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ON COGNITIVE STRATEGIES FOR FACILITATING ACQUISITION, RETENTION, AND RETRIEVAL IN TRAINING AND EDUCATION

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The idea that students could be taught to be more effective learners, in distinction to being taught subject matter, is explored in relation to recent advances in the cognitive and neurosciences, with the objective of integrating information from these sources into a unified viewpoint that could serve as a roadmap for research and as a context for discussion.

According to this viewpoint, cognitive strategies for facilitating acquisition, retention, and retrieval of information and of performance are composed of specifications, called orienting tasks, for how cognitive processes are to be used, and of cognitive processes drawn from representational, selectional, and self-directional resources. Representational resources include propositional and appositional processes of the left and right cerebral hemispheres, chiefly language and imagery. Selectional resources consist of attentional and intentional processes. Self-directional resources include self-programming and self-monitoring processes. Possibilities for teaching students better control over attentional and intentional processes, by using neurophysiological indicators, particularly to reduce self-generated distractions during learning, are noted.

Concepts of processing capacity, depth of processing, expended processing capacity, resource-limited and data-limited processing, top down-bottom up processing, and graceful degradation of output, advanced by several different theorists, are considered in terms of possible sources of individual differences, possible electrophysiological indicators, and implications for cognitive strategies. The importance of long term memory in learning is recognized. Three types of long term store (LTS); semantic, episodic and motor, are described. Semantic and episodic LTS are of great current theoretical interest. Their implications, particularly of semantic LTS, for acquisition, retention, and retrieval are discussed. Norman's concept of web-learning is an example. The additional requirement for some kind of LTS for controlling skilled performances is noted, and two recent theoretical formulations of cerebral-cerebellar roles in this regard are reviewed.

Several kinds of subject-matter are described under information and performance and these are tentatively cross-classified with types of long term memory and strategies for acquisition, retention, and retrieval. Different approaches to teaching students cognitive strategies are described in terms of possible combinations of instructional control and explicitness of the strategy. Finally, techniques for implementation of appropriate approaches are considered. The Learning Assistance Center (LAC) concept is viewed as the context for applying implementation techniques in a systematic and long-term fashion; including diagnosis of individual student requirements and resources, prescription of an appropriate combination of strategies, and instruction in how to use them. It is proposed that LAC's might eventually be recognized as important resources in Naval training.

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SUMMARY

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I. INTRODUCTION

At this laboratory, research on instructional systems has been organized in relation to an analysis of elements and functions making up these systems, illustrated in Figure 1. This is intended to serve as a road map of areas where R & D should be done on these systems. In the section of the diagram in Figure 1 labelled EXTERNAL FACILITATION the two terms, content bridges and cognitive strategies, are intended to distinguish between material specific to a particular subject-matter and more general procedures that facilitate acquisition, retention, and retrieval, across different categories of subject-matter. Cognitive strategy will be used to signify operations and procedures that the student may use to acquire, to retain, and to retrieve different kinds of knowledge and performance. These operations and procedures may be cognitive information processing, as in the case of mental imagery, or may be cognitively controlled, as in the case of skimming through a textbook to identify major points. Cognitive strategies involve representational capabilities of the student; reading, imagery, speech, writing and drawing; selectional capabilities, attention and intention; and self-directional capabilities, self-programming and self-monitoring. It is considered that a cognitive strategy is composed of two parts: a cognitive orienting task and one or more representational, selectional, or self-directional capabilities.

This term, orienting task, will be used throughout this report to designate methods for inducing the student to perform particular kinds of operations. A similar term, orienting directions, was used by Frase (1969), which he defined as,

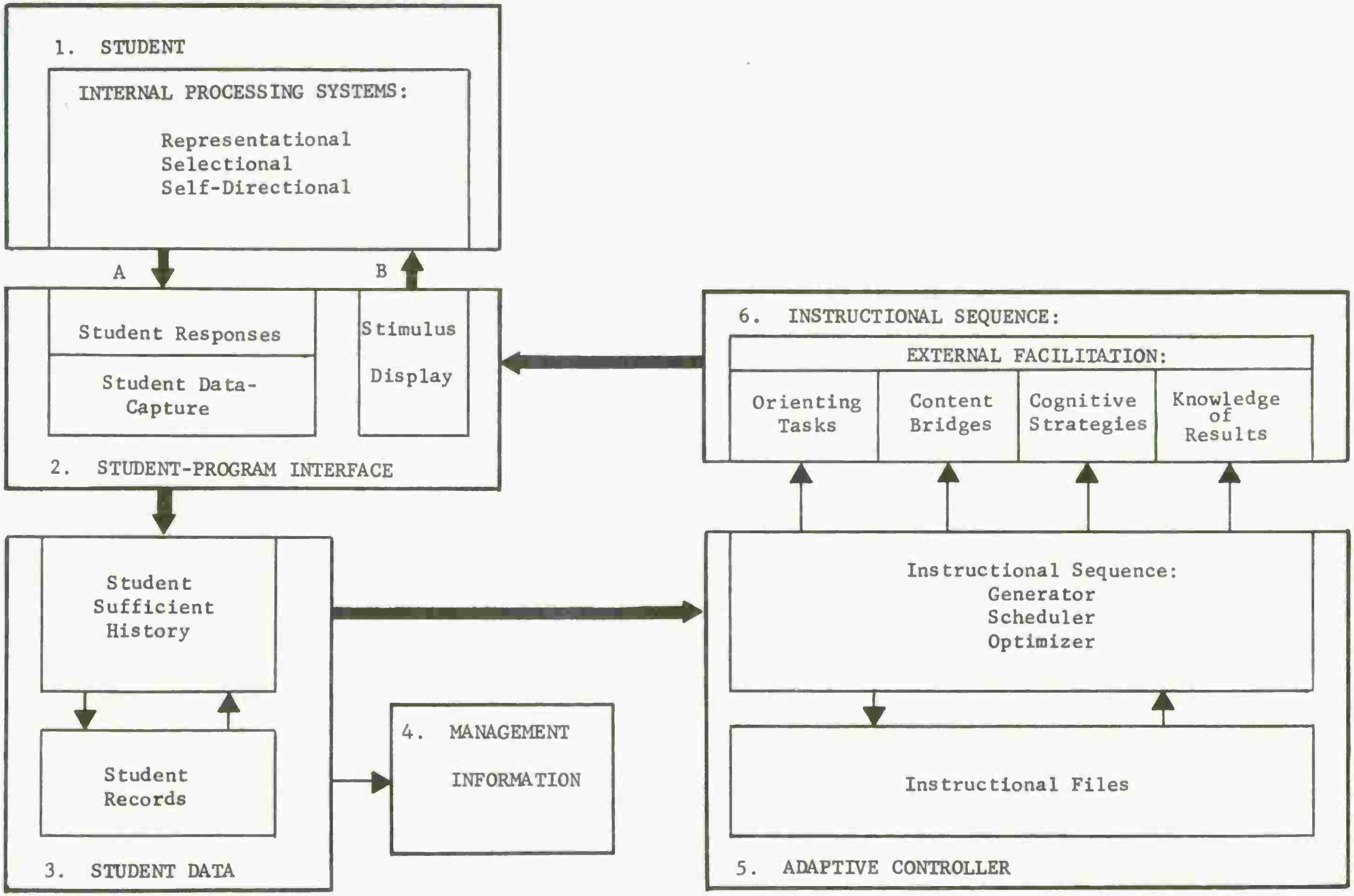

Figure 1. Outline of Major Subsystems in an Automatic Instructional System.

