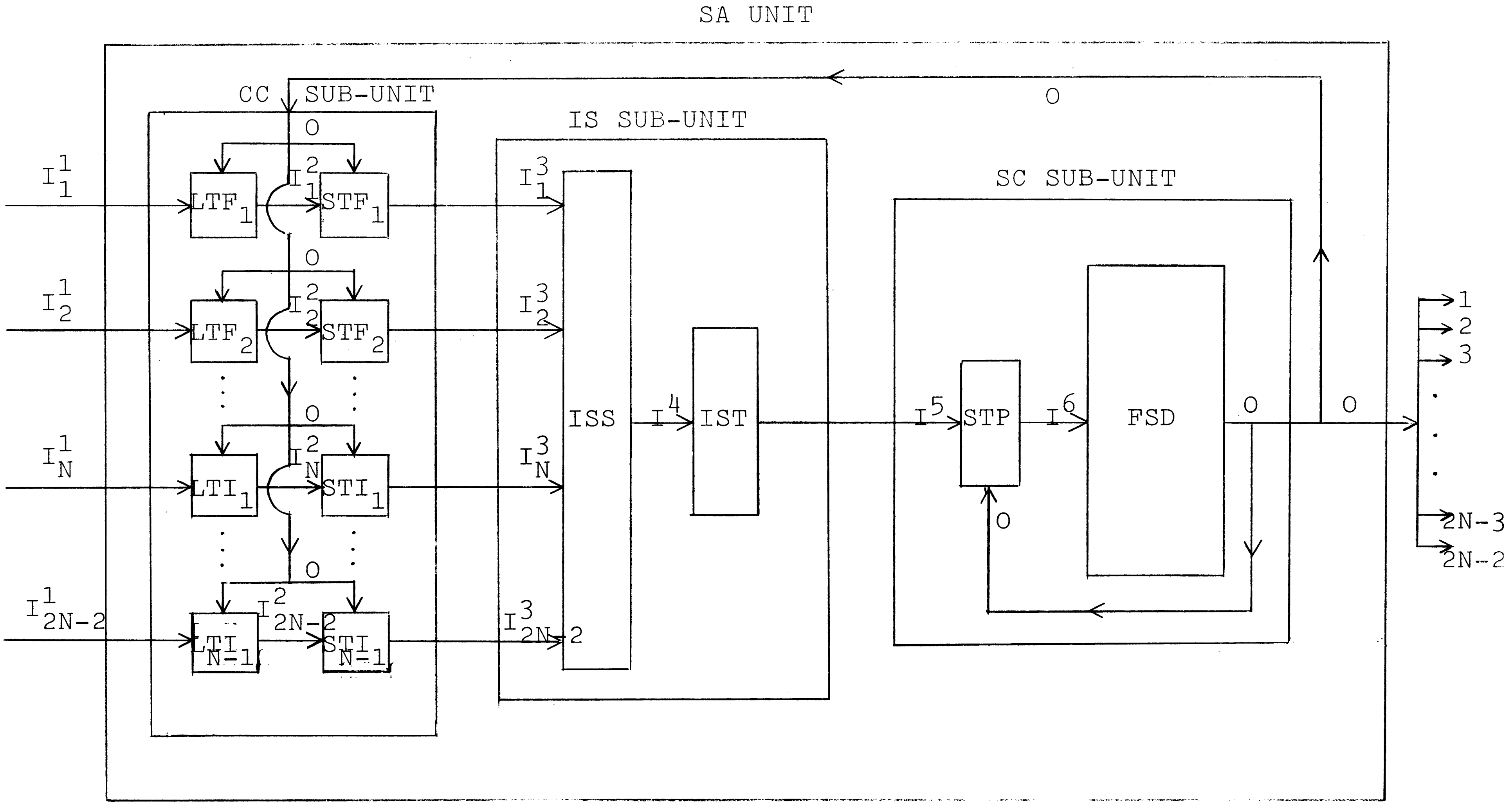


Fig. II-1. The Prototype SA Unit

product of s_1 ordered E (excitation) levels and s_2 ordered F (fatigue) levels.

$$S \subset E \times F, \text{ where } E = (e_1, e_2, \ldots, e_{s_1}), \text{ and } F = (f_1, f_2, \ldots, f_{s_2}). \tag{1}$$

The state-transition function, q, specifies permissible state changes under all possible input conditions. There may be up to five transitions from a given state.

$$S(t) = (e_i, f_j) \rightarrow \left\{ \begin{array}{l} (e_i, f_j) \\ (e_{i+1}, f_{j+1}) \\ (e_{i+2}, f_{j+1}) \\ (e_{i-1}, f_{j-1}) \\ (e_{i-2}, f_{j-1}) \end{array} \right\} = S(t+1), \quad \begin{array}{l} 0 < i \le s_1, \\ 0 < j \le s_2. \end{array} \tag{2}$$

These transitions are shown diagramatically in Fig. II-2.

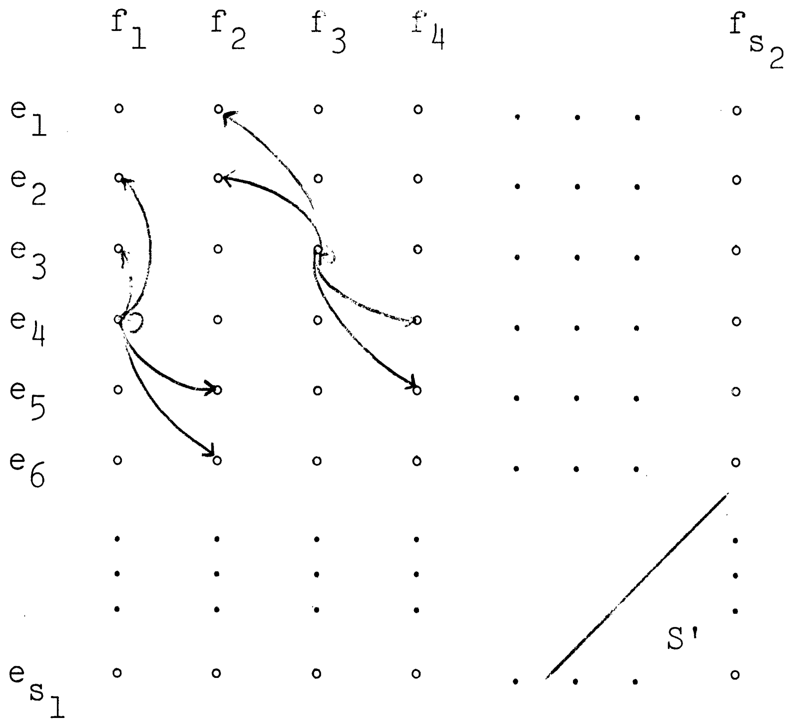


Fig. II-2. State-transition Relations

States on the edges of the state space have slightly different transitions, consistent with the ranges for i and j in (2).

Further, not all states are accessible. That is, for each i there is some maximum permissible value of j, which (especially for large i) will not always be as large as s_2. This set of restrictions deletes some subset S' (as shown in Fig. II-2) from the full product set in (1).

Appropriate partitions of the I^6 alphabet to govern the transitions in (2) will be discussed later, after the nature of the alphabet has been fully described.

(I) FSD is the heart of the subassembly. It contains the parameters regulating the amount of excitation or level of activity (corresponding to the average rate of neural firing) in the SA, as well as the amount (average level) of fatigue resulting from previous activity. The E and F levels are thus magnitude-ordered quantities of activity and fatigue, respectively; a subassembly at level one of each displays no (or perhaps minimal background) firings and has fully recovered from any earlier activity. Since there is no reason to believe that a given input will have identical increment or decrement effects on activity no matter what internal state it encounters, the state space may be contoured by differences in inter-level increments along either dimension; thus, if it takes slightly more input energy to produce a given excitation increment when the initial excitation level is higher, then the differences between successive E-level values would be considered to become gradually smaller as the level increases.

(I) The state transition relations allow various amounts of input energy to maintain the existing state or move to one of four others. Thus more intense (excitatory) input (and/or more enduring input, since temporal summation will be described shortly) will cause the state to cycle more quickly to a higher ultimate level of excitation (and fatigue). Inhibitory input will have the opposite effect, also in proportion to its strength (the concept of input strength will be more formally treated later). The static condition (maintenance of the same state) however, is not assigned to zero input; in this case, there is understood to be a normal slow decay in both E and F levels.

(I) This slow decay, which lends a sort of inertia to the system, is the counterpart of reverberatory activity among a trace's neurons following stimulus termination. Such reverberation is the basis for priming and memory effects during the very-short-term (VST) time period.

(I) Very-short-term priming (VSTP) is the term applied to this reverberatory process. It is priming from within, since the subassembly is increasing its own probable future response to a given input level. This is a result of the temporary heightening of the activity above what would be expected in the absence of (much) input. An input in the very-short-term future will thus be able to raise activity to a level greater than it would otherwise have been capable of producing.

(I) Very-short-term memory (VSTM) is the term applied to the heightened state of excitation that results from VSTP. This state contributes to an improved capacity for correct response in a recall task because retrieval (to be described later) is likely to be successful for an active circuit. Since what is retrieved is considered to be represented by a collection of subassemblies (once again, a fuller discussion will follow), most of which would be undergoing VSTP, recall may be regarded as the result of the application of retrieval processes to the whole collection in parallel.

(I) The strength of VSTM (i.e., the degree of improvement in chances for recall) is directly proportional to the duration of VSTP, which is a function of the degree of excitation from which the state is decaying. This last, in turn, depends upon the duration and strength of the input and on the initial state in FSD when the input commenced. This means that, all other things equal, the stronger and more enduring the input, the better the chance of VST recall.

(I) With regard to numerical values, s_1 (the number of E levels) would be quite large, since VST activity can persist for so many time steps, requiring the decayed-from state to be potentially quite far removed from the resting state. On the other hand, there is no apparent reason why s_2 could not be considerably smaller.

The output function in FSD, o, probabilistically controls the production of some frequency of pulses (ones) on the binary output line, for each E level. More specifically,

$$O(t+1) = 1, \text{ with probability } p_i, \text{ where } p_i = o(e_i(t)),\ i = 1, 2, \ldots, s_1; \text{ and } o \text{ is a non-decreasing function with respect to } i \text{ (i.e., } p_{i-1} \le p_i). \quad (3)$$

Thus, $o\colon E \rightarrow P$, where $P = (p_1, p_2, \ldots, p_{s_1})$ and $0 \le p_i \le 1$

for all i. Note that P is not a probability vector in the usual sense, since the sum of the p_i would normally be larger than one.

Note also that this output line, O, not only leaves the SA unit (as the output of the subassembly as a whole), but in addition returns in several feedback loops to other SA components. These loops will be treated later.

(I) The output line is binary, and the output function hence probabilistic, because greater physiological realism is preserved in a pulse-frequency coding scheme than in a variable amplitude scheme. (The input lines, which are the outputs of other SA units, are also binary.) This binary nature of the connection lines is not essential to the operation of the model.

(I) There seems to be no reason not to make the non-decreasing o function linear, with slope one, since the intention is for the output of any SA unit to mirror its current activity (excitation level). This relation is important to the feedback loops as well as to physiological realism.

The second component of the SC sub-unit is the short-term priming mechanism, STP, which is a quadruple (I^5, O, I^6, u). The function u performs the switching operation

$$I^6(t) = u(I^5, O) = \begin{cases} I^5(t)\cdot\left(1 + K_1\dfrac{\sum_{n=T_1}^{T_2} O(t-n)}{T_2 - T_1}\right), & I^5(t) \geq 0 \\ I^5(t), & I^5(t) < 0. \end{cases} \tag{4}$$

STP thus multiplies positive (facilitory) inputs by a factor which exceeds one in proportion to the frequency of non-zero outputs from FSD during a previous interval of time. The constant K_1 controls the magnitude of this effect.

(I) As its name suggests, STP is responsible for short-term priming from within (STPI, for short-term priming, internal; short-term priming from without will be discussed later). The subassembly increases its own probable future response to an input by actually augmenting the input. If a subassembly has been particularly active for a while (because of input stimulation and subsequent VSTP), and then quiet for a while, a new input will be especially effective.

(I) T_1 controls the delay before STPI becomes effective and is probably not zero for two reasons. First, the increased synaptic efficiency within the subassembly (which is what STPI is really representing) probably depends on chemical changes, which take time. Second, even if such synaptic changes were instantaneous, the fatigue level would be high as a result of the period of high activity just completed. The difference between T_1 and T_2 controls the maximum duration of STPI.

(I) There is a natural growth and decay inherent in the STPI process. The passage of time causes the particular period of high activity responsible for the priming to recede into the past. The priming first appears when the receding activity enters the relevant time frame (as the first pulse of the activity becomes T_1 time steps old) and increases until it is completely within the frame. The priming later decays as the successive pulses of the activity lose influence, as a result of having aged more than T_2 time steps. Since the time frame should be quite long relative to the usual burst of stimulation plus reverberation, most STPI functions will have relatively long and flat middle portions.

(I) Short-term memory (STM) is the term applied to the heightened state of potential excitability that results (in part) from such priming. This state contributes to an improved capacity for correct response in a recall task because retrieval depends upon input efficacy (as will later be made clear), which is directly augmented by the priming. Again, it should be remembered that what is really retrieved is probably a collection of subassemblies, many or most of which have STM strength. The other factor in STM, short-term priming from without, will be considered later.

(I) The strength of STM is, for the moment, a result of the strength and duration of STPI, which is in turn related to the strength and duration of the original input and its subsequent VSTP. Thus, for two externally identical inputs, the one which (for any reason) provokes greater VSTP will have a better chance of being recalled from either VSTM or STM (depending upon how much time has elapsed).

(I) With regard to quantitative considerations, the values of T_1 and T_2 have already been shown to be directly related to the latency and maximum duration of the ST time period. Another issue relates to the relative strength of VST and ST effects. Since VST effects reflect actual heightened activity (rather than potential, probabilistic behavior) their impact should be greater. Hence K_1 should be adjusted so that the increment in excitation due to current reverberation is larger than the increment due to the effects of this same reverberation via STPI.

B. The IS Sub-unit. Input summation involves two component operations. ISS (input summation, spatial) combines all the various inputs from the other SA units in the network. IST (input summation, temporal) allows the net input at a given time step to be influential for some time to follow.

More specifically, IST is a triple (I^4, I^5, v). The unit operates on a temporal sequence of I^4 inputs to produce a weighted sum of such inputs for the current time step plus the preceding T_3 time steps. The switching function is

$$I^5(t) = v(I^4) = \sum_{n=0}^{T_3} z_n I^4(t-n), \text{ where } 0 < z_n \leq 1 \text{ and } z_n \geq z_{n+1}, \text{ for all } n. \qquad (5)$$

(I) This summation within a subassembly is based on the capacity for single neurons to exhibit such behavior. The overall effect is a smoothing of the input; there are fewer drastic changes in input from one time step to the next. This contributes to what would seem to be a desirable stability in the behavior of the subassembly. Since a time step is quite large with respect to single-neuron temporal properties, the numerical value of T_3 should be quite small, probably less than ten. The z_n may be selected to give any desired appearance to the decay of temporal effects. Three alternatives are no decay

($z_n = 1$ for all n), linear decay to some small z_{T_3}, and exponential decay. The third choice seems most reasonable, on the basis of the shape of post-synaptic-potential decay in single cells.

ISS is also a triple, (I^3, I^4, w). (When no subscript is used on I^1, I^2, or I^3, the symbol is being used to refer to the entire array of input lines at the stage in question.) The unit treates the first N-1 of the input lines as facilitory and the last N-1 as inhibitory, performing the switching function

$$I^4(t) = w(I^3) = \sum_{n=1}^{N-1} I_n^3(t) - \sum_{n=N}^{2N-2} I_n^3(t). \qquad (6)$$

(I) Spatial summation is a natural feature. A subassembly is sufficiently small and tightly knit so that an input should be equally effective no matter where (i.e., with which neuron) it makes contact. And two inputs at divergent locations should have an additive effect.

(It might be observed at this point that the division of facilitory and inhibitory functions into two separate sets of input lines is a rather artificial distinction. There is more and more reason to believe that synapses in the central nervous system are not simply and forever facilitory or inhibitory as a consequence of the one type of transmitter substance the presynaptic neuron is capable of releasing. In fact, Kandel and Wachtel (1968) have recently uncovered some rather startling properties of neurons in the abdominal ganglion of <u>Aplysia</u>, properties which may (with appropriate caution) be generalizable to the human CNS. Among other things, these investigators have found a single pre-synaptic neuron making facilitory and inhibitory mono-synaptic connections with other neurons, while releasing acetylcholine at both types of junctions. Even more interesting is the demonstration that a single mono-synaptic cholinergic connection can be facilitory when driven at one rate and become inhibitory when driven faster. The hypothesis is proposed that there are at least two types of cholinergic receptor sites on the post-synaptic cell. On the basis of this kind of evidence, it might be more reasonable to implement the spatial summation just discussed, as well as the connection controls to be discussed next, in terms of single lines which retain flexibility as to the sign of the input. Alternatively the separation of function might be thought of as representing receptor site differences, rather than independent communication channels. Such changes in structure and/or interpretation would not alter the basic operation of the model, however.)

C. The CC Sub-unit. Connection control in the SA unit is accomplished by an array of units in the CC sub-unit. There are long-term connection controls on both the facilitory (LTF) and inhibitory (LTI) lines. And a similar distinction is employed with respect to the short-term (STF-STI) connection controls. Each of the four categories of units is thus subscripted from one through N-1. The short-term units will be described first.

The operations carried out by the STF-STI units are similar in many ways to that of the STP unit. The same period of past time is used, so that T_1 and T_2 have the same meaning as before. And the same growth and decay properties apply. The major difference is that the critical behavior is not merely activity in FSD but the correlation of such activity with incoming pulses. Specifically, STF_i is a quadruple, $(I_i^2, I_i^3, 0, g_s)$. The switching function, identical for all i, is

$$I_i^3(t) = g_s(I_i^2, 0) = I_i^2(t)\cdot(1 + K_2\frac{\sum_{n=T_1}^{T_2} 0(t-n)I_i^2(t-n)}{T_2 - T_1}). \quad (7)$$

And STI_i is a quadruple, $(I_{i+N-1}^2, I_{i+N-1}^3, 0, h_s)$. The switching function, identical for all i, is

$$I_{i+N-1}^3(t) = h_s(I_{i+N-1}^2, 0) = I_{i+N-1}^2(t)\cdot(1 - K_3\frac{\sum_{n=T_1}^{T_2} 0(t-n)I_{i+N-1}^2(t-n)}{T_2 - T_1}). \quad (8)$$

A facilitory (inhibitory) input is thus incremented (decremented) by a factor which exceeds one in proportion to the frequency with which the input line and 0 were simultaneously active during a previous interval of time. The constants K_2 and K_3 control the magnitudes of these effects.

(I) What these STF-STI units are implementing is the basis for formation of temporary associations between subassemblies and collections of subassemblies. Short-term priming from without (STPE, for short-term priming, external) refers to any activity on the part of two interconnected subassemblies which is sufficiently coordinated for one or both of them temporarily to achieve a stronger facilitory link with the other, by means of incremented facilitation and/or decremented inhibition in the relevant connections. This is a form of priming, since one subassembly is increasing the probable future response of another subassembly to inputs to the latter from the former.

(I) The use of the same temporal parameters and general functional forms as were employed for STPI (see equation (4)) is reasonable. Although one term applies to the global effects of synaptic changes within the SA units and the other to the global effects of synaptic changes between such units, there is no apparent reason to believe that the individual synapses involved behave differently during the time period in question.

(I) The requirement of simultaneous, as opposed to successive, activity to initiate STPE creates no special problems. When temporarily heightened association is established between the representations of two stimulus items, this is assumed to be the result of successive activity among the two *collections* of subassemblies. As activity is dying down in one collection, it is growing in the other. Thus the STPE links may be set up by the group of subassemblies which is simultaneously active during this transition.

(I) Short-term memory (STM) has already been discussed in connection with STPI. This memory state is further enhanced by STPE, and in two ways. First, the simultaneous activity among members of a subassembly collection representing an item will cause a transient heightening of their already strong mutual ties; this can facilitate activity of the collection as a whole during retrieval, especially if some members are weak in STPI. Second, transient association bonds between such collections (resulting from temporal contiguity in stimulus presentation) can help by directing retrieval along such bonds. This idea will be more fully considered in the subsequent discussion of retrieval.

(I) The K_2 and K_3 constants provide control of the relative impact of STPE, much as did K_1 for STPI. These should likewise be set so that STPE is weaker than VSTP. There is still flexibility with respect to the relative strengths of STPI and the facilitory and inhibitory components of STPE. A rank ordering of K_1 (STPI) $\geq$ K_2 (facilitory STPE) $\geq$ K_3 (inhibitory STPE) seems intuitively reasonable; but no further justification can be offered.

The second set of components in CC is the LTF-LTI series. The facilitory-inhibitory distinction is the same as for the preceeding (short-term) case; but the function of these units is a little different. First, they act as gates, probabilistically controlling the effective proportion of input on the particular line that will ultimately reach FSD. That is, LTF_i is a quadruple, $(I_i^1, I_i^2, 0, g_i)$, where $0 \leq g_i \leq 1$ and

$$I_i^2(t) = \begin{cases} 0, \text{ if } I_i^1(t) = 0 \\ 1, \text{ with probability } g_i \text{ (and 0, with} \\ \quad \text{probability } 1-g_i\text{), if } I_i^1(t) = 1. \end{cases} \tag{9}$$

Substituting h_i for g_i in (9) yields an equivalent definition, specifying the gating properties of the LTI units. Note that, while there was only one function g_s (or h_s) whose values varied with differences in behavior among the STF (or STI) units, there are N-1 independent g_i (or h_i) probabilities for the LTF (or LTI) units.

(I) These gates play an important role, since the whole space of SA units is viewed as fully interconnected (as will be described). In other words, each SA has potential input, both facilitory and inhibitory, from every other SA. In a realistic network space, many (if not most) of the g_i and h_i would be zero for most of the SAs. Initial settings of these parameters throughout the space would correspond to specifying subassembly collections established by previous experience. The subject of initial conditions will be treated in greater depth later.

It remains to specify the way in which the g_i and h_i values can change (within the zero-to-one bounds). The general scheme is similar to that employed for the STF-STI changes. That is, changes are based on a comparison of the activity during some past time period on the input line and in the SA itself (as reflected in O). The actual function has some differences, however.

$$g_i(t+1) = g_i(t)\cdot(1 - K_4 + K_5\frac{\sum_{n=T_4}^{T_5} O(t-n)I_i^1(t-n)}{T_5 - T_4}). \qquad (10)$$

Note that a new time period has been employed and that there is the added feature of a natural decay rate, K_4, which the correlated activity must at least compensate for if the connection strength is to be maintained. A connection which remains unused, or unimportant to the firing of O, for too long can become nonfunctional (as $g_i \rightarrow 0$). Also, (10) is not a switching function because (for the first time since the functions in FSD) there is a time step delay involved; this time step delay, however, affects only the value of g_i, not the transmission of information through the LTF box. In other respects, (10) is similar to previous equations of this general form.

The scheme for altering the h_i is similar to that for the g_i. But here it is the failure of the two activities to correlate that is important to the strengthening of the connection.

$$h_i(t+1) = h_i(t)\cdot(1 - K_6 + K_7\frac{\sum_{n=T4}^{T5} \overline{O(t-n)}I^1_{i+N-1}(t-n)}{T_5 - T_4}), \quad (11)$$

where $\overline{O(t-n)}$ is interpreted as the binary complement of O(t-n). An inhibitory connection becomes weaker (i.e., less inhibitory) as its input tends to coincide with activity in the SA. There are two additional constants in (11), providing decay rate and relative magnitude of effect independent of those for the g_i; but the time period (as determined by T_4 and T_5) is the same for all long-term connections.

(I) In effect, when both the input and the output are active, facilitory connections are strengthened and inhibitory ones are weakened; when both are inactive, both kinds are weakened; and when one is active and the other is not, facilitory connections are weakened and inhibitory ones are strengthened. So "used" relations between subassemblies tend to become more facilitory, "unused" ones tend to disappear, and "misused" ones tend to become more inhibitory. This is a somewhat more explicit version of Hebb's (1949) postulate concerning changes in connection strength at the single-neuron level (see Chapter I).