> "A label for a general class of goal-inducing stimuli including questions, verbal commands, typegraphical cues, etc., which might be used to alter the effective stimulation from a text. Effective orienting directions seem to have two main components: they specify cues for initiating and determining information processing (the range of stimuli to be processed), and they also specify a processing activity to be performed with those stimuli." (p. 2)

For the purpose of this report, the orienting task part of a cognitive strategy specifies how a particular cognitive capability is to be used.

Some additional definitional considerations are necessary at this point. Although cognitive strategies are always performed by the student, the initiation of their use may come from the student's instructions to himself, or from an instructional system. The fact that the processing operations the student performs constitute a cognitive strategy may or may not be apparent to the student. It seems likely, in fact, that many students fall into ways of learning, possibly as a consequence of haphazard reinforcement, of which they are not aware. Furthermore, an instructional system can be designed to teach students to use some cognitive strategies without making the students aware that the operations they are performing are, in fact, cognitive strategies. If orienting tasks are categorized as Student-Assigned (SA) or Instructional System Assigned (ISA) then these distinctions can be summarized in Figure 2.

Some instructional systems are now designed to realize combination D. Their designers seek to induce students to use effective cognitive strategies by the design of the orienting tasks in relation to the subject matter to be taught, and by the design of other conditions, which together constitute an instructional strategy. Not all instructional strategies, it should be noted, are designed to induce students to use

Explicitness of Cognitive Strategy	Control of Orienting Task	
	SA	ISA
Detached	A	B
Embedded	C	D

Figure 2. Alternative approaches to teaching and using cognitive strategies.

cognitive strategies. They may instead be concerned with optimal allocation of trials or of time for learning content (Atkinson and Chant, 1976). It will be a premise of this report that combination A is desirable under at least some circumstances, and that it can be realized by first implementing combination B. That is, an instructional system can be designed to teach students that there are, in fact, cognitive strategies; and, furthermore, that if the students apply these strategies properly, their use will facilitate acquisition, retention, and retrieval. Although most of this report is concerned with these possibilities, rather than with subject matter variables, the content of the material to be taught cannot be ignored. In Figure 1, the term, content bridge, is used to signify a unit of subject matter that is incorporated into the instructional sequence and that is displayed to the student, in combination with a content orienting task which in this context, describes the specific processing operations that the student is to perform on this unit. The term content bridge, rather than content unit, is used, despite its admitted awkwardness, because it is intended to signify the idea that stimulus material in the external world, particularly meaningful stimulus material, when perceived, excites processes in long term memory in the internal world (e.g., Bobrow and Norman's schema, 1975), and in that sense is a bridge between external world events and internal world events. According to this idea, learning is a matter of modifying already existing, highly organized, internal representational systems and processes. The term, content orienting task, is essentially equivalent to the processing operations inherent in the content, which may also be most of what is to be learned about that subject matter, as in mathematics, or computer programming, or which may be already known processing operations, such as reading, used to extract meaning from a text.

Sometimes the content orienting task is implicit in the way the content bridge is presented and sometimes it is not. For example, if the following is displayed:

$$2 + 4 = \_\_\_\_\_?$$

If is usually inferred by the student that he is to add the two numbers and supply the sum. This content bridge assumes that the student already knows the meaning of "+" and "=" and knows how to perform the operations they require. In other cases, there may be a separate description of the operations the student is to perform to produce the required outcome. For example, in statistics, if the task is to compute the inverse of a matrix, the content orienting task could be a printed algorithm the student should use. Of course, this quite complicated task could be analyzed into a series of simpler tasks, each specified in this way. Cognitive strategies that helped the student to acquire and to retrieve the algorithm for inverting a matrix would be useful to that student for acquiring and retrieving other algorithms. It is likely, though, that cognitive strategies vary in generality and applicability. Mental imagery, for example, seems to be applicable in a variety of learning tasks, (Bower, 1972). Converting the letters of CVC's to words that form meaningful phrases clearly is a strategy of less generality (Prytulak, 1971).

According to this view of instruction, the instructional sequence is designed to help the student to develop and to organize internal mediational processes (Box 1, Figure 1). In these terms, external facilitation is a set of techniques for inducing internal mediation. The subject matter must be organized into content bridges, including content orienting tasks, to guide the student's information processing operations until he can respond correctly.

Observe that the student may be induced to respond in different ways to the same content bridges by giving him different cognitive orienting tasks to perform. For example, a student who is told he must memorize a text passage will process it differently than a student who is told he must learn the meaning of the passage. In both cases, the student reads the passage. Thus, cognitive orienting tasks can modify the execution of content orienting tasks.

In the traditional approach to education and training, teaching content-specific mediation has been the primary goal. Learning to learn has been recognized in the literature of verbal learning only as a by-product of practice in rote memorization (Duncan, 1960; Postman, 1967), and learning to remember has been, until recently (Bower, 1970) left to the purveyors of commercial memory courses. According to the traditional approach, requiring students to solve lots of problems will increase their ability to solve other problems; requiring students to process lots of text will increase their general text-processing ability, etc. In short, the approach to teaching students cognitive strategies has been through content-based instruction. There is no question that this kind of transfer does occur at least some of the time for at least some of the students. It is not clear, though, how this development occurs, or what variables are related to its occurrence, which, at best, must be a haphazard phenomenon, and which must be strongly dependent upon individual student characteristics.

Recently, the possibility of going the other way, of using cognitive strategies to facilitate acquisition, retention, and retrieval of content-based mediation, has been the subject of an increasing number of investigations. Most of the recent work on doing this has been concerned with the use of mental imagery. There is, by now, a vast literature on the effects, usually positive, of student-generated mental imagery on the recall of CVC's, noun lists, and the like (Rigney and Lutz, 1974).

Atkinson (1975) and his associates demonstrated powerful effects of a two-stage, acoustic link, imagery link, keyword method for learning foreign vocabulary. Students were instructed in how to use this method, in which the keyword for the acoustic link was experimenter-supplied, while each student then supplied his own mental image for an item.

Other cognitive strategies that have been investigated include several forms of inserted questions (Rothkopf and Bisbicos, 1967; Frase, 1968; and Anderson and Biddle, 1975). These, if inserted immediately following a text passage, resulted in better later retrieval of the information in the passage to which the inserted questions pertained.

Rigney and Lutz (in press) investigated the effects of interactive graphic representations of abstract concepts on their acquisition. Shimron (1975) investigated the relative effectiveness of several acquisition strategies on the learning of maps. Schaller (1975) varied orienting tasks to induce different levels of processing, in the Craik and Lockhart sense (see below) of prose passages, and found that students remembered more information when induced to process at a semantic level. Dansereau, et al., (1975) developed and evaluated a rather elaborate "effective learning strategy training program," for teaching more effective processing of text. They investigated the relative effectiveness of three techniques: question-answer, paraphrase, and imagery, which they taught different groups of students to use on passages each student had identified as difficult to comprehend. Dansereau and his associates may be the first to try a combination of strategies in a systematic way on text processing. They gave their students instructions on four aspects of the learning process: identifying important, unfamiliar, and difficult material; applying techniques for comprehending and retaining this material; retrieving this information; and coping with internal and external distractions during learning. In the last case, however, no specific coping techniques or behaviors were taught. The students were merely exposed to auditory distractions while they were applying some of the other techniques. It is likely that techniques for coping with external distractions also could be identified and also could be taught. One that some dormitory students have discovered is the use of music, ocean shore sounds, or even white noise from an amplifier, to mask nearby conversations. Methods for coping with internal distractions may be even more important to facilitating learning processes. The application of biofeedback techniques might lead to fruitful results in this case.

This growing research interest suggests the need for a more organized view of the field. Just how many cognitive strategies are there, how many different means exist for teaching students to use them, and how do these relate to what is known about learning and memory processes?