(I) Variation in the g_i and the h_i is the basis of long-term priming (LTP) and hence long-term memory (LTM). It should be emphasized that all long-term changes are considered to be usually quite small. Large, permanent changes in an adult's conceptual structure are assumed to be rare. So the constants, in particular K_5 and K_7, are set so as to make LT effects the weakest of those of the three time periods. Concomitant with this idea is the understanding that whatever changes do occur are usually temporary; LT connections tend to drift back to prior values, although this can take days or weeks. So it is possible to override long-established association patterns and conceptual habits through experimental manipulation, but usually not permanently.

(I) Long-term priming refers to the process, embodied in equations (10) and (11), by which one subassembly's capacity to influence another is increased. The change may be permanent; but, as just suggested, it will usually last for several days or so and then disappear, since the decay parameters will erase any change that is not "used" with some frequency.

(I) Long-term memory is the term used to refer to any current state of g_i and h_i values. Since these values can change from time step to time step, the term might seem inappropriate, were it not for the above discussion of the general stability of the values. LTM contributes to improved chances for recall, but in a way that cannot be clearly explained until the retrieval mechanism has been presented.

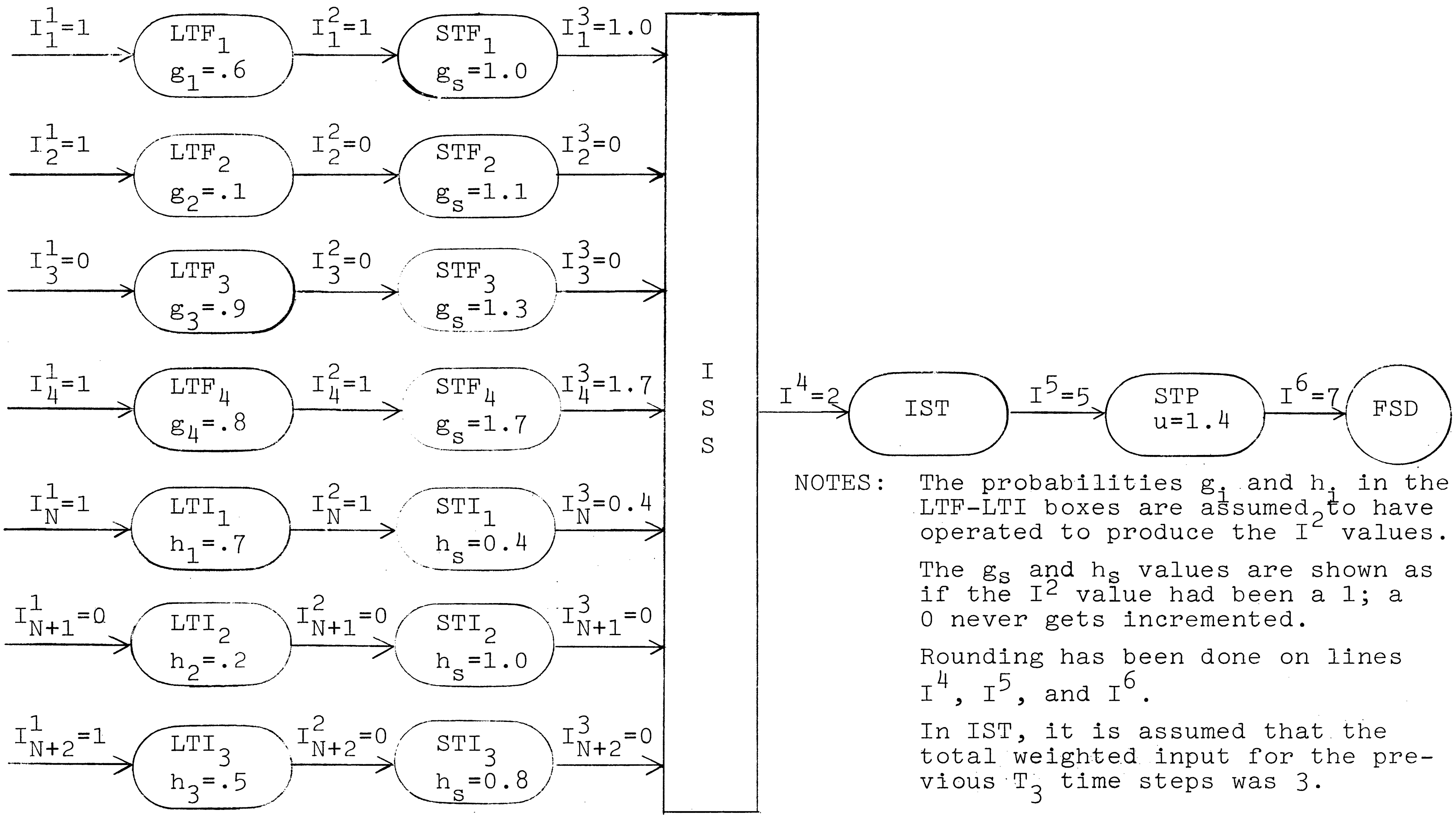
(I) With respect to numerical magnitudes, the temporal parameters T_4 and T_5 control the onset and duration of the period of past time that is used to determine LT changes, much in the way T_1 and T_2 controlled the comparable period for ST changes. The parameters should be adjusted to insure that the LT period is further back in time and of as long or longer duration than the ST period. The decay constants (K_4 and K_6) should be quite small, in order to make it possible for changes resulting from experimental manipulation to last for days or weeks. No claim is made here for any logical difference in the values of K_5 and K_7, which control the magnitude of the LT effects; but their impact on the activity of the SA unit should be minimal. LTM effects should generally be harder to produce experimentally than immediate memory effects. Combined with other statements about relative magnitude, this last comment implies the following order for strength of impact of effects during the various time periods: VST > ST > LT. The relation is just the opposite for the durability of these effects, however.

D. The Input Alphabets. As was apparent in the original sketch of the prototype SA unit (Fig. II-1), the initial inputs are subject to extensive processing, all of which has now been mentioned. It remains to consider the alphabets on these lines at each stage, with an eye to describing an appropriate partition of the alphabet on I^6 to govern the state transition relations in equation (2).

The I^1 lines are binary. And, since each one is either passed on or not (with some probability) by the LTF-LTI boxes, the I^2 lines are also binary. After this stage, it is useful to introduce some simplifying assumptions. First assume that the multiplying factors are sufficiently small so that none of the switching functions ever more than doubles the input value; this would seem to allow sufficient flexibility. Assume, second, that after spatial summation (inputs I^4 and following) all input magnitudes are rounded to the nearest integer; this involves no great loss of discrimination.

With these assumptions, any I^3 line carries at most a value of two. And the I^4 alphabet consists of all integers from $2-2N$ (maximum inhibition, fully primed, with no counteracting facilitation) to $2N-2$ (the opposite extreme). IST multiplies these values by up to T_3+1 (in the "worst" case of no decay during temporal summation), while STP could in turn double them again. With the rounding assumption, the result is that I^6, the input to FSD, has an alphabet no larger than all integers from $4(1-N)(T_3+1)$ to $4(N-1)(T_3+1)$, where N is the number of SA units in the network and T_3 is the temporal summation limit. Call these extrema MIN and MAX, respectively.

Fig. II-3 displays a simple example of input-alphabet



NOTES: The probabilities g_i and h_i in the LTF-LTI boxes are assumed to have operated to produce the I^2 values.

The g_s and h_s values are shown as if the I^2 value had been a 1; a 0 never gets incremented.

Rounding has been done on lines I^4, I^5, and I^6.

In IST, it is assumed that the total weighted input for the previous T_3 time steps was 3.

Fig. II-3. A Simple Example of Input-alphabet Dynamics

dynamics, involving only four facilitory and three inhibitory inputs. All remaining g_i and h_i are assumed to be zero. While many more inputs would probably be functional in practice, the extrema cited above would rarely be applicable, since those calculations assumed that all 2N-2 long-term gates had values of one.

In any case, it is now possible to complete the definition of state transition within FSD. Since there are up to five transitions from each state, four values, $a_{\dot{n}}$, $\dot{n} = 1, 2, 3, 4$, need to be selected to specify the following type of state transition function. For $S(t) = (e_i, f_j)$,

$$S(t+1) = \begin{cases} (e_{i-2}, f_{j-1}), & \text{MIN} \leq I^6 \leq a_1 \\ (e_{i-1}, f_{j-1}), & a_1 < I^6 \leq a_2 \\ (e_i, f_j), \quad \text{when} & a_2 < I^6 \leq a_3 \\ (e_{i+1}, f_{j+1}), & a_3 < I^6 \leq a_4 \\ (e_{i+2}, f_{j+1}), & a_4 < I^6 \leq \text{MAX}, \end{cases} \tag{12}$$

where $\text{MIN} = 4(1-N)(T_3+1)$ and $\text{MAX} = 4(N-1)(T_3+1)$.

(I) Parameter-value choice here is dictated by two considerations. The first, and most obvious, is that the $a_{\dot{n}}$ increase with respect to $\dot{n}$. Second, it seems appropriate to select a_2 just slightly greater than zero and a_1 just slightly less than zero; this will assure maintenance of the same state for slightly facilitory input and slow decay for zero or slightly inhibitory input. Assignment of the remaining parameters depends on the numerical values of the extrema.

(I) The concept of input strength has been mentioned previously; it is now possible to define it explicitly. Whether external stimulation (the source of which will be clarified shortly) or input from associated subassemblies is under consideration, one input can be stronger than another by lasting more time steps and/or by using more of the available input lines. In either case, the value reaching FSD has larger magnitude and/or longer duration. Strength thus refers to a magnitude-time product, where the sign of the input determines whether "facilitory strength" or "inhibitory strength" is being considered.

E. Networks of SA Units. Now that the functions of an individual SA unit have been outlined, it is possible to study interconnected collections of such units. The entire neural-trace space under consideration is understood to contain N SA units, with the potential for connecting the output of each to all of the others as both a facilitory and an inhibitory input (thus the 2N-2 inputs and output branches on the prototype unit). These N units are identical with respect to the following properties: internal componentry and connections, the state transition space and function in FSD, the output function in FSD, and the remaining switching functions and their parameters.

Nevertheless, there may be important differences among individual SAs, since it is possible to specify variable initial conditions in the following respects: initial state in FSD, initial output, initial increments in STP and the STF-STI series, initial values for long-term connections (the g_i and h_i), and current input values together with a history of inputs going back at least T_5 (the largest T) time steps. Of these initial settings, the most influential is the long-term connection pattern, since effects of the others are subject to early counteraction or decay.

The reason it was appropriate to specify both current inputs and current outputs in the above list of initial conditions rests in the assumption that any line connecting two SA units contains a delay of at least one time step. Thus the output from unit SA_a at time T reaches unit SA_b at time T+1 (or later) when there is a direct link from SA_a to SA_b.

(I) It is now possible to model some portion of "cognitive space." Assignment of long-term connection strengths would be done so as to reflect a history of activity which led to the development of the present hierarchical subassembly collections. The delay in the lines reflects physiological reality in that the transmission of neural impulses takes time. As long as such delays (1) do not vary tremendously throughout the net and (2) do not approach in magnitude the length of the temporal summation period, their presence makes little difference to the functioning of the network. Violations of these two assumptions will not be considered here; in fact, all lines will be assumed to carry just a unit delay.

A collection of SA units (any subset of the N units) has a number of properties, some of which will be explored now.

First, such a collection is itself a higher-order device in the model. Its inputs are those inputs to its constituent SA units which are not also outputs of other constituent SA units; its outputs are those outputs of its SA units which do not make all their non-zero connections with other constituent SA units. Its excitation-fatigue state space may be defined as all ordered permutations of the FSD state spaces of its constituents (with the understanding that there may be many inaccessible combinations).

Also, it is possible to define a measure of the degree of membership any constituent has with respect to the collection as a whole. For any collection, A, of SA units, a particular SA' can be said to have centrality $C_A(SA')$ with respect to A, where centrality is defined as follows:

$$C_A(SA') = \sum_{\substack{n \in A \\ n \neq SA'}} (f_{SA',n} - g_{SA',n})(f_{n,SA'} - g_{n,SA'}), \qquad (13)$$

where the notation $f_{a,b}$ (or $g_{a,b}$) refers to the value of the particular f_i (or g_i) on the line running from subassembly a to subassembly b. The index n in (13) thus runs over all SA units in A, except for SA' itself. One thing such a definition of centrality does is to make possible the establishment of some criterion (in terms of minimum centrality) for the determination of SA groups which "belong together."

(I) Such groups are the counterparts of cell assemblies and other higher-order neural traces. Notice that centrality is based only on long-term connection strength, reflecting the idea that cell-assembly components, after extensive experience, do not easily recombine into stable new configurations. The notion of the neural representation of a stimulus item (or other elementary unit of perception or thought) is now meaningful. An adequately large collection of subassemblies (probably more than ten) with sufficient average centrality can be thought of as the neural counterpart of such an item.

(I) Presentation of such an item as a stimulus results in markedly increased excitation levels in most of the constituent subassemblies. The priming and memory process already described operate in a parallel, mutually facilitory, fashion throughout the collection, with a strength determined by input intensity, degree of connectivity, current states, and other internal factors. Retrieval will be seen to involve reexcitement (or to take advantage of current excitement) in just such a collection. Details of the retrieval process are presented in subsection G below.

(I) Such higher-order traces can overlap, in the sense that given SA units may be strongly connected to members of two such collections, but nevertheless be rare enough so that the collections maintain their individual identities. The degree of overlap between two such collections will be determined by the centrality criterion for membership and, more importantly, by how often the two collections have been active together in the past.

No mention has thus far been made of "external" inputs and outputs, of lines which come from no other SA unit within the net or which "leave" the space altogether. The latter situation will not be considered in detail, since the issue of motor control, of how an active trace influences behavior, is admittedly beyond the scope of the model. If it is desirable to distinguish some subset of the N outputs as the ones which contain the information which directs motor control (by way of other brain centers) this can be done.

The issue of external inputs to the network, inputs which are not the outputs of other SA units but rather the source of "outside" information, is more complex and more important to the modeling of a number of features of learning and memory. Two specific types of external inputs will be considered at length in subsequent sections. For the moment, it will suffice to point out that, although "freely dangling" lines could be employed for such purposes, an equivalent and more elegant formulation involves distinguishing some subset of special, "external-input" SA units. The members of this subset have all f_i and g_i functions artifically held at zero, allowing no influence from the remaining units within the network. The FSD states (E and F levels), and hence the outputs, of such units are subject to direct external control or experimental manipulation (within reasonable transition constraints).

Before continuing with an examination of complex processes like encoding and retrieval in terms of the model, it should be pointed out at this juncture that the interpretation of the model is becoming progressively less tightly linked to the machinery of the model. This trend, which has appeared in the last few pages and will continue throughout the remainder of the chapter, is an unfortunate but not uncommon attribute of a new and evolving theory. If what has transpired to approximately this point deserves the term "rigorous," it might be best to think of the remainder of the discussion as embodying potential rigor. The extent to which some of the inferences to be drawn follow unequivocally from the machinery can sometimes be determined only after extensive computer simulation, if then. It is for this reason that the explicitness and "rigor" of the machinery (features which make the model simulatable) are important. This issue of rigor will be treated more fully in the last chapter, after the development and application of the model have been completed.

F. Attention and Encoding. The scheme for specifying external inputs to an SA network which was just developed makes it possible to deal with a variety of issues in the analysis of learning and memory. The first such issue is attention, which will be employed here in a much narrower context than is often implied by the current use of this term in psychology; there is little concern here with how informational aspects of stimuli influence attention.

Intuitively, attention refers to the amount of time, concentration, careful study of detail, and the like that a subject devotes to whatever he is looking at or thinking about. Since the second case (attention to what he is thinking about) will be dealt with in terms of the notion of dominance to be introduced in the next section, only the issue of attention to external stimulus items will be considered now.

In this limited context, attention is quite similar to the notion of input strength already developed. Assuming there is some maximal set of external-input units that may be active for the stimulus in question, the subject's attention is a function of (1) the proportion of the time that the stimulus is displayed during which at least some of these units are active and (2) the fraction that these active units comprise with respect to the maximal set. What this definition does is to provide a measure for the intuitive notion that attention is better (stronger) when (1) a higher proportion of time is spent actually seeing the stimulus rather than looking at it but thinking about something else (or even looking elsewhere) and/or (2) when as many details of the stimulus as possible are being processed.

Another issue related to external input is encoding. Here it is important to clarify what is meant in the model by the "neural representation of an item" and to look at the possibility of an item being represented in more than one way. This discussion is not concerned with the earliest stages in the transformation of an energy configuration into neural impulses or with the routing of such impulses through preliminary pattern-recognition structures; these issues are, as pointed out at the beginning of this chapter, outside the scope of the model. But, even with the assumption that there is some pre-established correspondence between items and activity in groups of external-input SA units, there is much that remains to be said about encoding.

Initially, it is essential to take a more detailed look at the collection of subassemblies which has, up to now, been called the representation of an item. This collection contains some external-input units which are responsive to the various stimulus configurations which "mean" the item. And it also contains a number of standard SA units which are linked to these external-input units and to each other in LT connection patterns based on prior experience. Furthermore, it is important to remember the hierarchical organization principle, which makes it possible to distinguish sub-collections of SA units within the larger collection.

What does such an elaborate array of equipment have to do with encoding? First, realize that the locus of neural activity responsive to seeing the word CAT is likely to overlap significantly with the locus responsive to a drawing of a cat; these two items are probably among each other's closest associates. In fact, it is not necessary to stop with these two visual inputs. Also overlapping with them and with each other could be the loci of neural activity responsive to hearing the word "cat" or to seeing an actual cat.

The claim here is that all these modes for the concept cat have representations in the model which correspond to overlapping sub-collections of SA units within the larger collection representing the concept generally. (Here is an example of an assertion which, while intuitively reasonable to the writer at least, does not follow inevitably from the machinery of the model; the reader has already been warned that such things will happen.) If input activity were to excite the whole collection of modal representations uniformly, it might be impossible to distinguish between, say, the word and the figure. So activity which is either partial or of varying intensities among the sub-collections is needed. This could be achieved through the initiation of activity via different external-input SA units. There is thus a counterpart in the model for the intuitive notion that, while the word CAT and a drawing of a cat may mean virtually the same thing, they are encoded differently.

But all of this rests on two assumptions. The first, as stated above, is that there is machinery external to the model capable of routing the various stimulus configurations to appropriate collections of external-input SA units. The second assumption is that different patterns of activity in such units will not produce the same uniform activity in the larger collection. This requires some justification.

The reason it is possible to have a number of different pathways or patterns of activity within a single collection of modal representations can be based on two features of the model, inhibition and the hierarchical structure. The vastly oversimplified example in Fig. II-4 will be used to illustrate the analysis. In this figure, A, B, C, and D are four sub-collections of subassemblies within some larger collection not fully shown. The general picture is as was described above for the various types of "cat" inputs. A', B', C', and D' are the respective groups of external-input SA units in each sub-collection. By means of a small number of communicating SAs, represented by the narrow channels, the four sub-collections

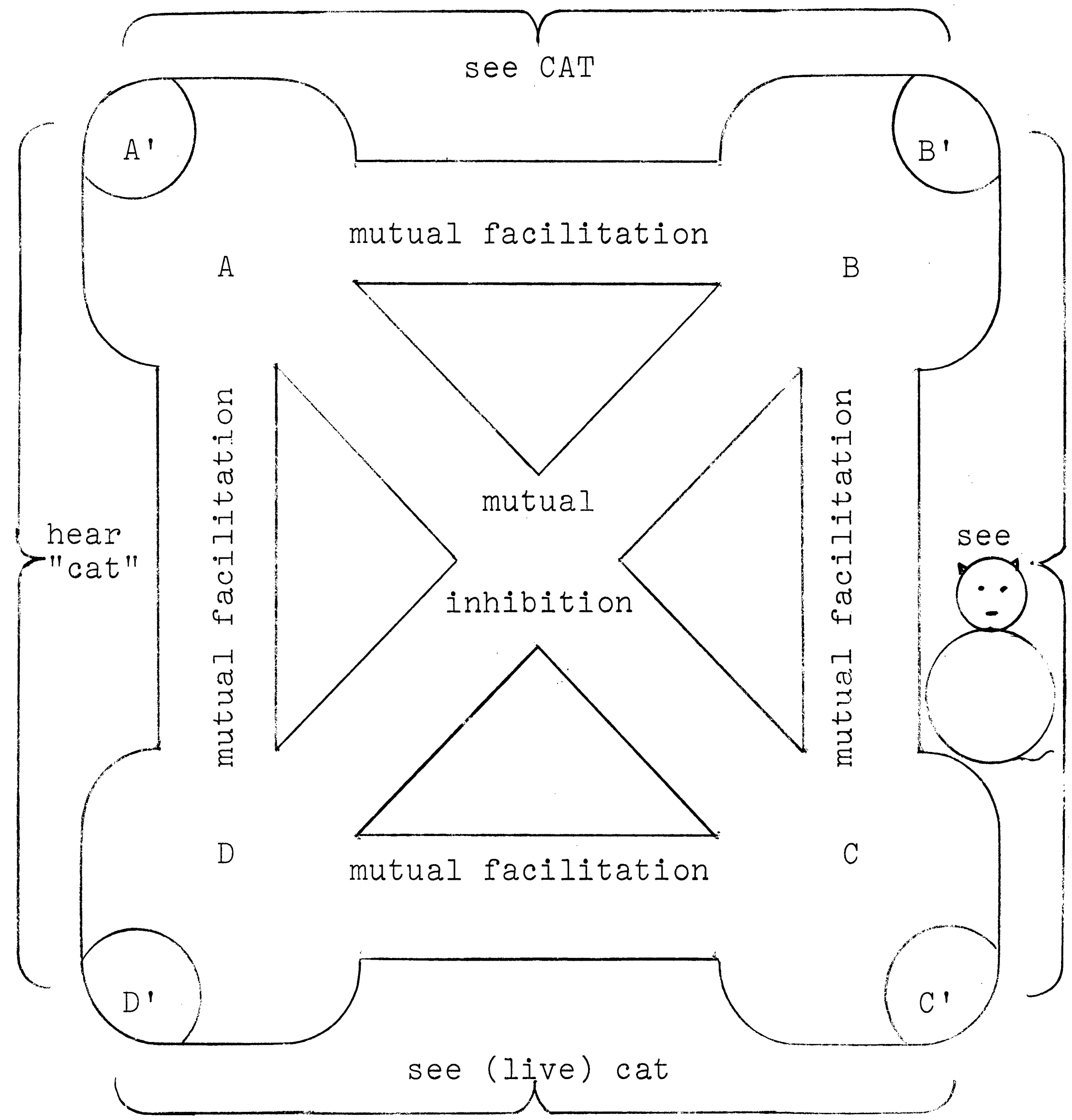


Fig. II-4. A Schematic Example of Multiple Encoding stand in the indicated facilitory and inhibitory relations to each other. Also, in a crude and oversimplified manner, various pairs of sub-collections are shown to be the representations of some of the common modes of the concept cat. Thus, when the word CAT is viewed, activity in A' and B' will presumably initiate activity in A-B as a unit (provided the input is strong enough), for example.

The important feature of the connection pattern shown is that, while the facilitation is such as to justify consideration of the four sub-collections as a single larger collection, sustained high activity is possible at any given time only in adjacent pairs of sub-collections. Activity in the remaining two is attenuated by the inhibitory connections. It is possible that the four would achieve some equilibrium state of low-level uniform activity. But this is where the external-input units come into play. If only (or primarily) A and B are subjected to external stimulation (as a result of activity concentrated in their external-input SAs, A' and B'), this, combined with their mutual facilitation will yield a level of activity sufficient to overpower C and D, which would in turn reduce the back inhibition from the latter to A-B.

Much more complicated patterns would normally be expected. But this example has suggested the possibility of many modes of activity within an interconnected collection of sub-collections of subassemblies. Hierarchical organization, inhibition, and external-input units are thus important to the functioning of the model. And notions of encoding and representation are hopefully somewhat clearer.

But there is more to be said about encoding. It would be nice to be able to account for the phenomenon called verbal encoding. Man's tendency to use his language capacity in non-verbal situations -- the most common example is the tendency for the name of an object to come to mind when the object is seen--raises the question of multiple encodings. In the discussion to follow, the notion of a verbal-label representation is not necessarily equivalent to the concept of an "acoustic image," as the latter term is used in contemporary psychology. On the other hand, it is the writer's opinion that the latter construct is probably a special case of the former, especially when issues like rehearsal are at stake (this argument gains some support from the discussion of Sperling's model in the next chapter).

In any case, the close relation between the representation of an object and the representation of its name has already been suggested. What remains to be explained is why there is a tendency for the verbal mode of activity to become active along with the figural (when the stimulus is purely figural) and why, more importantly, this tendency seems to be stronger (for most people) than the one in the opposite direction. That is, why is it usually more natural to think of the name for a perceived object than to generate an internal visual image in response to such a name?

For an admittedly oversimplified description of the types of neural structures which might underlie such behavior, it is useful to refer again to Fig. II-4. Assume again that the four indicated sub-collections of SA units are a part of some larger collection which is the overall representation of the concept cat. A-B is the representation of the word, while B-C is the representation of the figure. Now, if the inhibitory links between A and C were not (as previously assumed) symmetric, but were instead weighted so that A inhibited C more strongly than C inhibited A, the result would be that excitation of B-C would be likely to evoke activity in A, since B facilitates A strongly and C inhibits it only weakly. A-B would thus be active along with B-C; and the figure would have generated its own verbal label. The word as a stimulus would be less likely to initiate activity in C, since inhibition in the A-to-C direction is presumed to be strong enough to counterbalance the B-to-C facilitation.

It remains to speculate as to how such asymmetric inhibitory links might develop through experience. One argument is that, for children, the learning process is often a naming process in which the infant, seeing an object, gets told its name (or in which the youngster immediately asks the name of a new object). Thus if any order is likely when both object and name are stimuli during learning it is object first, then name. So activity in A while C is still active will tend to remove (or prevent formation of) inhibitory connections from C-to-A, via the mechanisms of LTP. On the other hand, the name is often present without the object in a child's experience. This means that associative priming from A to C is rarer;

inhibitory connections will develop strength while excitatory ones lose strength. This is a sketch of one basis for verbal encoding.

There is another basis however; and the two presumably work together. The second mechanism underlying verbal encoding rests on the concept of coherency. For a trace to be highly coherent means that the total number of SA units involved is smaller and that connections between these units are stronger than for most other comparable sub-collections. There is, in other words, relatively high centrality in a relatively small trace.

A more formal definition of coherency can be constructed in the following manner. Consider the two-dimensional space of Fig. II-5, in which traces are plotted in terms of their size (number of SA units) and mean centrality. The use of a logarithmic measure of size, as well as the suggested disproportion of the two scales, plays a role in the interpretation of this definition.

The coherency of any trace can now be defined as the

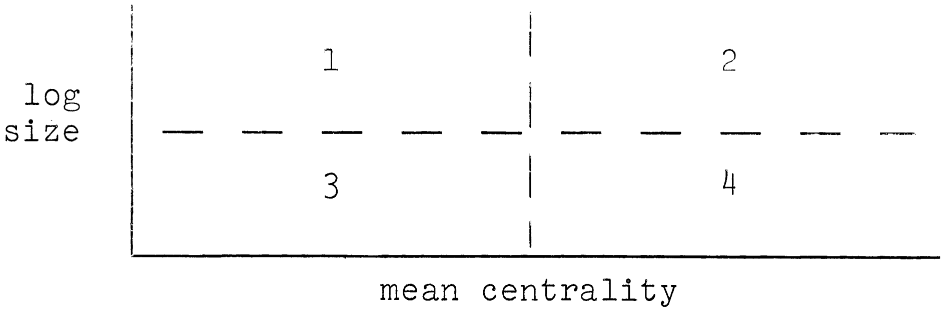


Fig. II-5. Definition of Coherency

vector length from the origin to the point representing the trace. A problem with this definition is that the most coherent traces would have both high centrality and large size, while it was suggested above that relatively small size would be coupled with high centrality to produce high coherency. The solution to this apparent dilemma lies in the fact that the combination of very large size and very high mean centrality is considered unlikely; the activity in such a trace would have to be so widely dispersed simply to hold it together that building up of very strong connections would be difficult. Thus the area labeled 2 in Fig. II-5 would be sparsely populated; most traces would fall in areas 1 and 4, where the centrality-size trade off is reflected. The logarithmic measure of size, and the consequent disproportion of axis lengths, makes the coherency of points in area 4 larger than that for most points in area 1, which is in accord with the informal definition. Area 3 contains those few traces which are both small and weakly connected and therefore have the lowest coherency of all.

To return to the second basis for verbal encoding, the argument here will be that verbal representations are more coherent than non-verbal ones. This is true for two reasons, both of which relate to a process similar to that which Hebb (1949) termed fractionation. In general, Hebb believed that a cell-assembly lost component neurons upon repeated activity in response to the same (or virtually the same) stimulus; nerve cells responsive only to unimportant variations in the stimulus tended to drop out. Any analogy to this process must be used with some caution here, since the units are subassemblies not individual neurons. The type of process involved does seem equally valid, however. Subassembly fractionation increases coherency because a smaller SA sub-collection is produced and the fewer inter-unit connections become stronger from more use.

The first reason verbal representations are subject to more fractionation is related to frequency of exposure. The average human being almost certainly encounters the word "cat," for example, far more often than an actual cat. (Even if he is a cat fancier and often in their company, he is also likely to talk even more about them.) Thus a greater number of exposures to the verbal form of the concept provides, in analogy with Hebb's notion, a greater opportunity and a greater impetus for fractionation (loss of subassemblies from the trace).

The second reason why verbal traces might be expected to be more coherent is interdependent with the argument just advanced. Even under conditions of repeated exposure, fractionation is more likely when the various exposures have smaller variance along important, cognitive dimensions. And stimulus variation is less important for verbal stimuli. That is, it makes little difference whether a word is printed in capital letters or scribbled in longhand. Unless one is attending to handwriting features or typeface style (which would presumably bring additional cognitive machinery into play), the meaning is identical and the stimulus therefore the same. To return to the cat example one more time, consider how much greater the cognitive difference is between a stylized drawing (as in Fig. II-4) and an artist's painting, or between the latter and a real cat, than it is between the two words CAT and cat, despite considerable variation in the surface representations in the verbal case.

Thus more important stimulus variations, combined with fewer total exposures, make figural representations considerably less coherent than verbal ones, in many cases. But how could this contribute to the machinery for verbal encoding? For one answer, consider the B sub-collection in Fig. II-4 (where non-symmetric inhibition between A and C is still being assumed). Now if "purely verbal" A is more coherent than "purely figural" C, by the above arguments for more coherency in verbal traces, then B represents a greater proportion of the verbal (A-B) units than it does of the figural (B-C) units. This would mean that the chances of activity in B-C leading to activity in A would be greater than the chances of activity in A-B leading to activity in C (especially with the asymmetric inhibition). Thus figural input would be more likely to provoke the verbal representation than vice versa. This analysis, in terms of coherency, when combined with the previous one based on the nature of childhood learning, makes verbal encoding at least a plausible feature of the model.

As a closing comment for this section, it must be admitted that much of the analysis so far, as well as some of that to follow, is most valid when the "items" being perceived (encoded, rehearsed, or whatever) are simple, concrete stimuli. It would be nice if higher levels of complexity and abstraction could be handled by simple extensions of the analyses given. But this may not always be true. What, for example, would be the "representations" of concepts like "redness," "integrity," or "time" in this model? It is questions like this which demonstrate how modest the goal of explaining memory for simple experimental stimuli really is. The fact that so modest a goal is also so challenging reflects on the primitive state of the art. While this is not the place to evaluate alternative models, it must be remembered that simple experimental stimuli are what most psychologists employ in their attempts to comprehend the sophisticated complexities of human behavior. And those few who are most willing to confront the nervous system directly are usually also those who are least willing to go beyond the nonsense syllable or its equivalent.

G. Retrieval, Rehearsal, and Recall. These are processes, central to an understanding of human memory, whose representation in the model is incomplete. No attempt is made to account for the initiation of rehearsal or retrieval, either voluntarily or in response to instructions. After such initiation, however, events in the realm of the model can be described. This will be done after a brief informal look at the processes under consideration in this section.

Rehearsal refers to any reasonably successful retrieval and transient dominance (a term to be fully defined shortly) of some of the items the subject has already seen, usually while subsequent items are being presented. Although variations can be used, the simplest and most common rehearsal strategy appears to be the review of the few items just preceding the current one. Rehearsal can also occur at the termination of the list, a situation most likely when there was no motivation or time to rehearse during stimulus presentation.

Recall resembles rehearsal in many respects. It too is a retrieval, but also a production (through motor systems outside the scope of the model), of preceding items.. Recall, however, is not usually subject to the time pressures that result from attempting to review items between successive presentations of new ones. Given these informal descriptions and similarities, the model should answer two questions about rehearsal and recall. First, what does it mean to retrieve an item, either for silent rehearsal or with an eye to motor programming for recall? Second, what considerations determine the priorities assigned to the items to be retrieved; specifically, what determines which items are rehearsed when there is only limited time available?

Some additional machinery is required before these questions can be answered completely. First, it is necessary to distinguish another class of external-input units, in addition to those for encoding. These retrieval external-input units may be thought of as being distributed somewhat randomly throughout the neural-trace space, making modest facilitory connection with most of the SA sub-collections. Some of the factors influencing the exact nature of the distribution and strength of these connections will be discussed shortly. The operation of these retrieval units is under voluntary control, although such control does not reside in the realm of the model.

Retrieval operates by means of such voluntarily initiated activity on the retrieval inputs. This activity enters many or most of the traces and serves to increment their excitation levels (i.e., the mean excitation levels of their component SA units). The likelihood that a given trace will actually be recovered and come to dominate the space (in a manner to be described shortly) is called its retrieval probability. This probability is a function of several factors. The relative proportion of retrieval input units that a particular trace has will be influential; this factor is regarded as partly a function of the organism's developmental history, partly random, and of small variance. The relative strength of the retrieval input connections which facilitate activity in the trace is also important; and this factor may be strongly influenced by the frequency of past use of these connections--the more often something is remembered, the easier it becomes to remember.

Conditions within the trace itself also influence its retrieval probability. The amount of fatigue resulting from recent activity may set an upper bound on the effects of retrieval input, for example. But the most important intra-trace parameters are the memory states. While retrieval may be partly random and partly influenced by other factors, the major determinant of the possibility of retrieving a trace should be how well the item the sub-collection represents is remembered. So it is important to examine how each of the memory states in the model may affect retrieval probability. In any of these states, the larger the proportion of SA units strong in the particular memory state, the greater the improvement in retrieval probability. Since the notion of a trace actually being retrieved and dominating the neural space has yet to be explained, it will be shown, in the discussion to follow, only how memory leads to augmented responses to retrieval input. Later, this response increment will be shown to make retrieval likely.

VSTM strength will certainly assist retrieval. In fact, the level of VST activity may itself already be high enough to mediate dominance. This means that the item is currently occupying the subject's attention, which is most likely during and just after its exposure as a stimulus (when VSTP is strong). But the presence of even modest VST activity will increase the level of activity that can be reached by the SA units in response to retrieval input.

In the case of STM, there need not be any current activity. But an input will have a larger than normal impact on a given SA unit because of the STP increment. This applies to a retrieval input as much as to any other type. (STF changes on the retrieval line itself could also play a part, if the item were recalled once and then subject to a second retrieval later. This is the short-term counterpart of the experience-determined effect on retrieval-input connection strength described above.) So, if enough SA units in the collection have enough STM, the chances of greater activity in the collection as a whole in response to retrieval input will be increased.

STPE can be as important as STPI, and in two ways. First, the connections between the SA units of a given collection may be temporarily enhanced by recent activity. Thus the retrieval input will lead not only to greater activity in individual SAs but also to more efficient transmission of this activity throughout the collection. Second, STPE between collections (items) can serve to direct the order of retrieval, as will now be explained.

When item B follows item A in the stimulus list, changes in the pattern of short-term connection strength are likely to result. In particular, A's capacity to facilitate B will be enhanced by their concurrent activity. (While there may be facilitation in the other direction as well, it is not likely to be as strong because there are fewer A units active, since the trace is dying out, and hence fewer opportunities for B-to-A facilitation; i.e., the fact that a few A units acquire the ability to "drive" many B units is likely to be more influential on B than the fact that many B units acquire the ability to drive a few A units will be on A.) Now suppose A has been retrieved and therefore has just undergone a very high level of activity. This activity should have led to some VST activity in B as well, because of the STPE bonds just described. Now, if the next retrieval input encounters a B that is still showing the residual activity resulting from A's retrieval, the chances for retrieving B will be improved. This suggests why subjects often tend to remember items in approximately the order of presentation, and, more importantly, why they almost always report rehearsing items in the "forward" direction (most recent last). In sum, the STF functions seem just about as important to retrieval as the STP function.

The above argument needs to be modified somewhat when the experimental situation involves recall of items that have been presented several times in different orders. In this situation, the possibilities for direction of short-term recall via order-of-presentation effects are minimal, because the STPE effects would tend to be rather evenly balanced instead of weighted in particular directions. In this case, another factor (which is really always present) assumes importance, namely the exceptional strengthening over the short term that long-term associations might receive. Those items which have been naturally grouped together in the subject's past experience will tend to have the most firm long-term ties and therefore the best opportunity to capitalize on short-term inter-item priming. This hypothesis may partially explain the phenomenon of "clustering" of similar items during free recall.

Finally, there is LTM. And perhaps it is useful to distinguish experimental LTM from "true" LTM. True LTM reflects life-long experience, in highly solidified association structures. Experimental LTM is an attempt to modify these long-term patterns temporarily (and perhaps to introduce some new ones); yet temporarily, on the LT scale, can often mean days and sometimes weeks. But it is seldom considered likely that the subject will employ the changed connections in such a manner and so often over the course of ensuing months as to place them on a par with true LTM.

Experimental LTM, then, attempts to capitalize on LTP in order to induce relatively small changes in existing associations and/or temporarily associate items with the experimental setting. In the first case, retrieval through association works much as it does for STM, although probably less effectively, since life-long patterns are unlikely to be altered much in a few minutes of experience, especially when LT effects are as weak as they are in the model. In the second case, association to the experimental situation, somewhat stronger effects might be expected. The association aids retrieval as before; but in this case there is a relatively new "item," the experimental setting, represented. The associations of features of this situation with the stimulus items could be stronger (because the exposure lasts longer) and freer from the influence of earlier experience. Thus a subject who returns for recall days after exposure to the stimuli should benefit considerably from again seeing the experimenter, the room, the equipment, etc., because these are the things which co-occurred with the stimuli (cf. the analogous phenomenon of state-dependent learning as reviewed by John, 1967).

It should now be reasonably clear what is meant by retrieval probability and how the various memory states influence it by increasing the probable response of a trace to retrieval input. But since (usually) only one item is rehearsed or recalled at a time, it is not sufficient just to have a number of fairly active traces around. There should be some means by which one of the items (presumably one of the most active ones) becomes dominant. Dominance, in this context, refers to a level of activity so high relative to other active traces that only the given trace occupies the subject's attention and is capable of directing motor output. The situation is like the one in which the subject is attending entirely to a stimulus item; there may be other activity, but the representation of that item is dominant. Rehearsal is thus the process of becoming dominant; a subject mentally reviews an item because the retrieval process brings it to mind. And recall is the motor implementation (by means outside the model) of the dominant trace. In either case, note that the greatly increased activity (which is dominance) will increase the various forms of priming and hence improve the various forms of memory. This may be why rehearsal is a useful technique and also why it is generally easier to remember something a second time.

But how does one of the more active traces, subsequent to retrieval input, take over and become dominant? The "winner" need not always be the most active item, or it would be pointless to speak of retrieval probabilities. It is the structure of inhibitory connections which primarily determines which one of the more active items will become dominant. This is the last variable in the retrieval process, all of the others having been grouped under the heading of retrieval probability.

To the extent that the various active traces represent items which are reasonably different from each other (the usual experimental situation) it is possible for there to be some mutual inhibition among them. This means that a number of the LTI boxes will contain gating values close to one in those SA units which receive inputs from units in the other traces. The exact distribution of these inhibitory relations is a function of prior experience. In any case, some one of the more highly active items will be broadcasting a pattern of inhibition to the other active items which will ensure its own survival and eventual dominance. This inhibition will at first slightly depress activity in the other traces, thereby slightly reducing their capacity to inhibit the one becoming dominant. The trace on its way to dominance thus becomes even more active and suppresses its competitors even more. This process snowballs until the retrieved item is dominant, at which point it is inhibiting competing items sufficiently so that (even though they may not be entirely quiescent) they are not in a position to compete for the subject's attention or for the control of motor subroutines.

This whole process, from retrieval input to enhanced activity to competition for dominance through mutual inhibition, is diagrammed for a few SA collections in a very schematic way in Fig. II-6. The circles represent four items, the arrows between them, inhibitory connections. Only inhibitory relations involving trace C are shown; the heaviness of the line is intended to suggest the strength of the inhibitory connection. The "ordinate" represents increasing activity (E level), with respect to which three levels, corresponding to three successive points in time, are shown for each trace. At time 1,

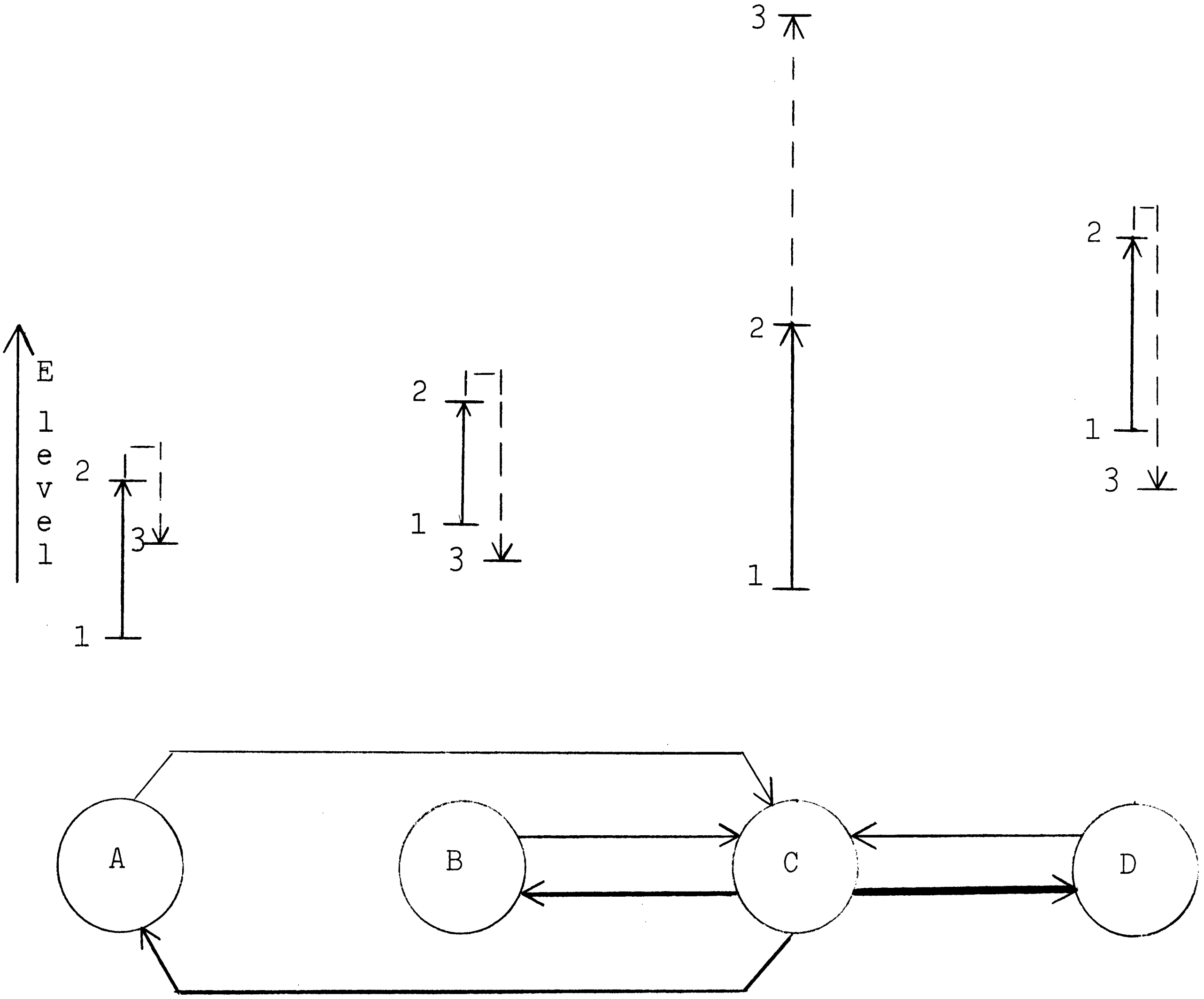


Fig. II-6. A Schematic Example of Retrieval

before there is any retrieval input, D is most active and A is least active. The solid arrows represent the change in activity in response to retrieval input; the length of the arrow directly reflects the retrieval probability, which has been described as a function of many factors, including memory. Thus, it might be inferred, for example, that C had more STPI than B, although any number of reasons could have contributed to the differences in the arrow lengths. At time 2 (not necessarily one time step later, probably much longer) the collections have reached new levels of activity as a result of the retrieval input, with D still most active. C has gained on B. At this point, competition for dominance begins. And since C inhibits each of the others more strongly than it is inhibited by them (by the design of the example), it is able to supress them, even overwhelming the more active D, and become dominant at time 3.

This is how retrieval probability and inhibition combine to produce dominance. The situation is naturally temporary, since the dominant trace is subject to fatigue and to competition from external inputs. When rehearsal of the item is accomplished, or when the recall response is completed, the dominant item decays back down to moderate levels, at which point retrieval input may again be initiated for the rehearsal or recall of another item. The complex time interrelations between rehearsal and stimulus input will be discussed in the context of a hypothetical experiment in the next section. And it will also be made clearer there just what items are most likely to be rehearsed. This section will close with two final comments about recall.

First of all, there is the question of repetitive recall. In the second and subsequent searches, the first item remembered is subject to a second retrieval. (This creates no special problems for rehearsal, because multiple rehearsals are often employed, about which more will later be said.) And during recall tasks, some subjects do inadvertently report an item twice, although almost never twice in a row. Since it has been argued that the retrieval process strengthens an item in memory, the rarity of double recalls needs to be explained. The reason an item is almost never reported twice in a row could be that its prior intense activity (dominance) has raised its fatigue level to a point at which it is no longer possible for it to succeed in another competition for dominance. This would be a temporary effect.

Two factors might contribute to the rarity of well-separated double recalls. First, there is the direction that forward short-term associations lend to recall, as described above; this gives a rough temporal order to the items during recall, making it somewhat less likely to return to an item already recalled. Second, the very strong STM (from the increment added by the first retrieval) may be thought of as corresponding to the subject's reasonably reliable memory for what he has already produced during recall.

The second closing comment about recall deals with extraneous items. Since the subject's visual input is not usually restricted to the experimental stimuli, he will quite probably encode a number of features or items in the non-relevant environment. Why is recall restricted to the stimuli? The first answer is that it is not--many subjects do introduce one or two extraneous items during recall. The low frequency of such intrusions can probably best be attributed to the generally reduced attention that extraneous items receive when the subject is concentrating on the experimental stimuli.

H. Summary. In this section, the material of this chapter will be reviewed in two ways. First a block diagram will be offered which is suggestive of the boundaries of the model--the limitations on what it tries to account for. Second, a prototype memory experiment, involving short-term free verbal recall, will be explored in the context of the model, in order to provide a preliminary view of the dynamic interactions among some of the parameters which have been developed in the preceding pages.

The block diagram is presented as Fig. II-7. The heavy line encloses what is accounted for by the present model; this includes the two categories of external-input SA units, the remaining regular SA units and their interconnections, and the various memory and priming variables which have been discussed. Among the things not included in the model are the subroutines for programming the motor expression of items in recall and the machinery for initiating rehearsal and recall.