In this report, the idea will be explored that it may be possible to teach students how to be more effective learners, that is, to be more effective in acquisition of and more effective in retention of and in retrieval of information and performance. This is not to say that we suppose that self-directed learning by the student would work for all students, all learning requirements, or all contexts, or that self-applied cognitive strategies are always alternatives to instructional systems with built-in instructional strategies, of which the student is never aware. Teaching students how to learn and how to retrieve what has been learned, as the primary objective, might, in fact, be done best by an instructional system; and having been taught these skills, the student might, in fact, profit more from an instructional system with the primary objective of teaching content. Beyond this, though, a time comes when a student finishes the course, graduates from school, and must then cope with requirements for further learning more or less by himself. The material he then must learn from may not be pre-programmed or pre-scheduled. It may, for example, be a technical manual, accompanying some fiendishly complex electronic equipment.

II. EXTERNAL FACILITATION AND INTERNAL MEDIATION IN INSTRUCTIONAL SYSTEMS

An instructional system, as diagrammed in Figure 1, creates a special environment in which the student is supported while learning to be more-or-less self-sufficient with respect to performing in some future environment. The system is designed to assist the student in progressing at a suitably rapid rate, from maximum dependence, for that student, on external information and instruction, to an appropriate degree of reliance on information stored in LTS, on self-generated instructions, and on self-monitoring. External facilitation and internal mediation are not mutually exclusive: some mixture of both always is required. The tasks for the instructional system are to determine the appropriate starting mixture for each student, the most effective ways to assist that student in achieving an optimal rate of progression, and an appropriate mixture for the termination of instruction. Some of these determinations involve considerations external to the instructional system, which in actuality is embedded in other systems.

The patterns of knowledge, skills, and abilities that the individual student brings to the learning situation obviously must be dealt with in some fashion by the instructional system; it must assess these in some way. The student will already possess capabilities that are useful to some extent in mediating the desired responses. In the matrix inversion case, he may know elementary matrix arithmetic, or he may know something about determinants, or he may even know some algorithms for performing matrix inversion. If so, it would be inefficient to teach those topics to him again. The situation can be crudely diagrammed as follows for each objective of instruction.

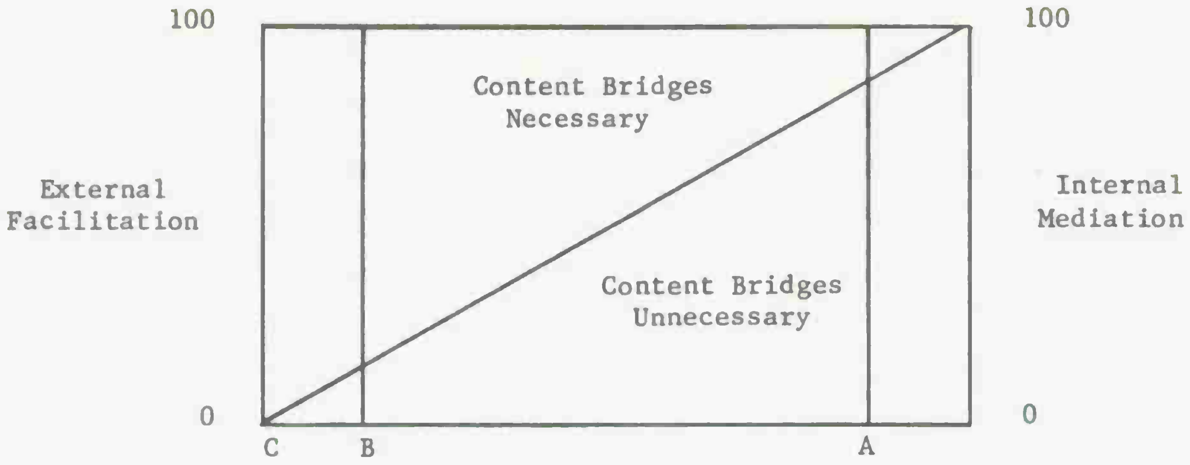

Figure 3. Relative amount of internal mediation and external facilitation required for different levels of entering skills and knowledge.

Whatever it is that is required to mediate the desired response(s) to some stimulus configuration in the subject matter, student A knows more of it than student B, who is close to requiring full external facilitation by the instructional sequence. In an extreme case of <u>no</u> content known, the student would start at what can be called the fully instructed baseline for a population. Student C would be at that point. Student C might first have to learn all relevant elementary matrix algebra, whereas student A might need only to review an algorithm for matrix inversion.

The concept of a content bridge is related to the old "step-size" in programmed instruction. The exact nature of both is difficult to specify. Programmed instruction dealt with the problem by using proportion of errors on a step, or frame, for a given population of students, as an operational definition of step-size. To reduce error rates, content was reduced to very small steps, or frames, which might be called a fully instructed baseline for that population. As students learned from a programmed instruction sequence, they would develop more internal processing from content bridges. Frames in later parts of a linear sequence could presume more internal mediation, so that the student could be given processing tasks requiring more internal mediation between stimulus and response, and the frames could be less explicit about all the intervening operations.

Multiple strands alternating in the instructional sequence, used by Suppes (1968), Atkinson (1968) and others, is another way of serially organizing content bridges. In one example, material relating to the development of different skills was put in different strands. An instructional sequence optimizer controlled the progress of students along a turnpike path which include both strands (Chant and Atkinson, 1975).

The semantic network provides the foundation for a third way of dealing with the organization of subject matter for instruction. Here, each topic or concept is ultimately related to every other topic or concept, and the student can progress either by asking or by answering questions, there not necessarily being one starting or one stopping point or anything like a standard sequence through the material. Norman (1976) calls this approach web learning. One characterization of it that he has given is as follows:

> "Suppose we have a large body of knowledge to teach--what would be the best way of doing it? Presumably, we need to interconnect the new information with the existing structure. One way to do this is to construct a supporting web structure first, and then fill in the details. To do the details first would not work, for without a supporting structure, the new material simply could not become integrated. In teaching, this means that an outline of the material to be learned should be acquired first, then a more detailed overview, and then progressively more and more detailed structures.

> The network representation of knowledge can guide the process of instruction in two different ways: (1) if we have a good representation of the knowledge we wish to teach, then we can organize it properly for efficient learning: (2) if we try to discover the network representation of the student, we can use this to guide our teaching. Knowing the knowledge structure of the student helps in devising the original level of organization of the material. In addition, as the lessons progress, we can use our understanding of the student's developing structures to guide us in teaching, telling us what old material has not been acquired and what new material might perhaps already be known. Thus, it is theoretically possible to tailor instruction to the knowledge base and competence of the student.
>
> Whether the network representation makes the goal easier to attain remains to be seen. The major drawbacks have resulted from the expense of using tutorial methods in mass education, and from the lack of sophistication in the implementation of most teaching machine programs and computer-assisted instructional systems to attempt these goals." (p. 12) Nonetheless, the analysis is instructive even if the complete implementation remains in the future.
>
> We can characterize two different strategies of presenting material: two different strategies of teaching. One is to present a cohesive organized structure to the student, carefully adding one new piece of information after another to the developing structure. This might be called <u>linear</u> <u>teaching</u>. It is the system that characterizes lectures, textbooks, and even the structure of this report. The other method is to present a coarse web of information, outlining the topics to be discussed, then giving a general overview followed by more detailed overviews, and finally the detailed substructure. This procedure might be called <u>web</u> <u>teaching</u>. Web teaching is often prescribed, seldom done. It is difficult to perform well. But we wish to suggest that for the learning of complex topic matters, web teaching may at times be more efficient." (p. 13).