The input is of two major varieties. "Items" are experimental stimuli, such as words, drawings, or nonsense syllables. There are also command inputs, which are a function of the experimental situation. The recall command is usually given at the end of stimulus presentation (or later) and may be thought of as setting up a non-specific recall factor, which continually re-initiates retrieval input and also provides the impetus for motor expression. It is the second aspect of the recall factor which is the major basis for differentiating retrieval-for-

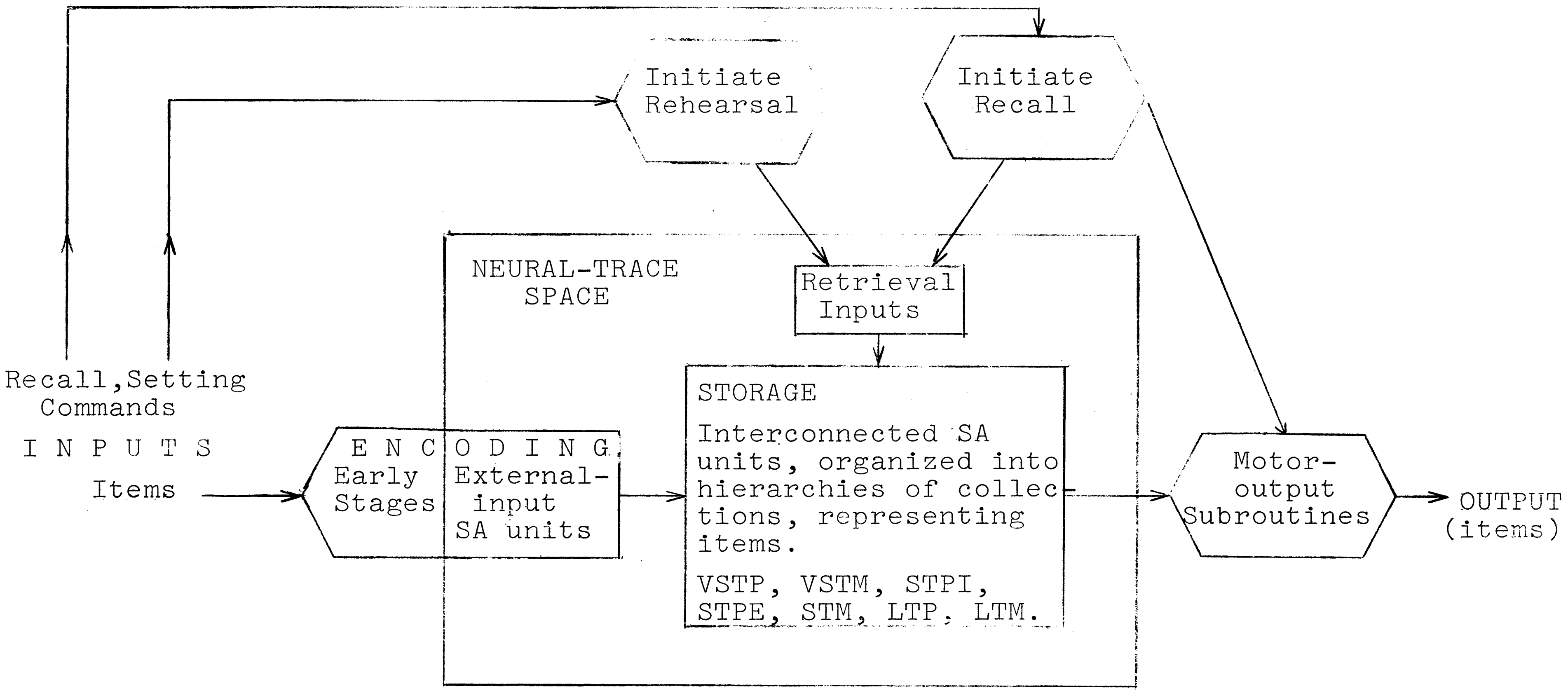


Fig. II-7. The Model and its Peripheral Equipment rehearsal from retrieval-for-recall.

The setting command is any information given to the subject before stimulus presentation which indicates that he will later be expected to remember the items. This also sets up a sort of non-specific impetus, in this case a rehearsal factor, which continually exerts pressure to produce retrieval input for the purpose of mentally reviewing items already seen. The strength of this rehearsal factor, which is probably an individual difference, determines the apportionment of the subject's time between rehearsal and attention to new stimuli. This and other aspects of rehearsal strategy will be discussed more fully in a moment. It should be noted that the relation between the setting command and the tendency to rehearse has been verified in the writer's experimental studies (see Chapter III and the Appendix).

A sort of dry run through a simple prototype memory experiment is a good initial test of the model. In the hypothetical experiment, a subject is successively shown twenty common words, each naming a familiar object and each exposed for several seconds. At the end of the presentation, he is asked to write down as many of the words as he can remember, in any order. He is aware from the beginning of the experiment that this recall task will be used.

Each item, after preliminary encoding in the lower stages of the visual system, enters the region of the model via the external-input units which are part of the SA collection that has come (through experience) to represent the particular concept in its verbal form. During the few seconds the item is exposed, the trace is pushed to a high level of activity by these external-input units, a process facilitated by its own high degree of interconnection among constituent SA units. When the stimulus is turned off, the activity dies out slowly, via VSTP in the individual SA units and consequent reverberation among them. The onset of the next item may slightly hasten this decay, especially if the second sub-collection has mainly inhibitory relations with the first. Nevertheless, there will be some period of co-occurrent activity, during which it is possible for STPE to develop (primarily "forward") short-term bonds.

After a given item's activity has mostly disappeared, it will be left with residual STPI among its SA units in proportion to the intensity of activity during stimulus presentation (related to the strength and duration of the input and to the initial state of the trace) and the duration of the VSTP which followed stimulus termination (related to the level of excitation reached, the degree to which connection strength facilitated reverberation among SAs, the amount of inhibition from other traces, and the like). The trace will also be left with STPE among its SA units in proportion to the duration of the reverberation, and with STPE with other collections in proportion to the duration of co-occurrent activity.

Since the subject knows he will later be asked to remember the items (the "setting command" has been given), the rehearsal factor is likely to be fairly strong. This means that, whenever strong external input from the presentation of a new stimulus item does not override the process, the retrieval inputs will be active and some previously presented item will become momentarily dominant. Which are the items most likely to be rehearsed? Since the rehearsal process operates under time constraints (the result of competition with the new-stimulus input), the retrieval inputs are active for a relatively short time during each "pause for retrieval." This means that their impact, in terms of the amount of increment they can lend to the activity of item representations, is relatively small. Hence only items with some activity already present (those with the highest retrieval probabilities) will have good chances of becoming dominant during rehearsal. And these will usually be the items just previously presented or those recently rehearsed.

This means that two major rehearsal strategies are possible (with other variations used infrequently). Repetitive rehearsal of the early items is possible because the item is thereby maintained at a relatively high level of activity throughout stimulus presentation, giving it a high retrieval probability long after it was initially viewed. The other, and more common, strategy is rehearsal of the few items just preceding the one currently exposed. This is possible because the items have not yet decayed much. Which of these two strategies is actually used probably depends in part on the relative proportion of time devoted to rehearsal. With more time spent on rehearsal, the early items can be rehearsed more frequently, making them better candidates for yet another retrieval. And, as suggested above, the relative proportion of time spent on rehearsal is a function of the strength of the rehearsal factor, which is probably an individual difference, related in part to the importance the subject attaches to the memory task and in part to his previous recall experiences. In any case, it is difficult to say which of the strategies improves memory more; there is a trade-off between number of items rehearsed and number of rehearsals per item.

When recall is requested at the end of the list (the "recall command"), the "recall factor" becomes operative and initiates successive searches (via the retrieval inputs) of the trace space. Each search terminates when an item becomes dominant and takes over the motor equipment as the subject writes the word. All of the previously considered factors with respect to retrieval probability, the importance of inhibition to the dominance mechanism, and the direction imparted to recall by forward STPE bonds apply to the experimental items the subject has seen. So all these items do not necessarily have equal chances of being recalled.

In fact, the last few items are probably still undergoing VSTP and have had little or no rehearsal. The remaining items have varying amounts of STPI (and of STPE within themselves and with other items), in accord with the variables which can influence short-term priming, as well as with the number of rehearsals received. The first few items are likely to have greater STM than the others, for two reasons. First, these items have the greatest opportunity to be rehearsed the most number of times, an opportunity which some rehearsal strategies capitalize on. Second, operation of the rehearsal factor during the presentation of later items (when there are more items available for rehearsal), as well as an expected lowering of attention as the experiment becomes familiar and boring, can reduce the input strength of items as the list progresses.

Thus, when retrieval is initiated after termination of the list, the chances are excellent for recall of the last few items, good for recall of the first few items, and not so good for recall of middle items. This pattern is the usual serial-position effect for free recall. It will be more thoroughly investigated in the next chapter.

Naturally a lot of factors have not been considered in this discussion, such as non-verbal items, subjects who do not rehearse (because they do not anticipate recall), long-term memory, and the like. The attempt at this stage has been mainly to give a general idea of the dynamics of the model. The other factors will be considered in Chapter III, when the model is considered in the light of specific experimental findings and of other models of learning and memory.

GLOSSARY OF SYMBOLS USED IN CHAPTER II

Names of Components and Lines

SA	Subassembly
SC	State Control
IS	Input Summation
CC	Connection Control
FSD	Finite State Device
STP	Short Term Primer
ISS	Input Summation, Spatial
IST	Input Summation, Temporal
STF	Short Term Facilitation
STI	Short Term Inhibition
LTF	Long Term Facilitation
LTI	Long Term Inhibition
I^1	Input array to LTF-LTI (and to SA as a whole)
I^2	Input array to STF-STI (and output of LTF-LTI)
I^3	Input array to ISS (and output of STF-STI)
I^4	Input line to IST (and output of ISS)
I^5	Input line to STP (and output of IST)
I^6	Input line to FSD (and output of STP)
O	Output from FSD (and from SA as a whole)

Names of Functions

q	State-transition function in FSD
o	Output function in FSD
u	Switching function in STP
v	Switching function in IST
w	Switching function in ISS
g_s	Switching function in (each) STF
h_s	Switching function in (each) STI
g_i	Array of variable probabilities in LTF units
h_i	Array of variable probabilities in LTI units
C_A	Centrality of an SA with respect to collection A

Constants and Miscellaneous Parameters

K_1	Controls magnitude of increment in STP
K_2	Controls magnitude of increment in STFs
K_3	Controls magnitude of decrement in STIs
K_4	Decay constant in LTFs
K_5	Controls magnitude of increment in LTFs
K_6	Decay constant in LTIs
K_7	Controls magnitude of increment in LTIs
T_1 T_2	Boundaries of time period used for ST processes
T_3	Boundary of temporal summation time period
T_4 T_5	Boundaries of time period used for LT processes
P	Vector of probabilities used in o function
p_i	An element of P
z_i	Element in vector of constants used in v function
a_i	Element in vector used to partition I^6 alphabet
S	State space in FSD
S'	Inaccessible area of S
E	Set of excitation levels in S
e_i	A particular E level
F	Set of fatigue levels in S
f_j	A particular F level
s_1	Number of E levels
s_2	Number of F levels
N	Number of SA units in trace space
n	Index used in summations

Constructs

VST	Very Short Term time period
VSTP	VST Priming
VSTM	VST Memory
ST	Short Term time period
STPI	ST Priming, Internal
STPE	ST Priming, External
STM	ST Memory
LT	Long Term time period
LTP	LT Priming
LTM	LT Memory

CHAPTER III: THE MODEL APPLIED

In this chapter, the machinery and constructs developed in Chapter II will be applied more directly to human behavior. First, experimental data dealing with several aspects of free recall will be considered, with an emphasis on the kinds of results obtained by the writer in two recent studies. Second, the model will be compared with other formal approaches to learning and memory, in order to discover some of its relative weaknesses and strengths.

It will be assumed throughout this chapter that the following notions, all defined and developed in the preceding chapter, can be employed as precise, formal terms: the list of constructs in the glossary to Chapter II, item, input, input strength, attention, activity (E-level), fatigue, SA collection and sub-collection, centrality, coherency, encoding, verbal encoding, retrieval, retrieval probability, dominance, rehearsal, and recall.

A short summary of the writer's two experiments is in order at this point; a more detailed treatment of the first may be found in Kaplan, _et_. _al_. (1968) and of the second in the appendix to this dissertation. In both experiments, male undergraduates viewed a sequence of twenty-four words (names of common objects) and pictures (simple line drawings of such objects) projected as every third slide in a series of slides which also contained colors for the subjects to name. Each stimulus was exposed for four seconds, while the inter-stimulus interval (including the two color slides) was twelve seconds. Stimulus lists were balanced for two orders of presentation and for which half of the items was seen as words (no subject saw both a picture and a name of a given object).

In the first study, all forty subjects knew in advance of stimulus presentation that a recall task would be involved. They were all asked to reproduce as many of the items as they could remember, in any order, both immediately after termination of the stimulus list and again thirty minutes later (after a series of tasks unrelated to the stimuli). In the second study, seventy-two subjects were divided according to a two-by-three design (six twelve-subject groups), where the two-level factor involved whether or not subjects knew that recall was to be required (the set and non-set conditions), and the three-level factor involved whether subjects were tested immediately after stimulus presentation, one day later, or on both occasions. Subjects were also interrogated after each recall task to see if they could report the use of any strategy in trying to remember the items.

A. Analysis of Free-recall Serial-position Data. The first type of data to which the model will be applied is the realm of serial-position effects, a term which generally refers to any relation between recall performance and the (temporal) position of the material in the presentation the subject saw. Usually of most interest are recency and primacy effects, which refer to tendencies to perform better on the last few and the first few items, respectively. Although there is a considerable body of serial-position literature, the following survey concentrates on recent studies involving free verbal recall. After a brief review of such studies, the writer's own data will be presented and an attempt will be made to account for as much of the overall picture as possible in the context of the subassembly model.

All of the studies to be discussed were uniform with respect to the following conditions and materials (except where specific exceptions are later noted): subjects were undergraduate college students; stimulus materials were common words, usually selected from a portion of the Thorndike-Lorge (1944) lists; free recall was employed as the memory task (i.e., there were no constraints on the order in which the subject produced the items he could recall); subjects usually learned many lists, but never saw a single list more than once. The number of items (list length) varied from five to forty; the presentation time per item varied from one to nine seconds; the delay before start of recall varied from zero to thirty seconds.

Deese and Kaufman (1957) studied the interaction of serial position effects with the amount of sequential organization or dependency in the stimulus material. In their first experiment, they compared memory for randomly selected words with that for passages of connected discourse and found both primacy and recency effects in both cases. For the random words, however, recency was more pronounced than primacy in each of the two list lengths used (ten and thirty-two items), while the opposite was true of the passages. A second experiment used fifty-item lists of words with increasing sequential dependencies. (In both studies, words were presented at a one-per-second rate.) The investigators found that zero and first order approximations to English yielded serial position curves with little primacy and marked recency; but as the order of approximation increased, so did the primacy, to the point where it surpassed the recency effect on the seventh-order approximation. Both the textual passages (from the first experiment) and the higher-order approximations yielded serial position data that resembled the type found in studies of serial-anticipation learning, rather than free recall. It would thus appear that redundancy of stimulus material and degree of primacy are positively correlated.

Bousfield, _et_. _al_. (1958) examined the effects of list length on serial position phenomena, using sequences of five, ten, twenty, and forty random words, with an exposure time of 2.5 seconds per word. They found serial position curves which progressed from a horizontal line to increasingly U-shaped functions as list length increased; primacy effects were significantly stronger than recency effects in all cases except the five-word sequence. Since this finding was at variance with the more usual free-recall serial-position curve for random words (where recency is more pronounced), the authors conjectured that their subjects used a rehearsal process which benefited the early items more and speculated that "the extent of the primacy effect varies directly with the amount of rehearsal of the stimulus items during learning."

Murdock (1962) varied list length (ten to forty items) and presentation rate (one or two seconds per item) in a classic study of "The Serial Position Effect of Free Recall." Recall probabilities decreased with longer lists and/or faster presentations; the shape of the serial position curve was relatively stable except for an enhancement of primacy associated with the slower rate. Murdock summarized as follows: "On the basis of the available evidence, it was concluded that . . . the serial position curve is characterized by a steep, possible exponential, primacy effect, extending over the first three or four words in the list, an S shaped recency effect extending over the last eight words in the list, and a horizontal asymptote spanning the primacy and recency effect. . . . it was suggested that the shape of the curve may well result from proactive and retroactive inhibition effects occurring within the list itself." The recency effect was stronger than the primacy effect (both in the sense of including more items and in the sense of reaching higher probability-of-recall levels) in all of Murdock's conditions. This is consistent with the Deese and Kaufman findings (for random words), but contradicts the results of Bousfield. Murdock was able to confirm his own findings even when he used Bousfield's slower (2.5 seconds per word) presentation rate; so he suggested other factors than presentation rate as responsible for the more pronounced primacy in Bousfield's data. In particular, Murdock believes that Bousfield's subjects may have tended to rehearse items in order of presentation because they did not know the length of the list (since each subject had only one list of each length, while Murdock's subjects each worked with only a single list length). Although he mentions other possibilities, Murdock seems willing to agree with Bousfield that rehearsal could be the major determinant of the relative strength of primacy vs. recency effects.

Postman and Phillips (1965) presented lists of ten, twenty, and thirty words at the rate of one per second and tested for recall either immediately or after a delay of either fifteen or thirty seconds. Recall performance decreased with increasing delay and/or list length. The serial position curves were not much affected by list length, but were strongly influenced by the delay. Although primacy effects were relatively stable, the pronounced recency effect in immediate recall dropped off sharply as a function of the delay, so much so that there was at most a negligible recency effect in the thirty-second delayed-recall data.

Glanzer and Cunitz (1966), using Army enlisted men instead of college students, conducted two experiments "to test the hypothesis that the bimodal serial position curve in free recall is produced by output from two storage mechanisms--short-term and long-term." The first study involved variable presentation rates (three, six, and nine seconds per item) and multiple successive presentations of the items (single presentation, two in a row, or three in a row) in twenty-item lists. Although the repetition variable did not affect the serial position curves significantly, there was an enhancement of primacy effects at slower presentation rates, in agreement with Murdock's finding. The second experiment employed a delayed recall variable like that of Postman and Phillips; the results confirmed the finding that recency decays with increasing delay.

Glanzer and Meinzer (1967), again using Army subjects, employed fifteen and sixteen item lists and inter-item intervals of approximately three seconds to study effects of intralist activity on free-recall serial position phenomena. The first experiment manipulated the degree of association between items and whether or not the subjects were required to perform an interpolated counting task between successive items. Although both high association and the absence of an interpolated task facilitated recall, neither variable had differential effects on primacy or recency. These results are somewhat disturbing, since the Deese and Kaufman study demonstrated that informational constraints enhanced primacy and since the interpolated task should have reduced rehearsal and therefore affected both primacy and recency. The second experiment removed the association variable and changed the interpolated task to one in which each stimulus word was repeated aloud six times. Such a task depressed performance, particularly in the earlier portion of the serial-position curve, leading the investigators to conclude that "simple repetition lowers overall recall. Effective rehearsal consists of some other activity."

Before a theoretical discussion of the above findings is begun, the writer's experimental results with respect to serial position will now be presented. Figures III-1 and III-2 on the next page show mean percent recall by quartile of presented list for the three groups of set subjects (Fig. III-1) and the three groups of non-set subjects (Fig. III-2) in the writer's second experiment. The uppermost curve in both cases is for all (twenty-four) subjects who were given an immediate recall task; the intermediate and lower curves show the one-day performance of subjects taking their second test (having had a prior immediate test) and first test, respectively. Data on serial position in the writer's first study are not shown, but resemble the upper curve in Fig. III-1 (immediate recall by set subjects); however both the immediate and thirty-minute curves from this first study are somewhat more symmetrically U-shaped (the primacy is only slightly enhanced with respect to the recency); differences between the immediate and thirty-minute curves are slight, with recency a little more depressed after the delay. Neither study revealed major differential effects at the ends of the serial-position curves when recall for word items was compared with recall for picture items.

Some of the important features of Figs. III-1 and III-2 can be stated verbally. It is apparent that primacy is stronger than recency for immediate recall by set subjects, while the opposite is true for non-set subjects. Recall, for the second time, at one day reveals relatively greater losses from the recency portion of the curves, an effect which is especially pronounced for set subjects. The performance in a one-day first-test situation is relatively featureless with respect to serial

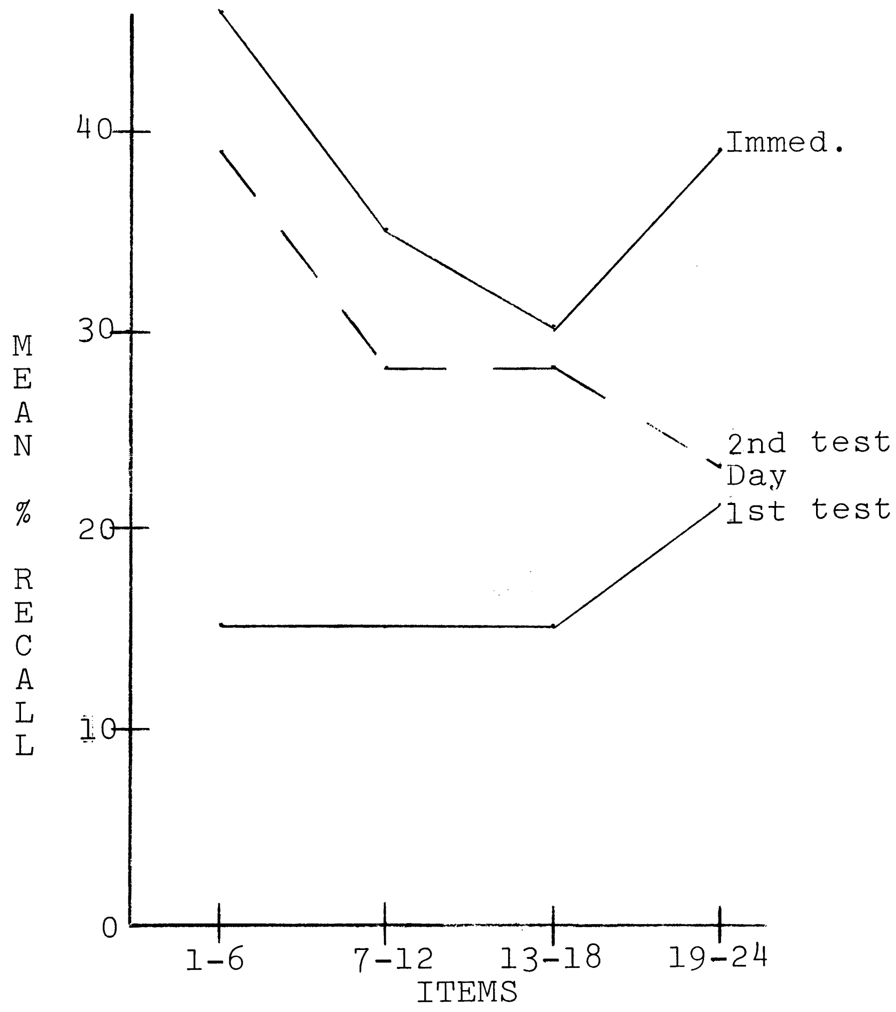


Fig. III-1. Serial Position, Set Subjects

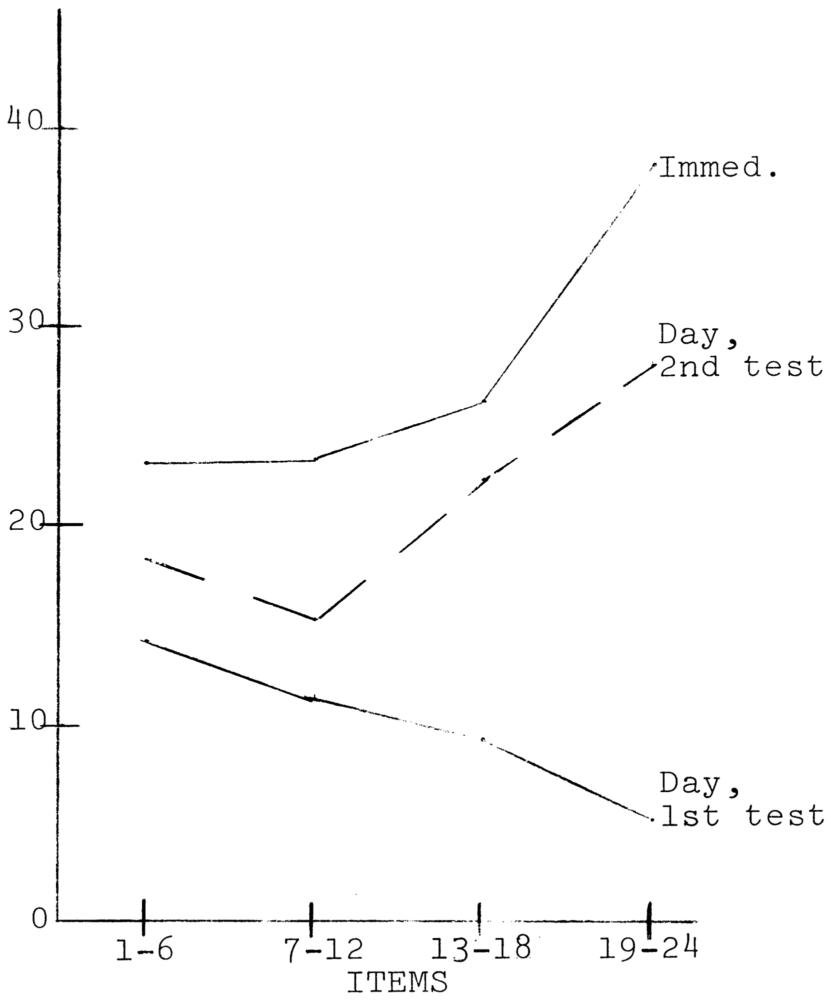


Fig. III-2. Serial Position, Non-set Subjects position, although the generally falling trend for non-set subjects should be noted. (It must also be emphasized that the "set" subjects in the one-day-only situation were not actually told to expect recall but only to watch for repetitions--see the Appendix.)

Some of these findings are relatively consistent with those of other investigators. The set subjects reported rehearsing during item presentation, while the non-set subjects did not; thus the serial-position differences resemble the contrast between the findings of Murdock (1962) and of Bousfield _et_. _al_. (1958), where both authors seem to agree that rehearsal depressed recency relative to primacy in the Bousfield study. The relative depression of recency after a delay is consistent with the findings of Glanzer and Cunitz (1966) and of Postman and Phillips (1965), although it must be kept in mind that their delays were much shorter and their subjects had not had a prior immediate test.

A summary of free-recall serial-position findings, based on the studies reviewed above, the writer's own work, and a survey in Tulving (1968), will now be offered. Although there are some seemingly conflicting results and a number of gray areas, the general picture seems to be of the sort displayed in Table III-1 on the next page. In this table are shown most of the variables that have been investigated and whether they have been found to increase (I) or decrease (D) or have no effect (N) on primacy or recency relative to the rest of the curve. Some comments on this table are necessary. First,

Table III-1. Summary of Serial-position Findings

VARIABLE		EFFECT ON: PRIMACY	RECENCY	INVESTIGATOR(S)
Rehearsal (Set)		I	D	Bousfield, *et*. *al*. (1958) Sampson (1969)
Redundancy	Associative	N	N	Glanzer & Meinzer (1967)
	Sequential	I	N	Deese & Kaufman (1957)
Delay	Short, or Long with prior Test	N	D	Postman & Phillips (1965) Glanzer & Cunitz (1966) Kaplan, *et*. *al*. (1968)
	Long without Prior Test	D	D	Sampson (1969)
Faster Presentation		D	N	Murdock (1962) Glanzer & Cunitz (1966)
Longer List		I	I	Bousfield, *et*. *al*. (1958)
Repetition	of Stimulus	N	N	Glanzer & Cunitz (1966)
	by Subject	D	D	Glanzer & Meinzer (1967)
Interpolated Task		N	N	Glanzer & Meinzer (1967)

rehearsal can safely be equated with set only in the writer's second study (shown in the table as "Sampson (1969)," but not an entry in the references). Second, redundancy is a global term applied by the writer to sequential dependencies and/or associative relations among stimuli. Third, the effects of delay are apparently somewhat related to the length of the interval and to whether or not there was a prior immediate test of recall. Finally, the effects of repetition seemingly depend upon whether the stimulus itself is presented several times or whether the subject repeats it aloud during the inter-stimulus interval.

In summary of Table III-1, the following generalizations may be offered: primacy is relatively enhanced by rehearsal and certain types of redundancy; primacy is relatively depressed by a long delay (twenty-four hours) before first recall test, by faster presentation rates, and by overt subject repetition of items; recency is relatively depressed by rehearsal, by the long-delay condition, but also by shorter delays (thirty seconds, thirty minutes) and by long delays where there has been a prior test, and by repetition by the subject; finally, both primacy and recency are enhanced (the function becomes more U-shaped) as list length progresses from very short (five items) to moderate.

A variety of theoretical mechanisms have been proposed to account for some of the phenomena in Table III-1, although no single model has taken on the complete picture. The ability of experimental manipulations to affect primacy and recency in seemingly independent ways has led most investigators to favor a two-process theory of free recall. Although some approaches (e.g., Glanzer and Meinzer, 1967) actually distinguish two separate memory stores, Tulving (1968) has said he prefers the "view that all input information is stored in the same unitary storage system, whatever its nature, and that differences in recall of early, middle, and late input items reflect primarily differences in the accessibility of these items." This view corresponds closely to the writer's general approach in the subassembly model. Another feature of many existing explanations of serial position phenomena is the stress on proactive and retroactive interference mechanisms (see, e.g., Murdock, 1962 and Glanzer and Cunitz, 1966). In the writer's approach however, decay is often more important than interference, especially where immediate memory is concerned.

Little more will be said here about present theories of free-recall serial-position effects. The emphasis in this section is on the productivity of the subassembly model, on how it fares in the light of such data. In part D, the subassembly model will be compared with another, comparably fully developed, theory (Atkinson and Shiffrin, 1965, 1968); at that time some direct comparisons of explanatory adequacy for serial-position phenomena will be considered. In the remainder of this section, most of the findings summarized in Table III-1 will be analyzed in terms of the machinery of the subassembly model.

It is natural to begin with the rather dramatic interaction of rehearsal with both primacy and recency. The contrast between the data of Bousfield and of Murdock, as well as the performance of set as opposed to non-set subjects in the writer's study, suggests that rehearsal (presumably of the type outlined in Chapter II) enhances primacy and depresses recency (in immediate recall), to the degree that "classic" serial position curves are reversed with respect to the strength of the two effects.

These results are not too difficult to understand in the context of the subassembly model. The marked primacy for set subjects is probably the result of two factors, both related to rehearsal. First, there are, for many subjects, a larger number of rehearsal passes through the early items; hence those items can amass greater short-term priming, permitting retrieval input to evoke an activity level with a relatively high retrieval probability. Second, because rehearsal probably becomes a more demanding (time-consuming) activity as the list progresses, set subjects may give relatively more attention (input time) to the early items; this would lead to longer, stronger VSTP and therefore to more short-time priming.

Only the second of these factors could operate in the absence of rehearsal; the modest primacy found by Murdock (the writer's non-set subjects displayed almost none) could thus be explained by better attention to the early items, before the task becomes routine. But it must be admitted that interference explanations are more plausible in this case. In the subassembly model, interference could take the form of inhibition put out by the decaying traces of items in the recent past; this effect would be negligible at the outset, but would grow to a maximum after the first few items. Primacy can thus be viewed as the result of a combination of inhibition and attention effects; the enhancement in rehearsing subjects is due to the greater rehearsal of early items and probably also to a greater disproportion in the attention effect.

Recency, which is fairly strong in all immediate recall groups, can also be thought of as the result of two factors. First, a few of the last items might well be still undergoing VSTP and thus be particularly easy to retrieve. Second, the opportunities for decay in ST priming would be less for items nearer the end of the list, even if significant amounts of VSTP were not still present. But the recency was relatively much stronger for the writer's non-set subjects; in fact, despite generally poorer performance, non-set subjects did as well or better than set subjects on five out of the last seven items they saw (as compared with only three out of the first seventeen items).

A partial explanation of this effect might be that the non-set subjects, as soon as they are given the recall instructions, begin to rehearse the last few items they saw, thereby enhancing both of the above-mentioned recency factors. Another, and probably more significant, consideration rests on the previously-stated hypothesis that rehearsal usually places the most demand on a set subject's time as he nears the end of the list; he has more items available for rehearsal and many of them are quite remote in the past and therefore take longer to retrieve (since the retrieval inputs must fire longer to excite a trace in which the VSTP and STPI have had more time to decay). So for those set subjects for whom rehearsal did not break down altogether by the end of the list, attention was probably lowest on the last few items. That there still was a recency effect at all may be attributed to the strength of the recency factors, factors which operated with the benefits of relatively full attention in the case of the non-set subjects.

The role of what has here been called "redundancy" in serial position is difficult to assess, since the findings of Deese and Kaufman (1957) seem to conflict with those of Glanzer and Meinzer (1967). The Deese and Kaufman result (greater primacy in sequentially-dependent material) can be at least partially understood in terms of recall which is being strongly directed by well-established LTP (associative) bonds; it is plausible that more early items will be remembered from material which tends to be remembered in the forward direction. And this may shed some light on the Glanzer and Meinzer finding, since the connections between their (paired-associate) stimulus words were not necessarily predominantly in the forward direction.

If the redundancy picture is confusing, the effects of delay are even more so. Delays as short as half a minute depress recency markedly. This is actually not too surprising, since the main factor in the subassembly explanation of recency was the number of items that could still be undergoing VSTP. If there is more time for decay, retrieval probabilities will be smaller, providing the delay interval is filled with activity designed to keep rehearsal to a minimum (as it was in all these studies). In the writer's second study, there was a much longer delay (one day) before the initial test of recall. So it is natural that there would be virtually no recency for these subjects. But there was no primacy either, which could be explained by the absence of rehearsal (the "set" subjects in this condition were told only to watch for repeated items; they did not report rehearsing). Thus it would seem that retrieval based only on LTP, when it has not been structured by an earlier recall session (a situation that will be discussed next), is essentially random, at least with respect to strength considerations arising from position in the stimulus list.

In the writer's studies, recall was also measured after thirty-minute and one-day delays when there had been a previous immediate test. There appears, in these cases, to be a decrement in recency, most pronounced for one-day recall by set subjects. This finding is difficult to handle, since the content (the items remembered) of the first recall session largely determines that of the second (see the discussion of time effects in part C below). A possible explanation rests on the notion that the recall of items near the end of the list depends largely on VST, or reverberatory, activity. The effects of VSTP can be so potent that even a small amount will greatly augment retrieval probability. So it could be argued that the immediate retrieval is incrementing a smaller base value than in the case of early and mid-list items, where the VSTP had to be sufficient to invoke ST effects. Thus, among items remembered immediately, those near the end of the list could have somewhat less LTP at a day, because they needed less VSTP for recall initially. In effect, this explanation of more forgetting of later items rests on the assumption that their immediate recall was "improbable" in some cases. If this effect is more pronounced for set subjects, as the data suggest, it could be because there are relatively more items in this class subject to "improbable" immediate recall, as a result of the lowered attention by set subjects to later items.

Faster presentation rates reliably depress primacy effects. This would be easy to understand for rehearsing subjects, since the marked primacy is considered to be dependent upon rehearsal, which is mainly carried out in the inter-stimulus intervals. But the Murdock and Glanzer-Cunitz subjects were presumably not rehearsing. The dilemma can be partially resolved when it is realized that the effect under consideration actually extends well beyond the primacy range and in fact involves all but the last two or three items. Perhaps the explanation is really as simple as lowered attention (input time) for all items, but with strong counteracting recency effects on the last few.

Bousfield's finding that very short (five-item) stimulus lists yielded relatively flat serial-position functions is not particularly difficult to understand. It would appear that the items would be on essentially equal footing with respect to VSTP and short-term priming after the passage of so little time. After all, since practically all the items are usually recalled, it is naturally hard to find serial-position differences.

The findings (in the two Glanzer studies) related to repetition and interpolated tasks present some problems for the subassembly model. While the overall performance decrement associated with an interpolated task has a straightforward attention interpretation, it would also be predicted that primacy would be particularly depressed, since the task would interfere with whatever rehearsal might be going on. This is not the case (at least not statistically, although the Glanzer-Meinzer graph appears to show slightly more loss in the earlier portion of the curve), perhaps because the subjects were not rehearsing at all.

Repetition of the stimulus (multiple presentations) and oral repetition of the word by the subject should act just like rehearsal, enhancing primacy particularly and recall in general. Yet multiple presentations had no effect (beyond the inherent one of reduced presentation rate); and subject repetition depressed performance throughout the list (except on the last three positions). There can thus be no doubt that Glanzer and Meinzer are correct in stating that effective rehearsal involves more than simple repetition. While it does not account for the depressive effect of subject repetition, one possibility is that the active retrieval (via the retrieval inputs) of true rehearsal is more effective than passive restimulation of the trace (when the subject reads the word aloud) because there is the added factor of STPE between the trace and the retrieval inputs. This extra short-term priming would be located on precisely the connections involved in subsequent retrieval attempts, making recall more probable.

In summary, the subassembly model is apparently equipped to explain many, though not all, of the findings in the literature and the writer's own studies related to serial-position phenomena in free recall.

B. Analysis of Verbal and Non-verbal Recall Data. Table III-2 on the next page summarizes the findings with respect to mean percentage recall of words (W) and pictures (P) in the writer's two experimental studies. The number of subjects in each group is shown in the top row (N). Pictures can be seen to be better remembered than words in all eight cases.

Table III-2. Word-Picture Recall Percentages

	1968 Study (All Ss set)		1969 Study					
			Immediate		Day-2nd Test		Day-1st Test	
	Immed	30-min	Set	Non-set	Set	Non-set	Set	Non-set
N	40	40	24	24	12	12	12	12
W	32	29	33	22	24	13	10	6
P	47	46	42	33	35	28	23	13

A number of other investigators have discovered a similar phenomenon of superior memory for non-verbal material, in spite of some rather different experimental procedures and tests of retention. Five other studies will be briefly surveyed here. In all these studies, the following features were present (except where specific exceptions are later noted): the stimulus materials were, on the one hand, familiar objects or pictures of such objects (generally similar to those employed by the writer, for which see the Appendix) and, on the other hand, the verbal labels attached as names to these objects by most people; the subjects were naive adults (usually college students) who knew in advance of stimulus presentation that some form of memory task was involved (i.e., there were no "non-set" subjects of the type employed by the writer); a given subject saw either words only or pictures only (in contrast to the writer's mixed-list design); recall was tested immediately following stimulus exposure (there were no delayed memory tasks like those used by the writer); and in the three free-recall studies, items were reported verbally (by writing down the name) regardless of the mode of presentation (in contrast to the writer's procedure of asking subjects to draw the figural stimuli). The three free-recall studies will be considered first, followed by two others which depart more radically from the writer's procedures.

Scott's (1967) stimuli were especially selected to study clustering of recall and consisted of seven objects (or their names) from each of four categories (e.g., tools, animals). The objects (or cards with their printed names) were displayed sequentially one time through after which subjects were asked to write down as many (names of) items as they could remember. Subjects viewing verbal stimuli remembered an average of 17.9 items (64%), while those viewing the objects remembered an average of 20.7 (74%). (Numbers of subjects used in studies reviewed in this section may be found in Fig. III-3, to follow.)

Lieberman and Culpepper (1965) performed two kinds of experiments. In the first, twenty objects or their names were displayed simultaneously for the subject to study, for one minute; the average number of words remembered was 11.1 (56%) and of objects, 14.2 (71%). In the second type of experiment (for which the results stated here are collapsed across the two independent of groups of males and females, since there were no great differences between them), these authors projected photographs of the same objects or their names sequentially from slides (at two seconds per item, with one second between items). In this case, an average of 13.4 words (67%) and 15.0 pictures (75%) were recalled.

In the third study employing free recall, Ducharme and Fraisse (1965) used colored drawings of twenty-five objects as one stimulus list, their names (in French, the native language of the subjects) as another, and the pictures paired with the names as the third list. Their subjects were children about eight years old (two groups differing in mean age by about a year are reported as one set of data here, since the differences between them were not great) and college students. Different sub-groups of subjects from each age group saw the three different lists (words, pictures, words and pictures paired), presented on slides in the same manner (and with the same timings) as for the Lieberman and Culpepper second study. Each group saw the same list three times in a row, with a recall session after each presentation. Because the children did not clearly understand the situation until the second time through, and because some adults achieved perfect scores the third time through, only the data from the second recall session were analyzed. The mean recall scores (followed by the percentage figure in parentheses) are shown in Table III-3.

Table III-3. Ducharme-Fraisse Mean Recall Data

	WORDS ONLY	PICTURES ONLY	WORDS & PICTURES
CHILDREN	10.6 (42%)	10.0 (40%)	12.1 (48%)
ADULTS	16.5 (66%)	18.1 (72%)	18.0 (72%)

The authors interpreted the findings for adults as evidence for spontaneous verbalization when a picture is seen, since the presence of the word does not improve recall over the picture-only situation. The lower figure for word recall was thought of as perhaps the result of the greater difficulty of generating visual associations to verbal stimuli. This type of theoretical account of superior memory for non-verbal stimuli will turn out to be quite similar to the writer's.

In the case of the children, the results can be best understood by assuming that the tendency for spontaneous verbal encoding is not yet well developed; and this was how Ducharme and Fraisse explained the finding that the children did no better on the pictures than on the words, but quite a bit better when they had both the picture and the name to look at. Additional credence is given to this sort of hypothesis by Dale's (1968) finding that young children perform better in a delayed color-matching task if they tend spontaneously to say the names of the test colors. Dale's hypothesis is (in part) that both a representation and a verbal code are stored at the time of stimulus presentation, but that the verbal code is quickly lost by the non-verbalizing (silent) children.

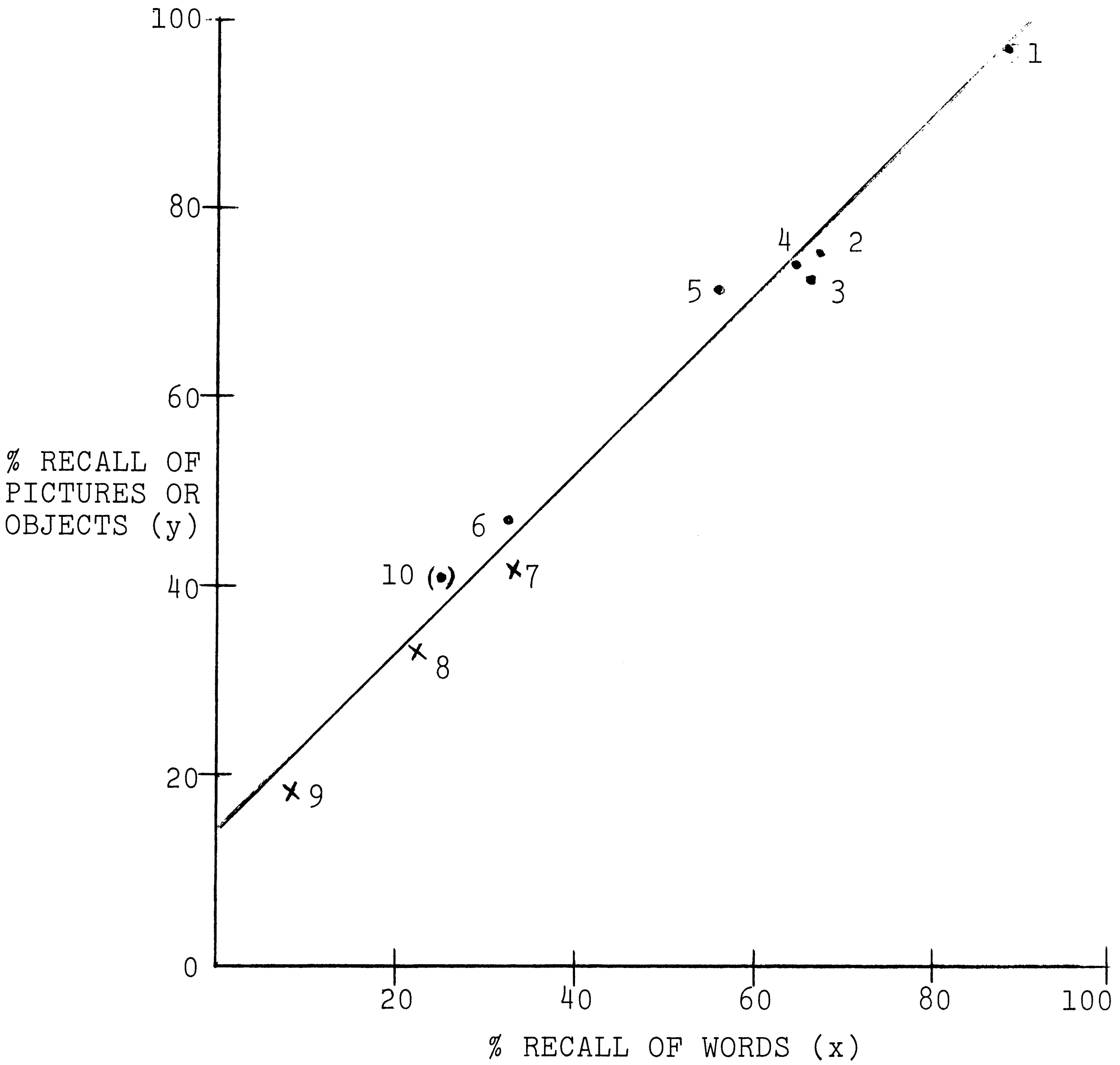
The remaining two studies of verbal and non-verbal recall employed procedures other than free recall. Wimer and Lambert (1959) studied paired associates in which one member of a pair was always a nonsense syllable while the other was either an object or its name. In terms of mean trials to criterion, subjects learned object associations faster (6.05 trials, vs. 8.35 for the word list); they also made fewer errors during learning (means of 25.30 and 40.95, respectively).

Finally, Shepard (1967) employed a forced-choice procedure to study recognition memory for words, pictures, and sentences. After a self-paced sequential examination of a long series (600-

700) of individual items of a given type, the subject was asked to select which member of each of a set of (60-70) test pairs he had seen earlier. Mean percentages of correct identifications were 88.4 for words, 89.0 for sentences, and 96.7 for pictures.

The composite results of these five studies, combined with the writer's two experiments, are displayed in Fig. III-3 on the next page. Percentage recall of pictures or objects is plotted as a function of the corresonding figure for words wherever such a comparison was available (for adult subjects). The point for the Wimer-Lambert study is shown in parentheses because no percentage recall figures can be assigned; mean errors during learning are plotted instead.

It can be seen that the various results fall approximately on a straight line; and since the number and type of stimulus materials and subjects were reasonably homogeneous, it is appropriate to look to experimental procedures to account for the spread of points along that line. Shepard's study produced the highest recall figures by far, which can probably be attributed to his use of a recognition task instead of the (usually) more difficult reproduction procedure. The Ducharme-Fraisse data, the Scott study, and the two Lieberman-Culpepper experiments are in a group somewhat lower down. Finally, there are the data from the writer's two studies, with the immediate recall points for set and non-set subjects (and a single point for all one-day first-test subjects) in the second study shown as Xs. That all these points are relatively low can probably



Regression Line:

y = .94x + 14

Correlation:

r = .81

KEY

1. Shepard (1967) - 51 Ss
2. Lieberman & Culpepper (1965) - sequential presentation - 105 Ss
3. Ducharme & Fraisse (1965) - 41 (adult) Ss
4. Scott (1967) - 90 Ss
5. Lieberman & Culpepper (1965) - simultaneous presentation - 50 Ss
6. Kaplan et. al. (1968) - imm. recall - 40 Ss
7. Immediate, Set
8. Immediate, Non-set
9. One-day, First-test

} writer's current study - 24 Ss each

10. Wimer & Lambert (1959) - mean errors during learning - 40 Ss

Fig. III-3. Composite Data from Word vs. Picture/Object Recall Studies be attributed to the color-naming task in both of the writer's studies; no comparably distracting task was used in the other experiments. The relations among the points representing the writer's work will be discussed in the next section.