A number of theorists are investigating the semantic network representation of information for purposes related to instruction (Norman, Rumelhart and the LNR Research Group, 1975; Brown and Burton, 1975; Collins, et al., 1975). This network organization could be the basis for various ways of teaching the student to add to his own structure of knowledge. Collins (1976) is developing the Socratic method of tutoring for interacting with the student. He asserts that the central notion of this method is "to force the student to reason for himself, to derive general principles from special cases, and to apply the general principles that have been learned to new cases." His objective is to develop a computational theory of the Socratic method, using production rules to represent specific strategies, to express the theory in a general procedural formalism. He has listed twenty-three specific strategies, identified in discourses from sample content domains, which force the student to develop different parts of a knowledge structure in order to answer the questions that are asked of him. These would be classified, in the terms of this report, as embedded cognitive strategies. All of these ways of dealing with content bridges require that the subject matter be specially structured, or programmed, for instructional purposes.

To summarize, the elements of external facilitation in the instructional sequence are orienting tasks, content bridges, cognitive strategies, and knowledge of results. The stages of learning; acquisition, retention, and retrieval are composed of processes operating on external content bridges and on the existing structure of knowledge in LTS. Content bridges are chunks of subject matter presented to the student during instruction. They include content orienting tasks, which tell the student the kinds of operations to perform in relation to these chunks in order to respond appropriately in terms of the requirements of the objectives of instruction. Cognitive orienting tasks may be used to tell the student what kinds of cognitive processes to use to facilitate the learning of and the retrieval of internal mediational representations from content bridges. Given the same instructional sequence, because of individual differences in world knowledge; acquisition, retention, and retrieval skills, and processing capacity; each student in a population could start at a different place and progress at a different rate, from primary dependence on external facilitation of performance to primary dependence on internal mediation of performance. Because of the interrelationships and interactions of the elements in the instructional sequence, and of individual differences among students, procedures for control over outcomes of instruction must be sensitive to these complexities. The scheduling of these elements, as illustrated in Box 4, Figure 1, should be done by an adaptive controller. Under ideal conditions, scheduling would be guided by an optimizer, also indicated in Box 4, Figure 1, although suitable techniques for optimization of instruction (Chant and Atkinson, 1976), are not widely available, as yet, in instructional systems.

Types of Content

The preceding discussion set forth a general conception of instruction as the development in the student of internal mediation from external content, without regard for the type of content, which clearly is an important consideration for the application of cognitive strategies, as well as for the design of instructional systems. Although it is beyond the scope of this paper to deal exhaustively with the enormous variety of subject matter that is included in education and training, the implications of major categories for cognitive strategies must be noted, in the context of the acquisition of internal mediational equivalents which are the basis for knowing about something and for knowing how to do something. For this purpose, the domains will be divided first into information and performance. What are proposed to be major, relevant categories in each of these then will be considered briefly.

Information

Knowledge of the world stored in memory is acquired from direct observation of and participation in events, and through the medium of language and other external representational systems, presented in the form of speech, textual, and graphic materials. Some major forms of information are narrative accounts of sequential events, or episodes; scientific explanation using abstract concepts, often described in mathematical or other logical formalisms; representations of objects in the external world; and descriptions of operations or procedures. These will be labelled narratives, explanations, representations, and prescriptions. Each of these kinds of information has an intrinsic structure, or organization. Examples of these types are history (narrative), electronics (explanations using abstract concepts), descriptions of the structure and function of a machine (representations), and instructions for operating a vehicle or for computing a correlation coefficient (prescriptions).

A current view is that this information is transformed by internal representational systems: perceptual, imaginal, and verbal, into propositional form stored in long term memory. Acquisition of this information would seem to involve interactions between imaginal and verbal systems, and inference based on existing world knowledge already in memory. It is proposed that three kinds of long term storage (LTS) in memory are involved, as will be discussed in the next section .

Performance

Performances that are to be learned can be classified in terms of the requirements for guidance by information stored in LTS, and in terms of the complexity, timing, and precision of contractions of muscles used for the performance. Some performances, such as typing or playing the piano, are guided by complex semantic codes, and also require great muscular precision. Other performances, such as skating, or skiing, also require great precision of movement, but are less dependent on complex semantic codes. Requirements for learning and remembering these different kinds of performance are undoubtedly different, calling for different employments of the representational and motor systems, and presumably, for different cognitive strategies. As will be discussed below, the information needed to control patterns of muscle contractions during performance is assumed to be stored in a particular kind of LTS.

Cognitive Strategies and Individual Differences

It is unlikely that all students would find the same cognitive strategies equally effective. Information in the literature about cognitive styles (Pask, 1971; Pask and Scott, 1972), suggests this conclusion.

Although some students learn faster than others and some students retain material longer than others, or can retrieve more of it, not much is known about the casual differences in terms of internal processing and storage. Some neurophysiological speculation is stimulated by the discovery of differences in the elaboration of synpatic spikes on cortical neuron dendrites of rats raised in austere vs. enriched environments (Bennett, et al., 1964). Could learning and memory capacities be dependent upon the potential complexity of semantic networks in LTS determined by the densities of synaptic spikes on cortical neuronal dendrites? Does this provide for greater information packing density per cubic millimeter of cortex? Would this allow finer differentiation of details in world knowledge? As a consequence, would the world be comprehensible as a more complex place by the owner of cortical dendrites more richly endowed with synaptic spikes? It is unlikely that the full story will be this simple. Lashley (1950) searched for the engram in the cerebral cortex without running it to ground. Recently, the search has shifted to the hippocampus, where early in conditioning trials, unit activity rapidly forms a temporal neuronal model of the behavioral response. This rapidly developing hippocampal response has been suggested to be a neuronal correlate of short term memory (Berger, Alger, and Thompson, 1976). Thompson (1976) reviewed recent research on this classic problem. His conclusions are instructive:

> ".... To resolve these issues, it will be necessary to track the response through the brain, backward to structures projecting to the hippocampus and forward to structures innervated by the hippocampus.
>
> It is almost certain that many brain systems are involved in the formation of the engram. The organization of the brain implies parallel processing; there are many different routes for information to pass from input to output structures in the brain. The pattern that is beginning to emerge is one of different brain systems playing different roles in the memory system. Granting parallel processing, there could still be one set of places or systems in the normally functioning mammalian brain where the engram first makes its appearance. Because the hippocampal response develops very early in training and is large and reliable, localization of the initial formation of this learning-dependent brain response is feasible." (p. 224)

Can cognitive strategies compensate for low capacity? Since these must enable the more effective utilization of capacity during acquisition, retention, and retrieval, the answer must be, yes, to some extent. Do bright students use different strategies for learning and remembering than dull students? It is reasonable to assume that they do.

Teaching low capacity students cognitive strategies should improve their acquisition and retrieval efficiency, but they still would not be able to comprehend subject matter as complex as that comprehended by students with high capacity. It is reasonable to assume , too, that detached strategies generally might be more appropriate for bright students, who probably would be more able to direct themselves; while embedded strategies might be more effective with dull students, who might need simpler orienting tasks, more support and encouragement, and who might be less venturesome, and less motivated.

Cognitive capacity (Kahneman, 1973) is one of several general terms now current in cognitive science. The term is used here in the sense of some inherent, neurophysiologically determined intellectual power. The term, Expended Processing Capacity (EPC), used by Griffith (1976) and others, refers to the mobilization of processing resources for a particular information processing task, as described in the next section. The implication is that at any one moment, more or less of these resources will be occupied by the task. Thus, deep, or elaboration processing in semantic memory is thought to require the expenditure of more processing capacity than shallow, or maintenance processing, such as rehearsal in short term memory. As described below, secondary tasks often are superimposed on primary tasks to provide an estimate of EPC. This term has strong attentional implications. Norman and Bobrow (1975) used Resource Limited and Data Limited for cognitive processing that is (gracefully) degraded by limited processing resources of the subject, or that would not be facilitated by the mobilization of more of the subject's processing resources because there is nothing more in the input data to be processed to meet the requirements of the orienting task(s). They proposed that learning can shift processing from a resource-limited to a data-limited state. It seems, then, that Griffith's expended processing capacity depends upon how many of Norman and Bobrow's processing resources must be mobilized to meet the moment-by-moment processing load which may be inherent in the task, or which may be varied by the student, depending upon intentional considerations, between Craik and Lockhart's Type I or Type II processing! If the student mobilizes all the cognitive resources at his disposal and these still are not sufficient, his processing will be pushed into a gracefully degraded state. He will, for example, guess.

These are useful ideas that will lead to a better understanding of cognitive processing and processes. Cross-classifying the notion of cognitive capacity, defined above as built into the CNS, and the notion of processing resources, as having somehow accumulated through learning, results in the following diagram:

Processing Resources	Cognitive Capacity	
	High	Low
High	A	B
Low	C	D

Figure 4. Relationships Between Cognitive Capacity and Processing Resources.

Of the possible combinations, B seems most unlikely, since an individual with low cognitive capacity would not be able to accumulate a rich "library" of cognitive resources. The individual with combination C might be most helped by the kinds of cognitive strategies that are the primary topic of this report.

These ideas are related to the topic of aptitude-by-treatment interactions in educational psychology. Cronbach and Snow (in press) have exhaustively investigated evidence for ATI's. One of Cronbach's major conclusions from this investigation is as follows:

> "Contrary to our original view, conventional tests of mental ability or level of educational development do interact. They predict how much is learned from most instruction of fixed duration; but whether the regression slope is steep or shallow depends on the instructional procedure (Cronbach & Snow, in press, Chapters 5-11). One way to reduce the effect of general ability is to bring in pictures or diagrams. Another is to make lessons more didactic and less inductive. On the whole, the regression of outcome onto general ability tends to be relatively steep when the instruction requires the learner to actively transform information, and it tends to be shallow when the demands are less. But the generalization is weak, with many studies running counter to trend. (Cronbach, 1975, p. 119).

Parameter estimation procedures have been used to estimate learning ability for instructional optimization techniques (Chant and Atkinson, 1976). Also, error information obtained from retrieval tasks performed during acquisition might be used to build up some kind of model of the individual student that could guide selection and scheduling of cognitive strategies in an instructional system, as noted earlier. The instructional models being investigated by Norman (1976), Brown (1975), and Wescourt (1975) seem to be moving in this direction, although they are likely to be concerned primarily with embedded cognitive strategies rather than with detached strategies. These approaches have potential for dealing with individual differences at the individual student, micro-interaction level, in distinction to the cruder regression techniques used to investigate ATI's.

Of course, the organization of instruction for different levels of intellectual capacities and other aptitudes has been and continues to be a primary concern of the educational and training world. There are courses in Navy training, which tens of thousands of students take annually (approximately 1 in 3 sailors goes through the B E & E course). Reduction of attrition rates in such cases becomes a matter of sufficient economic importance to encourage investigating the usefulness of cognitive strategies in this context.

III. LEARNING AND MEMORY PROCESSES

The terms, acquisition, retention, and retrieval, signify sequential processes that are poorly understood and that must be, at the functional level in the CNS, complex indeed. For the purposes of this discussion, acquisition is defined to include all processes from entrance into Sensory Registers (SR) to storage in Long Term Storage (LTS). Retrieval is defined to include the processes required to access and to recover information in Short Term Storage (STS) and in LTS. Retrieval is an unavoidable stage in testing for acquisition and for retention. The only way for anyone, including the student, to know if a student has learned something, is to require him to recognize or to recall it, which obviously requires him to engage in retrieval operations. The outcomes of retrieving also provide feedback which is the basis for all forms of adaptive control of instruction.

The learning processes that constitute acquisition, retention, and retrieval could be divided into operations that have been, or could be described at a verbal level, and neurophysiological processes that are almost totally unknown and which are not under the learner's direct control. These processes are responsible for well-known effects. The sudden appearance of the solution to a problem, or of a creative idea in consciousness, are examples. Still another example is the apparent shift of performance control out of the focus of attention, with practice to fluency. The focus of attention shifts from the details of the task itself, to more general aspects of the situation and to the consequences of the performances.

There are many current theories of memory systems. The multistore theory (Atkinson and Shiffrin, 1968), and the levels of processing theory (Craik and Lockhart, 1972) will be briefly reviewed first. These seek to account for processes and events during acquisition, retention, and retrieval in different ways, although both emphasize the central role of information processing guided by orienting tasks.

In an outline of the multistore view (Atkinson and Shiffrin, 1968; Atkinson and Wickens, 1971) the sequence of events with respect to acquisition during learning was described more or less as follows: information from external displays enters sensory registers via receptors, where it is available to CNS processing. This information in sensory registers is sampled by selective attention and is transferred through LTS, where identification and other processing, e.g., pertinence judging, (Norman, 1969), occurs, back to STS. There, it may be retrieved, by a serial scanning process, serve some immediate goal, and be forgotten when that goal is achieved. Otherwise, the information is stored in LTS. A block diagram of this conception is given below in Figure 5.

In the development of the multistore theory of memory, Atkinson and his associates emphasized the importance of the role of what they called control processes:

> The term control process refers to those processes that are not permanent features of memory, but are instead transient phenomena under the control of the subject; their appearance depends on such factors as instructional set, the experimental task and the past history of the subject.