In summary, it would appear that better memory for visual than for verbal stimuli is a fairly linear phenomenon which is relatively insensitive to changes in experimental procedure (except as such changes affect overall performance). What remains to be done in this section is to account for this phenomenon in terms of the machinery developed in Chapter II. Probably the best general statement of the writer's hypothesis is found in the write-up of his first study (Kaplan, et. al., 1968), where it was proposed that "pictures are coded verbally and visually while words are coded only verbally"; this also seems to be the view of some other investigators, notably Ducharme and Fraisse (1965).

The implementation of this hypothesis in terms of the model can be based on the development of the verbal encoding machinery in the previous chapter. There it was postulated that verbal and figural representations of items could be overlapping subcollections of subassemblies, with the larger collection representing the item in its many modes. It was argued that the greater coherency of verbal traces, resulting from Hebb-like fractionation, together with the nature of childhood learning, could account for the greater tendency for a figural stimulus to produce activity in the verbal representation than vice versa. The notion of double-encoding thus has a place in the model.

But why are doubly encoded items better remembered (i.e., why is there likely to be a higher retrieval probability associated with the double representation)? One answer could be that, with so many more subassemblies in whichever memory state is relevant for the time of retrieval, the chances of random retrieval input activity producing a large response are better. The situation is similar to the improved chances of getting either of two separate items over the chances of retrieving a particular one of them; in the doubly-coded case, the chances are probably not twice as great, however, since the representations overlap and are therefore not independent.

Although this explanation could account for better performance on figural items, it does not explain why subjects rarely confuse the mode of presentation during recall. A low incidence of reversals (reproductions of pictures as words or vice versa) was a feature of the results of both of the writer's studies. Understanding of this phenomenon might rest in the fact that while both the figural and verbal representations are likely to be active during the input and retrieval of a figure, only the verbal representation is likely to be during the input and retrieval of most words. The reason retrieval input does not excite the figural mode very much when the input was verbal is that there has been little or no priming of the purely figural component (or of the connections from the verbal component to it), since verbal representations are not likely to excite their figural counterparts during item input. Thus the subject knows as a non-verbal item any stimulus retrieved with a strong visual component (with or without the addition of the verbal component, since it has never been suggested that verbal encoding always occurs). When the verbal component is present alone (or in the company of an especially weak figural component), the item is recalled as a word.

Yet this mechanism is not foolproof; if, for any reason, only the verbal trace is retrieved when the stimulus was non-verbal, or if a verbal trace does effectively prime the figural one, there would result the few instances of mode confusion in each direction which the data reveal. Without going into any detail, it is possible to speculate that fatigue in the figural trace might cause a picture to be remembered as a word, while individual differences in the capacity for visual imagery (reflected in the degree of asymmetric inhibition between the two trace components) might influence the number of words remembered as pictures.

C. Analysis of Delayed Recall and Set Phenomena. In this section, two relatively minor and unsurprising results from the writer's studies will be considered. Additional work by other investigators will not be brought into the picture, in contrast to the preceding sections.

The first result relates to the patterning of recall over time. From the writer's two studies taken together, four different recall conditions with respect to time are available. When the word and picture scores for set subjects in Table III-2 are averaged, the groups may be ranked as follows: (a) subjects asked to reproduce items immediately upon conclusion of stimulus presentation remembered about 38% of the items; (b) subjects, who had already participated in condition (a), when again asked to recall the items thirty minutes later, remembered about 37% of them; (c) subjects, who had also already participated in condition (a), when asked to recall the items one day later, remembered about 30% of them; and (d) subjects having their first recall test at one day remembered about 16% of the items.

Thus a subject who had an immediate recall test shows little or no performance decrement thirty minutes later but (without the thirty-minute test) a marked performance decrement one day later, while subjects tested for the first time at a day do even worse. Since the percentages listed above were for set subjects (the only kind used in the 1968 study), it is not quite legitimate to compare the 16% figure in condition (d) with the other results, since set one-day-only subjects were not told that recall was involved but only instructed to watch for duplicate items. However, the ordering of the conditions with respect to performance is still valid, as can be seen from a consideration of the the performance of the non-set groups (all of which were treated identically) in conditions (a)--27%, (c)--21%, and (d)--10%. (Set differences themselves will be explored shortly; the present concern is with the time factor only.)

How are these relations to be understood in terms of the model? First, it is necessary to assess the effects of the previous trial on performance in conditions (b) and (c). This earlier successful retrieval of many items with high VSTM or STM levels will be likely to fix them all the more firmly in memory --moving many of them from moderate STM values back to VST-type activity again, thereby further incrementing their short-term priming. This is the natural consequence of the dominance that accompanies recall. The lack of noticeable performance differences between conditions (a) and (b) is therefore understandable. The immediate recall of items produces greater STPI within (as well as greater STPE between) the SA units comprising the collections representing the items, thus counteracting the decay that would otherwise be expected to occur during the delay. The fact that recall did not approach 100% in these conditions can be attributed both to imperfect retrieval and to normal decay during the list presentation and the first part of the recall session itself. Imperfect retrieval at thirty minutes could account for the few items forgotten during the delay; the small reminiscence effect in the 1968 study will be explained in connection with the analysis used for reminiscence in condition (c).

The situation in conditions (c) and (d) differs from that in (a) and (b) in several respects. A test of recall at one day should involve LT variables. And LT changes have been assigned the position of least influence, especially with reference to retrieval of experimental items. This weakness of LTM, combined with the failure of some items to influence it at all (the result of insufficient VST activity), can explain the inferior performance in both one-day conditions.

But why is there such a marked difference between (c) and (d)? As already mentioned, the fact that the set was not for recall in (d) contributes little to the inferior performance of subjects being tested for the first time. So the immediate recall sessions apparently influence performance at one day, as well as at thirty minutes. (Since only about 3% of the items at one day were reminisced--had not been recalled immediately--subjects appear to find it easier to recall the same items after the delay. Although this may have seemed obvious, it is necessary to rule out a strong reminiscence factor if better one-day memory in (c) is to be attributed mainly to the influence of the earlier recall session.)

Why, then, does the enhancement of STM (via dominance) have an effect on one-day recall similar to, but smaller than, the one it seems to have on thirty-minute recall? After all, ST effects would seldom be present after a day. Perhaps the answer can be found in the greater chances of establishing strong LT effects. If VST activity is repeated (because of the immediate retrieval), then the ST and the LT effects it normally produces will be enhanced out of proportion to the original stimulus intensity. From the ST enhancement will come the potential for better thirty-minute recall; from the LT enhancement, the potential for better one-day recall. A greater proportion of reminisced items at thirty minutes (as found) is expected, since the original ST effects would in some cases still be influential, in spite of retrieval failure during immediate test. At one day however, recall coincides almost perfectly with "retrieval-boosted" LTM. And it is not surprising that many one-day-only subjects could remember only two or three items.

The second finding to be considered in this section relates to the superior performance of subjects who are set for recall, who know in advance of stimulus presentation that recall will be expected of them. Inspection of the last three pairs of columns of recall percentages in Table III-2 reveals the extent of this phenomenon; a typical case is in the immediate recall of words, where set subjects remembered 33% of the items and non-set subjects remembered 22%.

A number of factors probably enter into an adequate explanation of the superior performance by set subjects. For example, even though attention to the stimuli was stressed in instructions to all subjects, those set for recall probably attended somewhat better. This would mean more time spent actually processing the stimulus, leading to more VST activity and hence to a higher retrieval probability.

But interrogation of subjects revealed another difference between behaviors in the set and non-set conditions. As observed in section A above, most set subjects reported moderately successful rehearsal of the items during stimulus presentation; almost all non-set subjects made no such attempt. Rehearsal functions by retrieving an item (usually one in VSTM) and thereby returning it to a higher level of activity. This process may be repeated a number of times for a single item, if the subject has time. A subject could thus probably easily remember the first three or four items (and yet name colors correctly throughout) if he ignored all subsequent items and just rehearsed those first few. But the subject seems to realize that he faces a strategic problem of optimal apportionment of time among concentration on the current item, rehearsal of previous items, and an adequate performance at color naming.

It is necessary, then, for the model to account for a cumulative beneficial effect on recall of successive rehearsals during stimulus presentation. This is not especially difficult, since rehearsal is similar to the previously discussed immediate recall test (both employ retrieval), but with two limiting factors. First, rehearsal must usually be accomplished far more quickly if the subject is to apportion his time effectively (at least in any experiment with a reasonably rapid stimulus presentation rate). Thus the just-presented items (or, with another type of rehearsal strategy, the early items which have just been rehearsed again) are most easily retrieved upon brief activity in the retrieval units, a situation which was treated more fully in Chapter II. The second limiting factor is that the rehearsed item is not reproduced but only mentally reviewed (in most experiments of this general type). So, because the process involves less time spent on the item, and because there is not the added feedback of seeing the item again (having just put it on paper), the impact of a single rehearsal is weaker than that of an immediate recall trial; the rehearsal recreates VST-like activity to a lesser degree. The fact that an item may be rehearsed several times helps to reduce this disparity; so immediate differences due to set are not greatly different from one-day differences due to a prior test.

D. Comparison with the Atkinson and Shiffrin Model. In the last two sections of this chapter, the subassembly model will be analyzed in comparison with two other formal theories of human learning and memory. First, Atkinson and Shiffrin (1965, 1968) have developed mathematical models which deal extensively with free recall and long-term memory, two issues central to the present analysis. Their models generate fits to empirical data, such as serial-position curves. While it is not reasonable to require the subassembly model to compete in the generation of such curves (any more than it is reasonable to ask Atkinson and Shiffrin to specify physiological counterparts for their equations), some areas of fruitful comparison between the two approaches do exist. These will be explored after a summary of their model is presented.

In their 1965 paper, Mathematical Models for Memory and Learning, the authors consider models with three major components. There is a sensory buffer to accept incoming stimuli and pass them on to the memory system. This sensory buffer is not treated in detail; it is assumed that with stimulus exposures of a second or longer there is no information loss at this stage.

The second component is the memory buffer, a type of push-down store which items enter from the sensory buffer and leave, after a variable amount of time, by one or both of two routes. When the buffer is full, a new item must bump out an old one; in the meantime, this older item may have been copied into the third component of the model, the long-term store (LTS). If an item is copied, its status in the memory buffer is unchanged;

if an item is bumped out before it is copied, it is permanently lost. The memory buffer is assumed to be of constant size, containing r items, where r must be estimated for any experiment since the size (information content) of an item is quite variable and not considered in detail. Once the buffer fills up (in push-down order) at the beginning of an experiment, it stays filled, with each new item entering the top slot and bumping out an older (though not necessarily the oldest) item. Items still in the buffer at the time when recall is required are subject to perfect recall.

The transfer process to long-term store can be modeled as all-or-none (the initial copy is complete) or incremental (there is an accumulation of partial copies). Four possible models of the long-term store are considered. If transfer is all-or-none, there may still be either a single copy or multiple copies transferred. If transfer is incremental, LTS may be thought of as containing some strength measure on each item, which may be discrete (e.g., the number of partial copies) or continuous. In either of the latter two cases, the strength is proportional to the amount of time the item spent in the memory buffer.

Retrieval from LTS is imperfect and via a search process which may either (a) stop before an item is found or (b) sample randomly with replacement until the item is found, with the provision that each search may disrupt (destroy) the sought item with some probability. These descriptions of search schemes apply only to the all-or-none, single-copy hypothesis;

corresponding search schemes for multiple-copy or strength hypotheses are somewhat more complicated.

After a rather detailed description of the general type of model, Atkinson and Shiffrin then test three specific versions against data gathered from a simple short-term-memory experiment. Model I assumes perfect retrieval of items in LTS; Models II and III, respectively, use search schemes (a) and (b) described above. The fit is generally good and, although its quality decreases slightly with successive models, this is compensated for by elimination of the need for the parameters to vary with the size of the stimulus array.

These models are followed by a consideration of some strength models for LTS, which are motivated by a desire to account for confidence-rating situations, confusion errors, and repeated-presentation tasks. As mentioned above, the basic assumption of any strength model is that whatever quantity is stored in LTS is a function of the time that item spent in the buffer. For indication of how to proceed with respect to development of a retrieval scheme for strength models, an earlier model of Atkinson's, designed strictly for a repeated-trial paired-associate paradigm, is reviewed. Some possible ways for dealing with repeated items are then considered. And the use of absolute as well as relative strength in determining retrieval probabilities is suggested to account for recall approaching 100% as the number of trials increases.

Atkinson and Shiffrin next look at free verbal recall, modeling only experiments in which an arithmetical task is used following stimulus presentation; such a task is assumed to "clear the buffer" and eliminate any influence it might have on recall. Although they admit that the influence of multiple responses (reporting of several items) in free verbal recall is probably an important complicating factor, the authors choose to assume that the retrieval process has no effect on LTS. A strength model embodying the two already-mentioned features (storage process a function of time spent in the buffer, retrieval dependent on both relative and absolute strength) is then used to explain both the primacy effects and the better recall of mid-list items from shorter lists that the data reveal.

The article concludes with a summary of an information-theoretic version of the model, some comments about the use of a temporal dimension for keeping several lists separate, and a statement that the following three assumptions are crucial to the theory: (1) the various assumptions about the structure and operation of the memory buffer; (2) the fact that items can be in the buffer and in LTS simultaneously; and (3) the nature of the retrieval process, specifically that the decrement in recall associated with increasing list length is the result of an imperfect search of LTS at the time of the recall test.

Although not actually an extension of the model(s) just described, a more recent Atkinson and Shiffrin paper, entitled <u>Some Speculations on Storage and Retrieval Processes in Long-</u>

term Memory (1968), does reveal their thinking on a number of important issues. They begin with a distinction between control processes, which are task-dependent techniques like rehearsal mechanisms and certain kinds of search processes, and the structural components of the memory system. The latter include the three major memory stores: the sensory register, which holds information for less than a second; the short-term store (STS) which, in the absence of rehearsal, holds information for about half a minute and is the subject's "working memory"; and the long-term store (LTS), a permanent repository for information transferred from STS. The remainder of the paper is devoted to an informal discussion of storage and retrieval processes for LTS. Storage consists of three primary mechanisms: transfer, placement, and image production. Retrieval consists of search, recovery, and response generation. Each of these six primary mechanisms is discussed in turn.

Transfer of information from STS to LTS is an automatic process, but one whose usefulness and efficiency are highly dependent upon the subject's "storage strategy." This last term refers to efforts to maintain the information in STS (via rehearsal) for a longer period of time and thereby facilitate storage in LTS, to any special coding or mnemonic techniques the subject employs, and to all decisions the subject makes concerning what portion of the information to store in LTS. Placement refers to the location in LTS where the information is stored. The authors explain that they do not "refer to a physical location in the cortex, but to a position in the organization of memory along various informational dimensions" which may include things like sensory mode, part of speech, and temporal aspects of the item. Placement has directed and random components, the first of which is a function of the subject's control processes. Multiple copies may be placed in LTS, as when, for example, the subjects encode "an associate in two different ways and then store both resulting codes in each of the two locations defined by the codes." Image production determines what portion of the ensemble of information that has been placed at a particular location is permanently stored as an image there. The image contains chacteristics of the item (meaning, size, color, etc.), mnemonic or coding features added by the subject, and links to other images. For simplicity, it is assumed that images are essentially permanent and do not decay or disintegrate over time.

The first primary retrieval mechanism is search, a process which is monitored by the short-term store which contains the search strategy, the information so far recovered, a record of the locations in LTS examined so far, and the like. Like placement, search has directed (controlled by cues, the subject's strategy, and search habits) and random components. Search is stopped by a context-determined termination rule, such as a time limit (external or internal) or the number of unsuccessful search attempts ending at the same LTS location. Recovery is the process by which information from an image located by search is entered into the short-term store. Since recovery is probabilistic, recovery of all the information in a stored image is not assured. Response generation is the process by which recovered information is translated into the desired response; it is of greatest interest when the information is sufficiently incomplete so that the subject must employ one or another "guessing strategy."

Having described the three storage and the three retrieval processes, Atkinson and Shiffrin conclude with a discussion of a number of additional issues. First, decline in performance with time and intervening material is accounted for in terms of "the storage of an increasing number of images, without a corresponding increase in the accuracy of the placement and search processes." Thus, as in the original model, the authors account for decreasing free-verbal-recall performance with increasing list length in terms of storage and retrieval problems rather than in terms of loss of information from stored images.

Some consideration is also given to the question of random placement of images within a list. Although this was assumed in the earlier discussion, it is pointed out that clustering effects during free recall make a model which begins with random search, but exhausts categories of items as they are encountered, much more realistic.

Finally, the authors briefly discuss some ideas related to the differences in performance between recognition and recall memory-test procedures.

While this outline, in the last several pages, of the two Atkinson and Shiffrin studies does not provide anything like the understanding of their work that first-hand acquaintance does, it is hoped that the summary given here will make it possible for the reader who has not seen the original papers to grasp most of the comparative discussion to follow.

A comparison of the Atkinson-Shiffrin (AS) model(s) with the subassembly (SA) model of the present study will be developed along the following lines: first, the major similarities and differences will be reviewed; then the two primary components of the AS system (STS and LTS) will be analyzed from the viewpoint of the SA model; third, AS storage and retrieval processes, mainly as sketched in the 1968 paper, will be compared with analogous features of the SA model; and finally, since both approaches specialize in free-recall data, it will be important to compare their capacities in this area.

The major similarities of the two approaches relate mostly to what they do not claim to model in any detail. The experimental orientation that both have, for example, tends to play down what some might consider more "normal" behavior. And both models assume that they are dealing with sufficient exposure times for perfect transfer of information to the memory systems (although the SA model will later be extended to the domain of much shorter exposures for comparison with Sperling's approach). The third and final major similarity is that both models have little or no concern with the motor-output side of recall.

The major differences between the two approaches are closely related to one another. The first, which has already been mentioned, is that the AS model is more "mathematical" (in the sense of its greater concern with generating fits to empirical data) and less "physiological" (in the sense of its relative lack of concern for faithfulness to actual neural structures) than the SA model. The second major difference is that there is a discontinuity among the various memory stores in the AS organization, while in the SA approach an item is usually stored in a single location (or set of locations) and is retrievable from that locus during any memory stage. This contrast between the two models leads directly to the third major difference, which is that the representation or information content of an item must be considered as moving around from store to store in the AS approach, a notion which would not fit comfortably into the physiologically-oriented SA model.

It is probably unwise to make too much of these differences, since Atkinson and Shiffrin freely admit that they do not seek any correspondence between the constructs of their model and physiological entities. Nevertheless, other investigators with approaches quite similar to theirs have begun to reject such multi-structure memory schemes. In a recent article, for example, Norman (1968) argues against what he calls a "box theory" of primary and secondary storage, mainly because the almost immediate recognition of words and other familiar inputs that humans demonstrate requires the two boxes to be so strongly interconnected "that formal distinctions between the two storage systems become difficult to make." Norman therefore opts for a dual-process storage in which secondary and primary memory are "different properties of the same physical device." If a concept of "tertiary memory" were added to the idea, this would be an appropriate characterization of the writer's model.

A logical place to begin a more detailed comparison of the two theories is with the first primary component in the AS model, the memory buffer or STS. There is a fairly clear analogy here with VST processes in the SA model, although the latter would seem to have a longer time course. An item being lost or forgotten before being transferred from the memory buffer to LTS might correspond to an SA situation in which stimulus-induced plus VST activity is of such short duration or intensity that the resultant ST or LT processes will later make for quite low retrieval probabilities. But note that this loss is an essentially random occurrence in the AS scheme, while stimulus intensity, attention, and the like make definable contributions to the probability of an item's survival in the SA model. It would seem generally desirable to have descriptions of as many components of "random" processes as possible, although neither model completely escapes the need for arbitrary parameters.

There are some other differences. Constant buffer size, although useful mathematically, leads to an *ad hoc* definition of what constitutes an item. In the SA model, on the other hand, the only size limitation on VST activity is the constraint on how many SA units can be active before inter-trace inhibition mounts to the point that some of them are shut down (as in dominance during retrieval); thus the size, though limited, is variable. And items of the same variety need not be of the same size, as in the AS model; the notion of trace coherency, which was central to the understanding of verbal encoding, has no counterpart in that scheme.

VST activity is of a push-down variety, since the decay function allots greatest strength to the most recent item, all other things (input strength, attention, initial state) being equal. The notion of the buffer staying filled, on the other hand, is not especially meaningful in the absence of the constant-size assumption. For the same reason, each new item need not necessarily bump out an old one. The SA model seems, therefore, to be somewhat more flexible and more sensitive to the rate of item presentation.

Any item in the AS buffer can be perfectly recovered, just as any item undergoing VST activity has an extremely high retrieval probability. And to say that the buffer is unchanged by the transfer of an item to long-term store is equivalent to saying that the duration of VST activity is unaffected by the fact that it has been sufficient to initiate longer-term processes.

The other primary component is LTS. This discussion will be brief, since the critical issues of storage and retrieval processes (i.e., of how information gets into and out of LTS) will be taken up later. It is difficult to decide if the counterpart of LTS in the SA model is STM and LTM. The source of the problem seems to be the absence of any sort of intermediate memory in the AS scheme. In the SA model, it is possible for an item to be recallable for several hours and then permanently lost (either because of VST activity sufficient only for ST priming or through counteracting LTP changes). No such situation exists in the admittedly non-interference, non-decay LTS. If an item makes it into LTS, only a faulty retrieval scheme can destroy the item before it is found (ignoring the possibility of a stopping rule, which is either externally imposed or voluntary). But there is always the chance of retrieving it successfully on the first search, no matter how long after presentation that may be. In the SA model, however, there are situations in which retrieval probability can be effectively zero. Thus the AS scheme is in the somewhat paradoxical position of lacking an equivalent of the ST component and at the same time having explanatory adequacy only for short-term memory data.

These remarks need to be tempered somewhat when the AS strength models are considered. In such a case, an item which is quickly copied into LTS and lost just after that will have spent so little time in the buffer that its strength in LTS (and hence its chances of being retrieved) will presumably be quite small. Nevertheless, it will have some strength, which it can never lose except as a result of disruptive retrieval.

Also, the situation just described (quickly copied, then lost from the buffer) appears to have no relation to the circumstances of stimulus presentation; the items to have the lowest recall probabilities seem to be selected at random instead of on the basis of input strength and similar considerations.

The next portion of this discussion will be concerned with a fuller exploration of storage and retrieval processes, primarily as explicated in the 1968 paper. The first storage process, transfer, has no real counterpart in the SA model, since items are not moved around from store to store.

The notion of rehearsal (a control process in the AS scheme) as a storage strategy is interesting because of its apparent similarity to the function of that process in the SA model; the concept of storage strategy, were it to be made explicit in the SA approach, would likely involve the idea of maintaining an item in VST activity (cf., "in the buffer") for as long as possible, through repetitive rehearsals. As a final point concerning transfer and related processes, the idea of a subject deciding what portion of the information in the item is to be stored seems a little awkward; in the SA model, information is stored in accordance with its impact on the external-input SA units.

Since Atkinson and Shiffrin do not view placement, the second storage process, as involving actual physical locations, the only valid comparison would seem to be with the nature of the STPE and LTP links that exist or are established in the SA model. The concept of a subject's deciding (through the directed component of placement) where to place the information seems rather inelegant. The notion of multiple copies is interesting because of its similarity to multiple encoding, although the latter concept is developed more fully in the SA model.

The third storage process is image production. And the idea that only some portion of the information becomes permanent can be compared with the idea, in the SA model, that only certain of the excited subcollections might reach sufficient activity levels to effect LT changes. The "contents" of an image could thus be compared with the loci of sufficiently great activity.

The first retrieval process is search. The concept of a "search strategy" has no counterpart in the SA model, unless it might be the tendency for STPE to direct retrieval. And Atkinson and Shiffrin may be making too much of this anyway, since consciously employed retrieval strategies may be hard to demonstrate; in the writer's study, for example, few subjects reported such strategies, in contrast to the frequently reported rehearsal strategies (in the case of set subjects). Search in the SA model is parallel, while in the AS model it does not seem to be. Both models recognize random components in the search process, although these are spelled out somewhat more explicitly in the SA model. The notion of a stopping rule, on the other hand, may be an AS concept from which the SA model could benefit.

Recovery, the second retrieval process, involves the reentry of an item (image) into STS, a process suggestive of the dominance mechanism mediating retrieval in the SA situation.

Both approaches are probabilistic. The only major problem in the AS recovery scheme would seem to be in avoiding the re-entry of several items into STS, a situation which would not solve but only postpone the decision about which item has been retrieved. Perhaps this is taken care of by the serial nature of the search process; the authors do not say.

The last retrieval process is response generation, about which Atkinson and Shiffrin admit they have little new to say. The notion of a guessing strategy, however, is something from which the SA model might benefit. But it would first be necessary to discover what is meant in the AS scheme by phrases like "a feeling of familiarity on the part of the subject."

One final comment about retrieval is in order. Atkinson and Shiffrin admit that random placement of items in a (mental) list does not fit well with findings of clustering of items in free recall. Their solution, a directed search of the category from which the first item was obtained, leaves open the question of how the category was constructed, as well as the issue of how the search is directed. In this area the SA model can provide both temporal associations based on order of presentation (STPE) and clustering associations based on item similarity (LTP).

Finally, how the two models deal with free recall should be examined carefully, since both attempt to work specifically with this paradigm. The AS dismissal of any effects of the recall process on LTS would, as a first observation, seem rather undesirable, particularly in the light of the influence of the immediate recall trial on one-day performance in the writer's experiment.

The remaining comments about free recall all involve rehearsal to some extent. Since this process was not present in the earlier and more formal (1965) AS models, other explanations were used to account for results which the SA model explains (at least in part) by rehearsal. Rehearsal is introduced as a control process in the 1968 AS paper. But if the authors intend to substitute it for their earlier explanations of free recall phenomena, no hint of the change is given. The rest of this discussion therefore assumes (perhaps incorrectly) that Atkinson and Shiffrin continue to stand behind their 1965 explanations of free recall.

The poorer recall by non-set subjects found in the writer's studies might be explained as the result of lowered attention in the AS model; and this is probably a factor in the SA model too. But rehearsal seems far more important. Not only does rehearsal explain better retention, it also provides a reasonable account of the strong primacy effect for set subjects. The AS explanation of primacy, that the buffer starts out empty and the first items therefore spend the longest time in it, cannot account for the disappearance of the effect in non-set subjects (who also would presumably begin with empty buffers).

The AS discussion sidesteps the recency issue by analyzing only studies with interpolated arithmetic tasks which clear the buffer. Yet if recency is to be explained only by the presence of items in the buffer, which has a decay time of about thirty seconds, then the recency effect in the writer's studies should have been limited to the last one or two items instead of the last five or six (allowing for item presentation time plus recall instructions). So the AS scheme either underestimates the endurance of items in the buffer or lacks an adequate explanation for recency. It might also be wondered how Atkinson and Shiffrin would explain the relatively larger recency effect displayed by non-set subjects in the writer's study, where rehearsal again seemed to be a key factor.

The AS scheme is very concerned about providing an explanation of lowered performance (particularly on mid-list items) with increasing list length, which they do by means of an imperfect retrieval process. This, indeed, is one of the three assumptions the authors consider vital to their model. Here again, if the subjects are set, the phenomenon can be understood as the result of an increasing rehearsal load, which is most detrimental to recall of mid-list items (since they have no help from recency). It could thus be predicted that non-set subjects would not show a relatively greater loss of mid-list items with increasing list length.

E. Comparison with the Sperling Model. Although he uses the phrase "short-term memory," Sperling (1963, 1967) is mainly concerned with quite short stimulus-exposure durations, usually less than a tenth of a second, after which recall is immediately tested. In the terminology of the SA model, it seems safe to say that Sperling's area of interest lies entirely within the range of the VST time period.

The approach here will be similar to the one employed for the AS model--a brief account of the Sperling system, followed by a critical comparison in which it is hoped to show that the SA model can also account for some of the important phenomena. While the description to follow is based mainly on Sperling's 1967 paper, "Successive Approximations to a Model for Short-term Memory," the writer's understanding of Sperling's thinking has also been influenced by an earlier paper (1963) of his, as well as by a summary of the characteristics of short-term visual memory in Kaplan (1968).

Sperling begins by describing a simple memory task in which a subject looks at a row of random letters and then writes them down. Data reveal that a subject can reproduce about four or five letters in such a task when the row is exposed for a brief moment (1/20 second). Sperling then considers three, successively more complicated models which might account for such performance.

Model I proposes that the subject holds the letters in visual information storage (VIS) and then employs a translation component to perform the motor actions involved in copying the letters onto paper. (This translation component appears in all three models; it is never treated in detail.) The memory in VIS is presumed to decay so that the subject cannot remember any more letters by the time he gets to the fifth or sixth. Model I is immediately rejected because measures of the duration of visual storage demonstrate that the subject has already lost the visual image of the letters before he transcribes even one.

The tendency for subjects to repeat the letters aloud (especially when required to wait before writing them down) suggests Model II, which adds a (usually subvocal) auditory rehearsal mechanism to enable the subject to retain the information in VIS by repeating it over and over to himself. A number of experimental measures establish that subjects are able to rehearse in this manner at maximum rates of three to six letters per second. But subjects reliably report at least three letters from a row displayed for less than a tenth of a second, requiring the (first) rehearsal to exceed thirty letters per second in rate. So Model II is rejected.

Sperling then reviews a number of experiments which demonstrate that VIS holds more information than can be used (his partial-report technique indicated a capacity of fourteen letters), loses information rapidly (all fourteen were gone within half a second), and appears to employ a parallel recognition process for rows of up to at least five letters.

Model III best satisfies Sperling. The first component is again VIS, which is operated on by a scan component that selects information from VIS (possibly under heavy constraints) to pass on to subsequent components. The third stage, the recognition buffer, "converts the visual image of a letter provided by the scanner into a 'program of motor-instructions' and stores these instructions." The recognition buffer operates more efficiently than auditory rehearsal, partly because it can set up programs in parallel, but mostly because setting up a program to do something is "inherently a faster process than executing the program." The fourth component is rehearsal, which executes the stored programs. The sub-vocal rehearsal is then temporarily held in the fifth component, the auditory information store (AIS). Since the scan component has access to AIS as well as to VIS, this rehearsed information can be recycled through the recognition buffer and rehearsal process as often as necessary.

It is not easy to compare this model with the SA approach in the component-by-component manner that was used for the AS model because Sperling has postulated some fairly complex machinery in a realm where the SA model is relatively simple. So the best approach seems to be an attempt to account for the Sperling data with the SA model, followed by an inquiry into whether there are situations which Sperling's theory cannot handle as well as the SA model.

It is necessary to model the following phenomena: a subject can retain, at least momentarily, more than ten letters from an array he saw for a tenth of a second or less; on immediate cue (partial report technique) he can report any convenient subset (usually one row of a matrix) of letters; after a delay of only one or two seconds, he can report only three to six letters from the entire array; the initial letter-recognition process appears to be parallel; and subjects employ rehearsal in the non-cued (whole report) situation at maximum rates of three to six letters per second.

These and other short-term visual-memory data have already been discussed in a subassembly context by Kaplan (1968). Although his subassemblies were subject to reverberation and fatigue and could amass short-term connection strength, he did not employ a level of analysis with respect to specific machinery comparable to that of the present SA model. The discussion to follow will attempt to bring some of that machinery into play in a subassembly explanation of Sperling's results, but in a manner strongly influenced by Kaplan's thinking.

It is natural to begin by assuming that a subject has available a trace (representation, SA subcollection) for each letter of the alphabet. The parallel entry of much or all of the stimulus array into the memory system is then understood in the usual SA context of preliminary encoding plus activity in appropriate external-input SA units.

But the situation is unlike those considered previously; instead of sequential long exposures of single items, there is a simultaneous very brief exposure of many items. So the resultant activity in the traces will be small and hence subject to early disappearance through decay. Thus most of the information would be lost in a second or two. It remains to explain the mechanics of partial report, of whole report, and of the role of rehearsal in the latter case.

In the partial-report situation, a subject is given, immediately after stimulus presentation, a cue as to which row of the matrix he should report. Since he is capable of reporting any single row, he must have all the information available for at least a fraction of a second. This means that there is still enough activity (VSTP) in most of the traces for retrieval input to boost them to a level with a good chance for dominance. Note that while stimulus input was short and therefore weak, there is no limitation on the strength of the retrieval input.

But the real question is how the cue selects the row. Retrieval input is non-specific; so the cue must markedly assist the members of the indicated row toward dominance. This could happen as a result of additional facilitory input coming from elsewhere in the trace space. Possibly, through minimal practice, the subject can set up appropriate associations (STPE links) between the various cues and appropriate rows. But this leaves unanswered the question of how the subject "knows" which items were in (say) the middle row. Nothing has ever been said with respect to the processing of spatial-position information in the SA model; and this is not the time to introduce new equipment. So it will have to suffice to say that encoded information for position is probably represented in the space and is closely attached (via STPE) to the item that just occupied that position in the visual field. Thus, through a complicated series of STPE links (from cue, to "middleness," to the middle items), the cue gives additional support to the proper row. While this argument is incomplete, it would seem to be as adequate as the unexplained manner in which Sperling's scanner "selects" information from VIS.

Once the items in the proper row are aided by the cue, their competition for dominance (which they achieve successively) inhibits the remaining low-level activity; the subject cannot report more than the one row.

In the whole report situation, a similar analysis applies. Retrieval input, following hard on the heels of stimulus termination, manages to salvage a few of the items from immediate decay; competition for dominance in these few then wipes out any remaining items.

The tendency for subjects to rehearse material is not particularly surprising; it has already been suggested that rehearsal will be attempted almost any time a subject knows he is in a recall situation. Rehearsal here serves to maintain the few items that survived in a reasonably active status until (and during the first part of) reproduction. Rehearsal rate does not seem critical, since it is not claimed that the initial processing of the items (while they are on display) proceeds via an immediate rehearsal, an assumption that led Sperling to build the motor-program machinery. Initial survival of the items, in the SA explanation, is based on virtually instant retrieval input, a concept that has no place in Sperling's model.

Since the SA model seems to do about as well as Sperling's in accounting for his data, it is appropriate to ask if there are any ways in which it might do better. One way rests on his commitment to auditory rehearsal, a commitment which demands some sort of verbal encoding of all input, in order that the subject may say things over to himself. While verbal encoding is certainly important in the SA model, it was never suggested as an essential prerequisite for memory; rather, the position is that verbal encoding will usually be employed when it is convenient. It is not too difficult to imagine a set of nonverbal stimuli which are relatively simple and yet cannot be verbally encoded in any precise and/or compact manner. If a set of such items were employed in a Sperling paradigm, would the subject be able to remember at least three or four of them? If so, then the SA model would argue that he is probably rehearsing the visual images, since the clumsy verbal codes probably never arose. In any case, it is difficult to imagine a role for AIS in the recall of such items; but this is the only place that rehearsal (which is agreed to be important to recall) can occur in the Sperling model. The experiment clearly needs to be done before any final conclusions can be stated.

Even if Sperling were to limit the applicability of his model to readily named items, however, it would run into difficulties in attempting to account for superior recall of figural items. While Sperling would agree that both pictures and words have verbal representations, and while the writer would agree that rehearsal is likely to be verbal when a name is available, better retention for pictures was explained by the additional presence of a figural trace, a factor which the Sperling scheme cannot accomodate. (It is recognized that Sperling's model does not operate in the long-exposure-time domain of the writer's experiments; yet his commitment to verbal rehearsal as the primary vehicle for retention of incoming information would seem to be time-independent.)

This concludes the discussion of the subassembly model in comparison with other approaches. While the Atkinson-Shiffrin and Sperling models are by no means the only ones that could have been considered, they were selected both because of the current respect they command and because their goals and the formal character of their structures are sufficiently similar to the objectives and structure of the SA model to make comparisons meaningful.

CHAPTER IV: CONCLUSIONS AND PROSPECTS

This closing chapter will contain an evaluation of what the writer believes has and has not been accomplished in this study, together with a survey of the directions future research could take.

It is appropriate to begin with the shortcomings. The development of the model, like that of most new theories in their first exposures, is certainly incomplete. Perhaps the major problem with the present study relates to the physiological and (especially) the behaviorial interpretations which were developed in the latter parts of Chapter II and used as explanatory tools in Chapter III. Two related questions, concerned with the present and potential rigor of this interpretive material, will now be considered.

The first question relates to the degree to which the interpretation is "forced" (to the exclusion of alternative constructs) by the abstract structure, as opposed to being predicated upon *ad hoc* assumptions which are not tied to the theory.

One goal of model building is, in the words of Kaplan (1962), "that wherever possible each step follows from previously established statements, which ultimately lead back to the primitives of the system." The key phrase here is "wherever possible"; sooner or later most new models reach decision points which the preceding machinery cannot resolve unambiguously. At such times, the model builder must depart from the rigorous march of logical consequence and take a few arbitrary, but hopefully not counter-intuitive, essential steps forward. The subassembly model, too, contains such steps, although perhaps not an inordinately large number. Three such cases, all of which reflect essential steps toward explanatory power that do not follow from previously established structures, are the notions of hierarchy, encoding, and dominance. The fact that the experimental data could not be explained without these (or equally aribtrary) concepts, in combination with the fact that no way could be found to embody such concepts in the formal machinery, is suggestive of the inherent difficulties involved in developing a new theory that is both reasonable and rigorous. It may be instructive to examine the three examples just mentioned.

The concept of hierarchical structure among collections and sub-collections is vital to subsequent analyses of encoding, in particular with respect to multiple representations of an item. Yet the hierarchy is not, at least at present, a consequence of the nature of the SA units themselves. Computer simulation might demonstrate that such a hierarchy would form, given appropriate patterns of input stimulation, or at least that a pre-established hierarchy of the type suggested would not be unduly disturbed by the "normal" activities of the model (the latter possibility is suggested because the model is not offered as an account of developmental processes). Then again, computer simulation might not establish either of these outcomes. The result is in doubt. So the hierarchy concept, while plausible to the writer and essential to the development, has (at best) a claim to potential rigor.

The theoretical structure set up to explain verbal encoding does not everywhere follow inevitably from the model. For one thing, the seemingly reasonable notion that the representations of an object and of its name are overlapping subcollections of SA units is not a consequence of the nature of those units and their interconnections.

The situation is similar for dominance. While such a mechanism may be a plausible approach to the retrieval problem, only simulation could establish that the indicated structure of inhibitory connections would actually lead to a competitive type of situation like that described. Once again, while rigor has not been ruled out as a future possibility, neither has it been established as a present reality.

The second question concerning rigor of interpretation relates to the extent to which the values claimed for the model, particularly with respect to its precision, are based on potential refinements of, or additions to, the interpretation. This question goes beyond the simulation issue raised above; the concern here is more with the future of the model as a more generally powerful descriptive device, especially insofar as that future depends on present rigor.

It should be clear that the SA model is not ready to take on the whole brain. Whether it will ever be is hard to say. The potential of a new theory is always difficult to assess in the beginning. This makes it hard to evaluate claims about the solidity of its foundation as a basis for further research. There can be little doubt that the SA model has revealed a minority of its implications; whether the rest will accelerate present lines of thought or turn the emphasis in a radically new direction remains to be seen. In any case, as was pointed out above, the rigor of the model rests at the moment predominately in the structure; the interpretation is only beginning to acquire precision. But it may be hoped that the primitive foundations of the model are solid enough to offer a reasonable prospect for applications which improve on and go beyond present ones. At the very least, the precision of the basic machinery makes it possible to expose flaws in the model, flaws which could otherwise remain forever shrouded in ambiguity.

Commenting on the difficulty of attributing properties like memory, computation, learning, and purposiveness to "mere mechanisms," Arbib (1964) writes as follows: "By making mathematical models, we have proved that there do exist purely electrochemical mechanisms which have the above properties. In other words, we have helped to 'banish the ghost from the machine.' We may not _yet_ have modeled _the_ mechanisms that the brain employs, but we have at least modeled _possible_ mechanisms, and that in itself is a great stride forward." In this respect at least, the present model may have a contribution to make.

To continue with the more positive side of this final perspective, the following claims seem reasonable to make for this study.

(1) To the extent that the model is successful, it has suggested that a fruitful approach to the formal analysis of behavior rests in models that are based, insofar as possible, on physiological reality. In the words of John Hopkins anatomist David Bodian (1967), "While behavior . . . can be studied without respect to the neuron, one can hardly anticipate a satisfying scientific theory of behavior that does not encompass the neuronal level of organization."

(2) The model is, to the writer's knowledge, one of the first neural models to use the subassembly (or any small collection of neurons) as a primitive unit of analysis. Models based on individual neurons have been important in the past, but have sometimes proved less than optimal for large-scale simulations or explications of even moderately complicated behavior.

(3) The model has been shown to be a reasonably useful descriptive tool in analysis of experimental data, in particular some new data contributed by the writer.

(4) The model has accounted fairly well for itself when compared with other formal theories of learning and memory.

(5) In the course of the analysis, the model has generated a number of predictions which can be tested experimentally; it has thus helped to provide the means for its own improvement.

As for the future, research can proceed along three major lines. First, there is a wide range of experimental studies that could be performed in order more fully to test the model and its predictions. Some of these experiments have been suggested in earlier chapters. The following is a partial list of what could be done: (1) since the verbal encoding process, which seems important to superior memory for non-verbal stimuli, is apparently not as spontaneous or well-developed in children as in adults, a longitudinal study of the acquisition of this trait would be interesting; (2) if (non-set) subjects show no relatively greater loss of mid-list items with increasing list length, the SA model will be in a position to challenge the Atkinson-Shiffrin interpretation of such phenomena; (3) simple visual stimuli which lack simple verbal labels could be used in a Sperling paradigm to test the importance of purely auditory rehearsal against the more general approach to rehearsal in the subassembly model.

The second research path is physiological. Despite much impressive work, neurophysiologists have yet to provide a conclusive demonstration of the existence of entities resembling cell-assemblies or subassemblies; at present the evidence is largely suggestive. The writer would not presume to indicate the best approach in this realm. But increasingly powerful equipment and techniques, notably in relation to microelectrodes and electron microscopy, are continually being developed. So it may be possible to lend biological credence to theoretical constructs in the not too distant future.

The last, and possibly most important, area of research is computer simulation. While some plausible analyses can be produced from paper mathematics and involved reasoning, the best test of much of the SA model will come when the computer enters the picture, as was suggested in the earlier portions of this chapter. Plans are, in fact, already in motion to employ a large scale digital computer in the simulation of at least portions of the model that has been developed in this study.

In sum, it would seem that, like most useful models, the present one has generated at least as many research opportunities as it has made contributions. To the extent that there are investigators willing to explore the area further, prospects for a better understanding of the biological foundations of adaptive behavior are perhaps a little brighter.

APPENDIX: EXPERIMENTAL METHODS AND RAW DATA

While two separate studies were carried out, the first is available in the literature (Kaplan, et. al., 1968) and will not be considered in detail here. The two experiments used identical stimulus items, similar instructions, and comparable subjects. The major departures in the second study from the more limited format of the first were as follows: (1) the delayed recall session was advanced from thirty minutes after stimulus presentation to one day later; (2) some of the subjects were not told in advance that recall of stimulus items would be expected of them (all subjects knew this in the earlier experiment); and (3) many of the subjects participated in only one of the two recall sessions, instead of all subjects being doubly tested as in the first study. The remainder of this appendix reports method and data for the second study only.

The subjects were seventy-two undergraduate males, whose participation in the experiment partially fulfilled an introductory course requirement. The twenty-four stimuli were displayed individually on every third slide of a group of seventy-three slides, each of which was exposed for four seconds, with a negligible inter-slide interval. Except for an initial slide containing the word READY, every non-stimulus slide contained four differently colored dots, the colors of which were to be named aloud by the subject in any order. Two orders of presentation were used and each subject saw half the items as words (typed, capital letters) and the other half as pictures (simple line drawings). This design yielded four different stimulus lists, whose specific contents will be detailed in connection with the raw data tables at the end of this appendix. All subjects were given a brief practice trial, insuring that they understood the instructions, which were to name the colors but not to respond to the words and drawings.

The subjects wore zinc electrodes throughout all sessions. Skin resistance was recorded during the slide presentations and the first few minutes of each recall session. The modified Lykken electrodes are described in Kaplan and Fisher (1964); and the skin-resistance recording set-up is described in Kaplan and Hobart (1965).

Two conditions were systematically varied, in order to produce six twelve-subject treatment groups. The recall condition involved whether subjects had a single recall task (either immediately after stimulus presentation or one day later) or were doubly-tested both immediately and at a day. The set condition involved whether or not subjects were told, as part of the pre-stimulus instructions, that they would later be asked to remember the items. Non-set subjects were told only that it was important for them to pay careful attention to the items so that a meaningful measure of their skin resistance could be obtained. One set group was treated somewhat differently, since it was considered undesirable to set subjects for recall when they would not have a memory task until the next day (in fact, not even set, doubly-tested subjects knew in advance about their second recall task). So the set, one-day only subjects were instructed to try to detect any repetitions of stimulus items during presentation of the list (there were none), in contrast to their non-set counterparts who received ordinary non-set instructions.

The recall task itself consisted of giving subjects paper and pencil and instructing them to reproduce as accurately as possible as many items as they could remember, in any order. The immediate recall session was begun approximately half a minute after the last stimulus item (and thus about five minutes after the start of stimulus presentation). For the one-day recall session, the subjects involved returned during the same hour on the day after stimulus presentation; the immediate-only groups did not return at all. Each subject was interrogated after each of his recall trials concerning any method or strategy he could report using in trying to memorize or recall the items. Non-set subjects and all one-day subjects were also asked if they had anticipated the particular recall session.

A GSR score was computed for each subject for each word and picture item. This was obtained by calculating the percentage decrements in skin resistance (a) from the maximum point in the 12-second interval following stimulus onset to the lowest value following it (in time) in the interval, and (b) from the minimum in the interval backward to the highest value preceding it; the difference of the two values in each case was divided by the larger value to produce the percentage. The larger of the two values (a) and (b), which are equal unless the maximum value in the interval follows the minimum value, is then taken as the GSR on that item for that subject. The procedure actually produces a measure of the largest drop in the forward (time) direction, ignoring local maxima, in the 12-second interval beginning with stimulus onset and ending with termination of the second color slide to follow (except for the last item, where only one color slide followed the stimulus, leaving the last four seconds of the scoring interval blank).

The basic recall and GSR data are displayed on the last six pages of this appendix, one page for each group of twelve subjects. Along the top row of each chart are shown the subject's identification (S ID), consisting of a letter and a number, and (preceded by a hyphen) the particular one of the four stimulus lists he saw. The stimuli are listed, in the order of presentation for lists 1 and 3, down the left-hand side of each chart. The order of presentation for lists 2 and 4 was as follows: CIRCLE, FLOWER, BELL, WINDOW, BOTTLE, WATCH, BOOK, CUP, STAR, WHEEL, PIPE, FISH, BOAT, FUNNEL, MOON, CANE, ARROW, CAT, SQUARE, SUN, PENCIL, LAMP, BIRD, FORK.

The R sub-column for each subject is a record of his recall performance, with a w or p being entered for each remembered item, depending upon whether the mode of presentation was as a word or as a picture. This letter is not related to the mode in which he reproduced the item. Reversals, where the subject reproduced the item in the opposite mode from which it was presented, are indicated by a circle drawn around the w or p; thus a circled w indicates an item presented as a word but recalled as a picture. One further refinement is introduced in the case of the two groups of doubly-tested subjects. Here if an item was remembered only the first time and not the second, the w or p symbol is followed by an f (for forgotten); items recalled only at a day by doubly-tested subjects are signified by an r (for reminisced) after the mode letter. The last row of the R sub-columns displays the total number of items remembered; in the case of the doubly-tested subjects, the upper number is for immediate recall and the lower is for performance at one day.

If it is desired to determine the mode of presentation of non-recalled items, the following system was used: in lists 1 and 2, these items were words, CAT, ARROW, FUNNEL, BOAT, SUN, LAMP, BELL, BOTTLE, WINDOW, CIRCLE, PIPE, and STAR, and the remaining twelve items were pictures; the situation was reversed for lists 3 and 4.

The GSR sub-column for each subject indicates the decrement in his skin resistance as he viewed the item. An increment or immeasurably small decrement is shown by a "-"; the numbers are in tenths of a percent (i.e., a 10.3% decrement is shown as 103). The final row gives the subject's mean GSR to the nearest tenth of a percent.