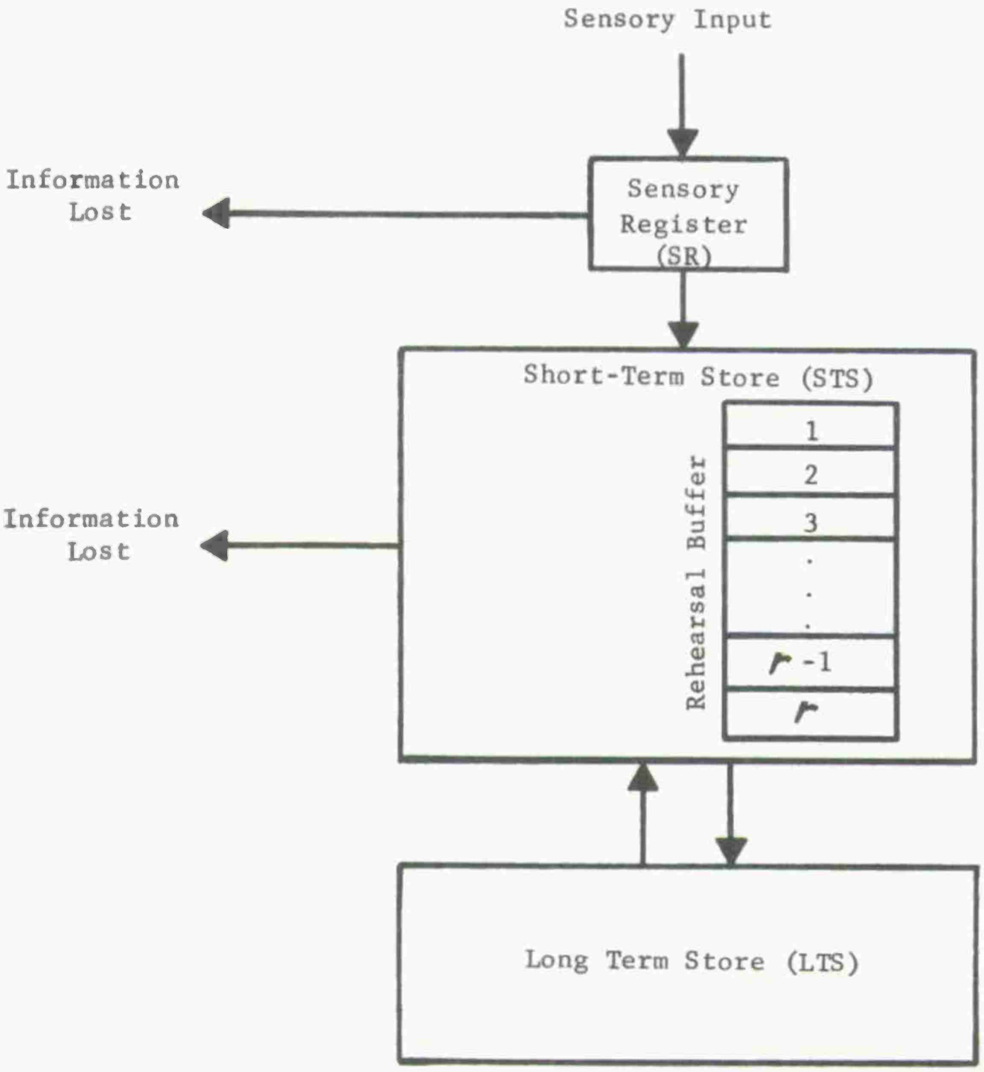

Figure 5. Structure of the memory system, according to Atkinson and Wickens (1971) p. 72.

> Since the subject-controlled memory processes include any schemes, coding techniques, or mnemonics used by the subject in his effort to remember, their variety is virtually unlimited and classification becomes difficult. Such classification as is possible arises because these processes, while under voluntary control of the subject, are nevertheless dependent upon the permanent memory structures described in the previous section. (Atkinson and Shiffrin, 1969, p. 106).

Atkinson and Shiffrin (1968) reviewed control processes in terms of the boxes in the multistore model: (SR), (STS), and (LTS); noting that: ",,.the presentation will be somewhat fragmentary, drawing upon examples from many disparate experiments in an attempt to emphasize the variety, pervasiveness, and importance of the subject-controlled processes" (p. 107).

Generally speaking, they discussed processes that select information fron sensory registers to be transferred to STS; storage, search and retrieval strategies in STS, noting the importance of rehearsal for maintenance of information in STS; coding processes and transfer between STS and LTS; and storage and long-term search processes in LTS. Atkinson and Wickens (1971) analyzed the influence of reinforcement on these control processes, taking the view that reinforcement is the modulation of information flow in the memory system; that it is a means of controlling control processes. They viewed reinforcement as a complex process derived from other, more fundamental aspects of the learning situation, and their discussion of reinforcement in these terms illustrates possibilities for getting better control over cognitive strategies. Rather than reviewing these possibilities here, it will be assumed that these possibilities could be incorporated in combinations B and D in Figure 2, and that the term "knowledge of results" in the instructional sequence box in Figure 1 could be expanded to include reinforcement as conceived by these authors.

Craik and Lockhart (1972) proposed a modification to the multi-store model in which they focused on the encoding operations themselves as determining relative permanence of storage. They conceived of a limited-capacity information processor that can be deployed over a series, or hierarchy of processing stages; such as analysis of physical or sensory features of the physical stimulus, matching the input against stored abstractions from past learning, and extraction of meaning. Greater depth of processing implies a greater degree of semantic or cognitive analysis. They suggested that the persistence of the memory trace is a function of depth of analysis, with the deeper levels of analysis resulting in more elaborate, longer lasting, and stronger traces. Thus, in this view, retention is a function of depth of processing, and memory is a continuum "from the transient products of sensory analyses to the highly durable products of semantic-associative operations" (p. 676). They noted, however, a second way in which stimuli can be retained, by recirculating information at one level of processing. This they called Primary Memory (PM), which is STS renamed, and equated PM retention with continued processing, which they called Type I processing. Type I processing is repetition of analyzes which have already been carried out. The deeper levels of analysis of the stimulus they called Type II processing. Only this Type II processing leads to improved memory performance; to the extent that the subject utilizes Type II processing, memory will improve with total study time (the total time hypothesis). When the subject does only Type I processing, the total time hypothesis does not hold.

According to the levels-of-processing model of acquisition; repetition, or practice, merely provides opportunities to learn, it does not necessarily, without the intervention of cognitive processing during the trials, result in storage in LTS. The burden of acquisition is placed on the kind of processing that is elicited by orienting tasks, either assigned to the learner, or self-imposed by the learner. Craik and Lockhart reviewed several examples of the effects of different orienting tasks, in the incidental learning paradigm, which illustrates these differential effects.

Craik and Tulving (1976) elaborated on the concept of depth of processing, from the results of a series of ten studies. They found that many of the ideas expressed by Craik and Lockhart are in need of considerable modification:

> "Is spread of encoding a more satisfactory metaphor than depth? The implication of this second description is that while a verbal stimulus is usually identified as a particular word, this minimal core encoding can be elaborated by a context of further structural, phonemic, and semantic encodings. Again, the memory trace can be conceptualized as a record of the various pattern-recognition and interpretive analyses carried out on the stimulus and its context; the difference between the depth and spread viewpoints lies only in the postulated organization of the cognitive structures responsible for pattern recognition and elaboration, with depth implying that encoding operations are carried out in a fixed (p. 290) sequence and spread leading to the more flexible notion that the basic perceptual core of the event can be elaborated in many different ways. However, while spread and elaboration may indeed be better descriptive terms for the results reported in this paper, it should be borne in mind that retention depends critically on the qualitative nature of the encoding operations performed--a minimal semantic analysis is more beneficial for memory than an elaborate structural analysis." (p. 291)
>
> It seems necessary to bring in the principle of integration or congruity for a complete description of encoding. That is, memory performance is enhanced to the extent that the encoding question or context forms an integrated unit with the target word.

> "The question immediately arises as to why integration with the encoding context is so helpful. One possibility is that an encoded unit is unitized or integrated on the basis of past experience and, just as the target stimulus fits naturally into a compatible context at encoding, so to retrieval, re-presentation of part of the encoded unit will lead easily to regeneration of the total unit. The suggestion is that at encoding the stimulus is interpreted in terms of the system's structured record of past learning, that is, knowledge of the world or "semantic memory" (Tulving, 1972); at retrieval, the information provided as a cue again utilizes the structure of semantic memory to reconstruct the initial encoding. An integrated or congruous encoding thus yields better memory performance, first, because a more elaborate trace is laid down and, second, because (p. 291) richer encoding implies greater compatibility with the structure, rules, and organization of semantic memory. This structure, in turn, is drawn upon to facilitate retrieval processes. (p. 292) It is abundantly clear that what determines the level of recall or recognition of a word event is not intention to learn, the amount of effort involved, the difficulty of the orienting task, the amount of rehearsal the items receive (Craik and Watkins, 1973); rather it is the qualitative nature of the task, the kind of operations carried out on the items, that determines retention. The problem now is to develop an adequate theoretical formulation which can take us beyond such vague statements as "meaningful things are well remembered." (p. 289)
>
> "Finally, the major questions generated by the present approach is what are the encoding operations underlying "normal" learning and remembering." The experiments reported in this article show that people do not necessarily learn best when they are merely given "learn" instructions. The present viewpoint suggests that when subjects are instructed to learn a list of items, they perform self initiated encoding operations on the items. Thus, by comparing quantitative and qualitative aspects of performance under learn instructions with performance after various combinations of incidental orienting tasks, the nature of learning processes may be further elucidated. The possibility of analysis and control of learning through its constituent mental operations opens up exciting vistas for theory and application." (p. 292)

A study by Griffith (1976) illustrates interrelationships among attention, intention, and student-supplied or experimenter-supplied mediators, using the same subject matter in the context of a paired-associates paradigm modified to involve a measure of depth of processing. Griffith used a secondary task during acquisition and recall to estimate the processing demands of Type II and Type I processing, which he called

Expended Processing Capacity (EPC). This secondary task required subjects to press a "yes" button when they heard a digit from a designated set of four, and a "no" otherwise. This had to be done at the same time the subjects were doing verbal processing during acquisition and during recall. The Choice Reaction Time (CRT) was taken as a measure of EPC; the greater the processing demands of the primary task, the slower the reaction times on the secondary task, and the greater the inferred expended processing capacity. The primary task was to learn lists of pairs of high imagery nouns by either making a sentence of the form "article <u>noun</u> <u>1</u> verbal article <u>noun</u> <u>2</u>" (Type II processing) or repeating sentences of this form supplied by the experimenter (Type I processing). The intentional condition was created by telling one group of subjects that they were going to be given a recall test after the acquisition session.

As expected, subject-generated mediators resulted in better recall accuracy under both intentional and incidental learning conditions. The EPC measure, CRT in milliseconds, did indicate that generating sentences used more processing capacity (1147ms) than merely repeating experimenter supplied sentences (917ms). Conversely, during recall, CRT's were lower for the subject-generated sentence condition (1183ms vs. 1386ms), implying that retrieval of the more deeply processed words required less processing capacity. The intentional variable did not affect depth of processing.

The significance for this paper of these two views of the memory system is that both recognized the central role of cognitive strategies used by the learner for effective acquisition and retrieval. The STS they discussed will be viewed here as forming, with selective attention, a limited input channel, or window into LTS, as well as serving as the buffer memory which has been so extensively investigated in the experimental laboratory (e.g., Sternberg, 1969).

It is likely that the paradigms using extremely simple stimulus material, digits or CVC's, and concentrating on storage and processing in STS, have not revealed the whole story. The visual system clearly is designed to do parallel processing at certain levels, and visual pathways from retina to striate cortex contain millions of axons. It is not unreasonable to expect that visual pattern information could be input to LTS through a broader channel than the STS defined by short-term memory theorists. That non-semantic, pattern information also is stored in LTS was reported by Kolers (1976), who demonstrated that practice in reading text composed of lines rotated about their own horizontal axes resulted in substantially faster reading of the passages, in comparison to the new passages, 13 to 15 months later. Nor, is all STS necessarily a CNS phenomenon. Sakett (1976) reported evidence for a form of visual STS located in the neuronal substrate of the retina. Finally, although Sternberg's classic studies revealed search and retrieval processes in STS, these are trivial in comparison to the processing that goes on in LTS, where the attention of theorists is currently focused.

Types of Long-Term Storage

Semantic Memory

Current theories of one kind of LTS (Tulving and Donaldson, 1972; Anderson and Bower, 1973; Norman and Rumelhart, 1974; Norman and Bobrow, 1975; Fiksel and Bower, 1976), maintain that it is a semantic network. There are differences of opinion as to the kinds of nodes, the kinds of internode relations, and kinds of information stored, and the kinds of processing. Some theorists include operations and self-programs in the semantic network, others do not. Some theorists suggest that semantic networks in LTS develop from cognitive primitives, which are irreducible concepts and relations. Cognitive primitives presumably are common to a species. It is reasonable to assume that they are the products of genetic blueprints guiding early developmental experience during embryologically critical periods. It is assumed by some theorists that these primitives initially are the foundations of understanding.

Bobrow and Norman (1975) proposed a theory of memory that is an amalgamation of principles from the literature on semantic networks, on actors, and on frames:

> "In conclusion, we proposed that memory structures be comprised of a set of active schemata, each capable of evaluating information passed to it and capable of passing information and requests to other schemata. We suggest that a memory schema refers to others by means of a description that is only precise enough to disambiguate the reference within the context in which the original situation occurred. This context-dependent description thereby provides an automatic process for creating general memory references from specific events, allowing for automatic generation of analogical or metaphorical memory matches. The retrieval mechanism that operates upon the descriptions must be intelligent enough to combine both descriptions and context in a meaningful, useful manner, and it must be relatively insensitive to mismatches and underspecifications.
>
> "The processing structure of the memory system is one that has a limit on resources that are available. Any given process is either data- or resource-limited. Some scheduling device is necessary to keep things operating smoothly. We believe the system to be driven both by the data (in a bottom-up fashion) and conceptually (in a top-down fashion). The principle that 'all data must be accounted for' guides the bottom-up processing. We believe that a single, conscious high-level mechanism guides the conceptual processing, taking into consideration the motivation and purposes of the organism.

> "Conscious processes are invoked whenever underlying schemata provide information for evaluation, whenever new processes must be invoked or old ones terminated, or whenever the output of one schema must be communicated to others not immediately invoked. Any time that there is a mismatch between data and process or expectations and occurrences, conscious processes are brought in. The automatic, active schemata of memory and perception provide a bottom-up, data driven set of parallel, subconscious processes. Conscious processes are guided by high-level hypotheses and plans. Thus consciousness drives the processing system from the top down, in a slow, serial fashion. Both the automatic and the conscious processes must go on together; each requires the other." (Bobrow and Norman, 1975, p. 148).

Fiksel and Bower (1976) described semantic memory as a collection of finite automata at nodes, with labelled arcs connecting the nodes. They developed a theory of memory that utilizes parallel, local processing among automata to accomplish retrieval, without the requirement for an executive level of processing. The idea of finite automata linked together by relational paths is reminiscent of notions from physiological psychology (e.g., Pribram, 1971), that collections of neurons accomplish processing via local, graded potentials in cell membranes and dendrites, sending the results on to other groups of cells via all-or-none spike potentials along longer axons. The Fiksel and Bower conception clearly assumes parallel processing. They point out that this is in distinction to AI theories of memory, which tend to emphasize serial processing because they can be implemented on computers.

Meyer and Schvaneveldt (1976) used the reaction time method to help reveal how stored semantic information is retrieved. They used existential affirmatives, e.g., "some pines are trees," and universal affirmatives, e.g., "all pines are trees," to explore comprehension based on set relations. Their reaction time data could be explained in terms of a semantic network structure for LTS. However, the sentence judging process (true or false) appeared to depend on comparison of defining attributes of the two items being compared, rather than on checking labels of links between nodes in a semantic network. These authors speculated that links may lack precise labels, whereas comparing attributes of the categories would provide a way to compute the exact relations from other information.

Gentner (1975) reported a study of the structure and recall of narrative prose in which he decomposed a short passage from a history book into smaller units, using Rumelhart's (1975) story grammer. This resulted in a semantic network of 143 "facts" corresponding to units described by the story grammer, interconnected by approximately 200 predicates or relations. Neighboring facts are connected by a single predicate or relation. There were clusters of neighbors varying from two to several. The 143 facts also could be arranged in serial order, as they occurred in the passage. A tape-recording of the text was played four times. Verbal recalls were collected after each presentation. The serial structure at first influenced which facts were recalled, but as the subjects learned the passages they evidently organized the passage in LTS closer to its underlying meaning structure. As this happened, the story grammar structure dominated recall of elements on subsequent trials.

Recall of knowledge may be strongly influenced by organization imposed by acquisition strategies. For example, Shimron (1975) found differences in recall of details of a map that were determined by three different kinds of strategies for acquisition: associating details with schemes, like rivers, highways, or mountains; learning details from one section of the map at a time; or integrating details from the map into two stories which had the map as the background of the events described.