GROUP: Set, Immed., Singly-tested

S ID, LIST	A1-1		A2-2		A3-3		A4-4		A5-2		A6-4		A7-1		A8-3		A9-4		A10-3		A11-2		A12-1	
	R	GSR	R	GSR	R	GSR	R	GSR	R	GSR	R	GSR	R	GSR	R	GSR	R	GSR	R	GSR	R	GSR	R	GSR
CAT	w	41		152	p	76		-		89		65	w	31	p	14	p	42	p	80	w	-		5
MOON	p	75		-	w	55		33		45		26	p	21	w	-		44	w	42		20		-
ARROW	w	38	w	30	p	33	p	-		-	p	26		21	p	-	p	14	p	-	w	-		-
FUNNEL		62		-		52		11	w	111		53		-	p	-		29		10	w	-	w	20
CANE	p	32		-	w	10		-	p	24		53		10	w	27	w	83	w	19		-	p	-
BOAT		37	w	-		10		21		141		41		-	p	11	p	59	p	56	w	7		59
FORK		66		63		65		-	p	11	w	38		20	ⓦ	-	w	118	w	111		-		-
PENCIL		6		-	w	63		-		-		53	p	10		-	w	29	w	40	p	-		70
BIRD	p	21		11		98		-	p	78		38		-		-	w	44	w	20	p	6	p	5
SUN	w	45	w	-		43	p	-		45	p	42		10	p	-	p	71	p	19		-		40
SQUARE		61		34		52		-		33		103		-	w	-		14	w	19	p	-		10
LAMP		65	w	21		34	p	-		-		38		-	p	-	p	70	p	55		-	w	40
WATCH	p	40	p	33	w	-		-	p	22	w	54	p	19		11		50		9		-		40
BELL		45	w	12		105	p	-		39		81		-		-		92		37		42		36
BOTTLE		20		6		75		-		23		81		-		44		81		19	w	44		36
FLOWER		40	p	60	w	17		24		26		83		-		-		77		19	p	29		36
WINDOW		35		-		81	p	-		24	p	81		5	p	11	p	121		74		12	w	57
CIRCLE		21	w	36		-	p	6		14		100		10	p	-		108	p	38	w	34		36
FISH		26		-		73		-	p	54		41	p	10		-		44		20	p	-		-
BOOK	p	10	p	22	w	8		12		-		27	p	10		-	w	16		20		39	p	62
PIPE		5		11	p	16	p	-	w	-	p	40		29	p	11		15		19		7		5
CUP		20		-		8		-		-		14		-		-		76		19		-	p	-
WHEEL		24		32	w	8		-		44		53		10		21		45	w	9	p	-		41
STAR	w	34		-	p	91		-		146	p	81	w	-	p	64		45		37		20		21
ΣR,$\overline{GSR}$	9	36	9	22	11	45	7	5	7	40	7	55	7	9	14	9	11	58	13	33	12	11	7	26

GROUP: Non-set, Immed., Singly-tested

S ID, LIST	B1-2		B2-4		B3-1		B4-3		B5-1		B6-3		B7-2		B8-1		B9-3		B10-1		B11-4		B12-2	
	R	GSR	R	GSR	R	GSR	R	GSR	R	GSR	R	GSR	R	GSR	R	GSR	R	GSR	R	GSR	R	GSR	R	GSR
CAT		44	ⓟ	143		52		16		8		54		32		18	p	31		80	p	-		111
MOON	p	51	w	160		82		8	p	9		53		5		9		12	p	69		-		91
ARROW		40	p	99	w	32	p	16		8		-		11		-		107		64	p	25		56
FUNNEL		40		126		71		30		33	p	25		5	w	16		37	w	34	p	-		34
CANE		51		81		78		-		-		47		52		16		-	p	6		25		34
BOAT		23		66		15		44		-		-	w	-		8	p	48	w	5	p	13		255
FORK	p	26		81	p	15		14		-	w	-	p	5		31		49		-	w	-	ⓟ	44
PENCIL	p	61		176		53	w	4	p	-	w	87		-		8	w	-		51		-	p	43
BIRD	p	16		144		68	w	49		-		91	p	44	p	15		-		35	w	7	p	118
SUN	w	33		109		46	p	21		-		70		-	ⓦ	29	p	12	w	40		53		22
SQUARE	p	51	ⓦ	77		68		-		-	w	95	p	43		29		-	p	-		50	p	13
LAMP		17		77		-	p	40		16		24		21	w	-		12	w	10		81		54
WATCH		50	w	161		61	w	26	p	-		12		22		-		36		38		38		140
BELL		68		123		45		-		-		-		-		15		31		15		27		115
BOTTLE		49		111		53		6	w	-		87		12		29		31		24		38	w	73
FLOWER		93		180		63		7		8		44		23		7	w	3	p	14		13		95
WINDOW		56		134		31		66		17		44		22		28	p	25		-	p	13		150
CIRCLE	w	75	p	139		63		20		16		-	ⓦ	48		29	p	39	w	5		27	w	117
FISH		18		161		54		46	p	52		-	p	31	p	7	w	19	p	24		25		11
BOOK	ⓟ	67		121	ⓟ	-		83		18		63		86		-	w	39		5		6		71
PIPE		48		77	w	39		57		-		45		21		-	p	39		5		-		33
CUP		67		130		47		43		-	w	25		-		28	w	33		-		25	p	70
WHEEL		30		149		31		-		-	w	49		21		14	w	-		14		-		11
STAR		55		109		39		43	w	9	p	50		11		-	p	-		-		13		56
ΣR,$\overline{\text{GSR}}$	8	47	6	122	4	46	6	27	6	8	7	40	6	21	5	14	13	25	10	22	7	20	7	76

GROUP: Set, Doubly-tested

S ID, LIST	C1-3		C2-1		C3-4		C4-2		C5-1		C6-2		C7-3		C8-4		C9-2		C10-4		C11-1		C12-3	
	R	GSR	R	GSR	R	GSR	R	GSR	R	GSR	R	GSR	R	GSR	R	GSR	R	GSR	R	GSR	R	GSR	R	GSR
CAT		50	w	27		13	w	-	w	31	w	-	p	-		82		57		58	wf	13		27
MOON	w	83	p	-	w	16		86	p	45		71		26		127		46		59		25	w	18
ARROW		32	w	26	pf	31		37	w	73		7	p	-	p	20		74	p	47		6		19
FUNNEL	p	46	w	-		16		7		73		139		-		18		20		59		13		-
CANE	w	30		-		13		7	pf	41		58	w	-		88		28		70		6	w	17
BOAT		30		-		26		7	wr	7		23	p	22	p	73		38		49		-		25
FORK		29	p	36		9	p	178	p	54	pf	88		-		93	p	29		44		-	w	42
PENCIL		29	p	12		34		108		53		6		-	wf	60		28	w	24	p	-	w	25
BIRD	wf	15		-	w	6	p	41	p	37		-		21		80	p	29	wf	35		48		-
SUN	p	43		12	p	12		130		92		-	p	43	p	40		10		48	w	12		8
SQUARE		29	p	-		6	p	14	p	135		-		-	wf	20	p	38		59		-		23
LAMP		73	w	-		18		24	wf	153		-	pf	10		100		37		24		24		-
WATCH	w	45	p	11		17		47	p	26	p	129	w	20		20		40		56		12		8
BELL		46	w	68		11	w	33		129		14		20		23	wf	33		29		50	p	-
BOTTLE	p	31		-	p	41		40		16		6		11		21	w	30		29		13		-
FLOWER		46		-		4		89	p	63		35		10	w	68		-		8		26	w	4
WINDOW	p	31		-		-	w	24		88	w	6	p	-		31	w	21	p	29		26	p	7
CIRCLE	p	16		-	p	35	w	-		-		-	p	10		24		-		34		7		4
FISH		62	p	-		17	p	59		113	p	-		10	wf	100	p	28		25	p	13	w	-
BOOK		47		10		7		63		71		97	w	-		58		20		29		14		-
PIPE	p	48	wf	21		33	w	36	wf	100	wf	55		-		55		5	p	25		54		42
CUP	wf	48		-		20		15		59		-		-		-		30		-		7		-
WHEEL		32		-		33		44		15		50		10		27	p	20		13	p	-		-
STAR	p	32		-		33	wf	-		172		12	pf	19		46		10		27		7		-
ΣR^{I}_{D}, $\overline{GSR}$	12 10	40	12 11	9	6 5	19	10 9	45	11 9	69	6 4	33	11 9	10	7 4	53	8 7	28	5 4	37	5 4	16	8 8	11

GROUP: Non-set, Doubly-tested

S ID, LIST	D1-4		D2-3		D3-2		D4-1		D5-3		D6-1		D7-4		D8-2		D9-1		D10-2		D11-3		D12-4	
	R	GSR	R	GSR	R	GSR	R	GSR	R	GSR	R	GSR	R	GSR	R	GSR	R	GSR	R	GSR	R	GSR	R	GSR
CAT		-		15		8		95	p	42		11	p	-		69		67	ⓦⓡ	-	p	11	p	-
MOON		10	w	8	p	31		62		25		5		9		-		49		-	wf	23		-
ARROW		-		46		-		84	p	78		7	pf	-		30		98		-	p	22	p	33
FUNNEL		21		-		16		95		10		9	pf	5		79		24		88	p	22		-
CANE		-	w	29		60		84		5		-		18		79		54		73		11		32
BOAT		-		15	wf	60		72	p	19		27	p	-		39		61	ⓦⓡ	18		6	p	8
FORK		10		29	pf	45		69		28		27	w	-		146		16	p	75		22		-
PENCIL	w	-		14		47	p	23		19		18		85		-		38		9		33		16
BIRD	w	20		29		31	p	45	wf	-		18	w	-	p	78		23	p	-		6		66
SUN	p	-	pf	29		60		55		-		9	p	-		61		23		34		-		8
SQUARE		40		15	pf	15		74		-		18		4	p	71		58	p	18	w	21	w	-
LAMP		20	p	14		-		72		23		-		-		228		15		76		32		41
WATCH		-		86		32		40		23	p	61	w	30		50		4		-		43	w	17
BELL		25		29		65		78		32	wf	-		10		42		44		10		-		35
BOTTLE		12		15		49	ⓦ	68		14		-		20		110		14		5	pr	5		43
FLOWER		26		59		-	pf	20		-		-		21		115		7		11	wf	5		27
WINDOW		48		-	w	33		38		14		8		20		99		141		21	p	5	p	43
CIRCLE		13	p	30		19		48	p	-	w	-		73	w	105		14	wf	22	ⓟ	11		36
FISH		11		30		8		69		18		-		38	p	20	p	50	p	43		11		17
BOOK		46		-	p	32		16		9		16		137		59	p	21		9		5		9
PIPE		22		15		32		10		9		8	p	10		59		36		18		11		4
CUP		23	wf	45		32	ⓟ	35		14		81		10		59		14		9	w	11		42
WHEEL		43	w	30		38		11		18	p	-	w	29	p	30		14	p	18	wf	5		17
STAR		43	pf	-		16		20	p	9		4		10		99		28		-	p	21		-
$\Sigma R^{I}_{D}, \overline{GSR}$	3 3	18	8 5	24	6 3	30	5 4	54	6 5	17	4 3	14	10 8	22	5 5	72	2 2	38	6 7	23	11 9	14	6 6	21

GROUP: Set, One-day only

S ID, LIST	E7-1		E8-3		E9-4		E10-3		E17-4		E18-3		E19-2		E20-1		E21-3		E22-1		E23-4		E24-2	
	R	GSR	R	GSR	R	GSR	R	GSR	R	GSR	R	GSR	R	GSR	R	GSR	R	GSR	R	GSR	R	GSR	R	GSR
CAT		29	p	7		44		-		29		50		25		63		11		56	p	68		57
MOON	p	14	w	-		45		-		14		34		38	p	9		31		32		81		34
ARROW		29	p	4		44		-		-		49	w	60		44		52		57	p	54		5
FUNNEL		29	p	-		78		-		15		33	w	25		93		21		63		41		-
CANE		7		-		56		-		86	w	17		-		52		21	p	76		54		-
BOAT		7		7		87		-		29		33		26		52	p	20		63		57		-
FORK		41		7		21		-		16		67		24	p	8		5		13		54		25
PENCIL		28		7	w	10	w	-	w	30		17	p	23		17		-	ⓟ	51		68	p	20
BIRD		28		14		20		-		30		8	p	116	p	48		20		64		57	p	44
SUN		14	p	-		43		-		30		32		-		39		10		65	p	54		48
SQUARE		28		-		22	ⓦ	17	w	15		47		24		47		10	p	46		68		-
LAMP		29	p	29		30		-		46		31		-		30		5		46		68		43
WATCH		14		29		74		-		63		63	p	38		61		10		13		15		-
BELL		14		15		54		34	p	48		119		41	ⓦ	15		20		66		45		27
BOTTLE		14	p	7		64		-		149		35		7		8		-		48		58		5
FLOWER		7		-		85		4		32		18		81		84		-		27		16		39
WINDOW		7		37		64	p	-		15		16		-	w	48		5	w	48		59		27
CIRCLE		28		8		11	p	121		50		16		68		61	p	10		27		65		36
FISH	p	7		37		21	ⓦ	5		-		-		26		54		-	p	53		44		35
BOOK		7		-	w	32		112		16		44		12		39		10		34		28		30
PIPE		7	p	-		82		-		15	p	30		51		16		-		14		91		39
CUP		14		45		71		49		32		-		75		16		-		7		11		25
WHEEL		28		-		20		-		64		-		51	p	70		10		41		41		-
STAR	w	29		-		10		98	p	-		29		14		49		-		7	p	81		-
ΣR, $\overline{GSR}$	3	19	8	11	2	45	5	18	4	34	2	33	5	34	6	43	2	11	5	42	4	53	2	22

GROUP: Non-set, One-day only

S ID, LIST	E1-1		E2-2		E3-3		E4-4		E5-2		E6-4		E11-2		E12-1		E13-2		E14-4		E15-1		E16-3	
	R	GSR	R	GSR	R	GSR	R	GSR	R	GSR	R	GSR	R	GSR	R	GSR	R	GSR	R	GSR	R	GSR	R	GSR
CAT		7		132		14		22		68		24		-		121		45		-		59		26
MOON		14		-		-		23		28		11		18		79		-		-		28		51
ARROW		40		56		13		22	ⓦ	56		24	ⓦ	18		167		-		-		80		-
FUNNEL		93		74		-		23		83	p	11		19		52		9		-		41	p	-
CANE	p	14		107		13		34		56		29		-		67		-		-		67		28
BOAT		40		161	p	39		23		99		23		19		50		18	p	-		41	p	-
FORK	p	13		82	w	-		65		53		25		-		50		27		14		40	w	-
PENCIL		40		100		26		70		27		13		36		54		36		-		39	w	47
BIRD		7		58		-		122		27		25		18		42		18		-		50		24
SUN		53		98		-		23		56		50		36		7		63		-	ⓦ	50		-
SQUARE		-		83		26		122		55		25		-		86		37		-		50		12
LAMP		-		60		25		95		27		13		18		80		-		-		25		-
WATCH		6		55		-	w	101		32		12	p	19	p	97		9		-		25		-
BELL		-		80		-		90		65		25		20		27		10		-		72		59
BOTTLE		26		91		25		103		8		28		19		71		-		-		95		-
FLOWER		-		83		-		91		68		26	ⓟ	-		70	p	10		7		49		-
WINDOW		13		58	p	38	p	139		79		12		20		115		18		13		48		48
CIRCLE		-		87		13		79		-		13	ⓦ	21		7		10		14		-		25
FISH		-		-		50		60		71		-		36	p	-		-		-	ⓟ	24		25
BOOK		24		-		13		75		32		28		19	ⓟ	-		18		-		82		-
PIPE		-		38		13		71		-		11		-		53		10	p	-		72		75
CUP		24	p	71		26		25		32		12		19		48		34		-		49		-
WHEEL		-		51		26		48		44	w	23		18		25		19		6		73		-
STAR		-		103		38		49		15		23		19		40		-		-		25		55
ΣR, $\overline{GSR}$	2	17	1	72	3	17	2	66	1	45	2	20	4	16	3	59	1	16	2	2	2	49	4	20

REFERENCES

Adams, Jack A. (1967), Human Memory, McGraw-Hill Book Company, New York.

Arbib, Michael A. (1964), Brains, Machines, and Mathematics, McGraw-Hill Book Company, New York.

Atkinson, R. C. and Shiffrin, R. M. (1965), "Mathematical Models for Memory and Learning," Technical Report No. 79 (Psychology Series), Institute for Mathematical Studies in the Social Sciences, Stanford University, Stanford, Calif.

Atkinson, R. C. and Shiffrin, R. M. (1968), "Some Speculations on Storage and Retrieval Processes in Long-term Memory," Technical Report No. 127 (Psychology Series), Institute for Mathematical Studies in the Social Sciences, Stanford University, Stanford, Calif.

Bodian, David (1967), "Neurons, Circuits and Neuroglia," in The Neurosciences: a Study Program, ed. by G. C. Quarton, T. Melnechuk, and F. O. Schmitt, Rockefeller University Press, New York, pp. 6-24.

Bousfield, W. A., Whitmarsh, G. A., and Esterson, J. (1958), "Serial Position Effects and the 'Marbe' Effect in the Free Recall of Meaningful Words," Journal of General Psychology, 59:255-262.

Dale, Phillip S. (1968), "Children's Color Categories and the Problem of Language and Cognition," Unpublished Doctoral Dissertation, The University of Michigan, Ann Arbor, Mich.

Deese, James and Kaufman, Roger A. (1957), "Serial Effects in Recall of Unorganized and Sequentially Organized Verbal Material," Journal of Experimental Psychology, 54: 180-187.

Ducharme, Raymond and Fraisse, Paul (1965), "Etude Genetique de la Memorisation des Mots et d'Images," Canadian Journal of Psychology, 19(3):253-261.

Farley, B. G. (1962), "Some Similarities between the Behavior of a Neural Network Model and Electrophysiological Experiments," in Self-organizing Systems - 1962, ed. by M. C. Yovits, G. T. Jacobi, and G. D. Goldstein, Spartan Books, Washington, D.C., pp. 535-550.

Finley, Marion (1967), "An Experimental Study of the Formation and Development of Hebbian Cell-assemblies by Means of a Neural Network Simulation," Technical Report, Department of Communication Sciences, The University of Michigan, Ann Arbor, Mich.

Glanzer, Murray and Cunitz, Anita R. (1966), "Two Storage Mechanisms in Free Recall," Journal of Verbal Learning and Verbal Behavior, 5(4):351-360.

Glanzer, Murray and Meinzer, Arthur (1967), "The Effects of Interlist Activity on Free Recall," Journal of Verbal Learning and Verbal Behavior, 6(6):928-935.

Good, Irving J. (1965), "Speculations Concerning the First Ultraintelligent Machine," Advances in Computers, 6:31-88.

Halstead, Ward C. and Rucker, William B. (1968), "Memory: a Molecular Maze," Psychology Today, 2(1):38-41, 66-67.

Hebb, D. O. (1949), The Organization of Behavior, John Wiley and Sons, New York.

Hebb, D. O. (1968), "Concerning Imagery," Psychological Review, 75(6):466-477.

Herzog, Thomas (1968), "A Neural-circuit Analysis of Set and Perception," Unpublished paper, The University of Michigan, Ann Arbor, Mich.

John, E. Roy (1967), Mechanisms of Memory, Academic Press, New York.

Kandel, Eric R. and Wachtel, Howard (1968), "The Functional Organization of Neural Aggregates in Aplysia," in Physiological and Biochemical Aspects of Nervous Integration, ed. by F. D. Carlson, Prentice-Hall, Englewood Cliffs, New Jersey, pp. 17-66.

Kaplan, Stephen (1962), "Arousal and Perseveration: a Theoretical Model," Unpublished Doctoral Dissertation, The University of Michigan, Ann Arbor, Mich.

Kaplan, Stephen (1968), "The Formation of a Percept: an Application of a Neural Net Model," Unpublished paper, The University of Michigan, Ann Arbor, Mich.

Kaplan, Stephen and Fisher, George R. (1964), "A Modified Design for the Lykken Zinc Electrodes," Psychophysiology, 1:88-89.

Kaplan, S. and Hobart, J. L. (1965), "New Technique for Recording Skin Resistance," American Journal of Medical Electronics, 4:117-120.

Kaplan, Stephen, Kaplan, Rachel, and Sampson, Jeffrey R. (1968), "Encoding and Arousal Factors in Free Recall of Verbal and Visual Material," Psychonomic Science, 12(2):73-74.

Kimble, Daniel P. (ed.) (1967), The Organization of Recall, New York Academy of Sciences, New York.

Levonian, Edward (1966), "Attention and Consolidation as Factors in Retention," Psychonomic Science, 6(6):275-276.

Lieberman, Lewis R. and Culpepper, James T. (1965), "Words vs. Objects: Comparison of Free Verbal Recall," Psychological Reports, 17(3):983-988.

McCulloch, W. S. and Pitts, W. (1943), "A Logical Calculus Immanent in Nervous Activity," Bulletin of Mathematical Biophysics, 5:115-133.

Milner, Peter M. (1957), "The Cell Assembly: Mark II," Psychological Review, 64(4):242-252.

Murdock, Bennet B. (1962), "The Serial Position Effect of Free Recall," Journal of Experimental Psychology, 64(5):482-488.

Norman, Donald A. (1968), "Toward a Theory of Memory and Attention," Psychological Review, 75(6):522-536.

Postman, Leo and Phillips, Laura W. (1965), "Short-term Temporal Changes in Free Recall, " Quarterly Journal of Experimental Psychology, 17:132-138.

Rochester, N., Holland, J., Haibt, L. H., and Duda, W. L. (1956), "Tests on a Cell Assembly Theory of the Action of the Brain," IRE Transactions on Information Theory, IT-2:80-93.

Rosenblatt, R. F. (1958), "The Perceptron," Psychological Review, 65:386-407.

Scott, Keith G. (1967), "Clustering with Perceptual and Symbolic Stimuli in Free Recall," Journal of Verbal Learning and Verbal Behavior, 6(6):864-866.

Shepard, Roger N. (1967), "Recognition Memory for Words, Sentences, and Pictures," Journal of Verbal Learning and Verbal Behavior, 6(1):156-163.

Sperling, George (1963), "A Model for Visual Memory Tasks," Human Factors, 5:19-31.

Sperling, George (1967), "Successive Approximations to a Model for Short-term Memory," in Proceedings of the Eighteenth International Congress of Psychology, Moscow, U.S.S.R., 1966, North-Holland Publishing Company, Amsterdam.

Thorndike, E. L. and Lorge, I. (1944), The Teacher's Word Book of 30,000 Words, Columbia University Teacher's College, New York.

Tulving, Endel (1968), "Theoretical Issues in Free Recall," in Verbal Behavior and General Behavior Theory, ed. by T. R. Dixon and D. L. Horton, Prentice-Hall, Englewood Cliffs, New Jersey, pp. 2-36.

Wilson, Donald M. (1968), "The Flight Control System of the Locust," Scientific American, 218(5):83-90.

Wimer, C. C. and Lambert, W. E. (1959), "The Differential Effects of Word and Object Stimuli on the Learning of Paired Associates," Journal of Experimental Psychology, 57:31-36.

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The primary objective of this study is the development and application of an automata-theoretic neural model of human learning and memory, using the subassembly (a small, tightly interconnected set of neurons) as the primitive unit of analysis. In a larger context, the research reported here is viewed as a contribution to an understanding of the biological bases of adaptive behavior, particularly language behavior.

The first chapter reviews the historical background of the area of research, beginning with the cell-assembly theory of Hebb; simulation projects are considered along with theoretical advances. The tppe of neural network model employed is then put in its appropriate context wiht respect to neural models in general.

The development of the model is undertaken in the second chapter, where the primitive SA (subassembly) unit is seen to consist of connection control, input summation, and state control units. The nature of the sub-components of each of these units is described mathematically and interpreted behaviorally. The representation of stimulus items in hierarchically organized networks is then considered, with emphasis on mechanisms mediating attention, encoding, retrieval, rehearsal, and recall.

The third chapter applies the model to experimental data and compares it with other models of learning and memory.

The last chapter considers the degree of rigor in the model, outlines the major claims made for the study, and looks at the prospects for future avenues of research.

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