These theoretical formulations of and these studies of semantic memory suggest certain tentative conclusions, which are listed below:

1. Semantic LTS also must be the site of much of the information processing required for acquisition, retention, and retrieval. This information processing is parallel processing (Bobrow and Norman, 1975; Fiksel and Bower, 1976).

2. The limited input channel of selective attention and STS is not so limited as experimental studies of STS suggest. Although attention can span only a few chunks at a time, these activate a large amount of processing; they "turn on" portions of the semantic network, so that serial verbal input is not stored a word at a time, but rather influences complex, already existing internal representations and contexts, resulting in the acquisition of much more than just the words in the serial input string (Norman, 1976).

3. Cotton (1976) pointed out that these semantic network models, "...raise a question whether practice effects or tasks requiring extensive practice during acquisition are a central aspect of learning. Indeed, it could be argued that one of the finest learning models available, that of Norman, Rumelhart, and the LNR group, discusses (practice) only peripherally as a side issue to treatment of memory storage, question answering, and problem solving." (p. 155)

4. Retention of knowledge, because of the web of relationships, is robust. Parts of knowledge forgotten or even never learned, can be reconstructed by inferential processes (Tulving, 1972; Norman, 1976).

5. Retrieval of information from LTS is strongly influenced by the structure of knowledge in LTS. Retrieval of information from semantic memory may utilize pathways represented by interrelationships among nodes, resulting in searches of varying length and duration (Meyer and Schvaneveldt, 1976; Genter, 1975).

6. Retrieval of information from LTS is influenced by acquisition strategies (Shimron, 1975).

Episodic Memory

Retrieval of some information may be strongly dependent on the temporal cues that were stored during acquisition. A good strategy for remembering where some lost object, such as car keys, checkbooks, or glasses might be, is to recall the sequence of events from the last time the object was known not to be lost. This is said to be dependent upon episodic memory, or memory for autobiography. Tulving (1972) distinguised between semantic memory and episodic memory, suggesting that semantic memory is not the kind of memory that psychologists have been studying in their laboratories since the time of Ebbinghaus:

> Let us think of episodic and semantic memory as two information processing systems that (a) selectively receive information from perceptual systems (Gibson, 1966) or other cognitive systems, (b) retain various aspects of this information, and (c) upon instructions transmit specified retained information to other systems, including those responsible for translating it into behavior and conscious awareness. The two systems differ from one another in terms of (a) the nature of stored information, (b) autobiographical versus cognitive reference, (c) conditions and consequences of retrieval, and probably also in terms of (d) their vulnerability to interference resulting in transformation and erasure of stored information, and (e) their dependence upon each other. In addition, psychological research on episodic memory differs from that on semantic memory in several respects.
>
> Episodic memory receives and stores information about temporally dated episodes or events, and temporal-spatial relations among these events. A perceptual event can be stored in the episodic system solely in terms of its perceptible properties or attributes, and it is always stored in terms of its autobiographical reference to the already existing contents of the episodic memory store. The act of retrieval of information from the episodic memory store, in addition to making the retrieved contents accessible to inspection, also serves as a special type of input into episodic memory and thus changes the contents of the episodic memory store. The system is probably quite susceptible to transformation and loss of information. While the specific form in which perceptual input is registered into the episodic memory can at times be strongly influenced by information in semantic memory--we refer to the phenomenon as encoding--it is also possible for the episodic system to operate relatively independently of the semantic system.
>
> Semantic memory is the memory necessary for the use of language. It is mental thesaurus, organized knowledge a person possesses about words and other verbal symbols, their meaning and referents, about relations among them, and about rules, formulas and algorithms for the manipulation of these symbols, concepts, and relations. Semantic memory does not register perceptible

> properties of inputs, but rather cognitive referents of input signals. The semantic system permits the retrieval of information that was not directly stored in it, and retrieval of information from this system leaves its contents unchanged, although any act of retrieval constitutes an input into episodic memory. The semantic system is probably much less susceptible to involuntary transformation and loss of information than the episodic system. Finally, the semantic system may be quite independent of the episodic system in recording and maintaining information since identical storage consequences may be brought about by a great variety of input signals (p. 385).
>
> Finally, we have heard frequent and justified complaints that many decades of research and study by psychologists interested in human learning and memory have not yielded many significant insights that could be used for the improvement of education and for the betterment of learning in classrooms. If it is true that past research in human learning and memory has been concerned primarily with episodic memory, and if it is true that classroom learning has little to do with students' remembering personally experienced events, then it is not surprising that empirical facts and theoretical ideas originating in the verbal learning and human memory laboratories have little bearing on theory and practice of acquisition of knowledge (p. 391).

Tulving proposed that there many be important differences between episodic and semantic memory in terms of acquisition, retention, and retrieval processes. In the following excerpts from Tulving's article, he discusses these differences:

> Thus, an integral part of the representation of a remembered experience in episodic memory is its reference to the rememberer's knowledge of his personal identity.
>
> Inputs into the semantic memory system are always referred to an existing cognitive structure, that is, they always have cognitive reference, and the information they contain is information about the referent they signify rather than information about the input signal as such. Information stored in the semantic memory system represents objects--general and specific, living and dead, past and present, simple and complex--concepts, relations, quantities, events, facts, propositions, and so on, detached from autobiographical reference. If a person possesses some semantic memory information, he obviously must have learned it, either directly or indirectly, at an earlier time, but he need not possess any mnemonic information about the episode of such learning in order to retain and to use semantic information.

Some relevant retrieval characteristics of the two memory systems follows from our discussion of the relation between input and storage in the two systems. For instance, information can be retrieved from episodic memory only if that information had been entered into the store on an earlier occasion. The episodic memory does not include the capabilities of inferential reasoning or generalization. Inferential reasoning, generalization, application of rules and formulas, and use of algorithms, on the other hand, represent important methods of utilization of information stored in semantic memory. By relying on his semantic memory, it is quite possible for a person to know something he did not learn. Thus, for instance, a person may have never learned that March follows June in the alphabetical listing of months, and yet be able to retrieve this bit of knowledge upon an appropriate query.

The consequences of retrieval also appear to differ for the two systems. While retrieval operations can be considered neutral with respect to the contents and structures of semantic memory, in the sense that they do not change the system, the act of retrieval from either system may be, and usually is, entered as an episode into episodic memory. Retrieval as feedback into the episodic system may lead to changes in the contents, and the retrievability of these contents, of episodic memory.

Episodic and semantic memory systems probably differ in their susceptibility to transformation and loss of stored information. While in both systems it is very much simpler to record information in the memory store than to eliminate it from the store, forgetting appears to be more readily produced in the episodic than in the semantic system.

We know a fair amount about conditions of forgetting in episodic memory, but almost nothing about how stored information becomes available or inaccessible. It is probably not entirely unreasonable to assume that loss of information from the episodic memory frequently takes the form of some sort of transformation of that information as a consequence of interference with the temporal coding of stored events. Since information in episodic memory is always temporally dated, and since it can only be retrieved if its temporal date is sufficiently accurately specified by the retrieval cue, interference with temporal coding may render access to the to-be-retrieved material difficult or impossible.

Information in semantic memory, on the other hand, is usually encoded as part of, or assimilated into, a rich multi-dimensional structure of concepts and their relations, and such embeddedness protects the stored information from interference by other inputs (p. 391).

Lateralization of Cerebral Functions

There is a general assumption among many semantic memory theorists that semantic networks in LTS represent propositional knowledge; that both imagery and language can be generated from this propositional base. These theorists (e.g., Pylyshyn, 1973) maintain that this view can be reconciled with experimental evidence for dual-coding systems (Paivio, 1976), and with evidence for dual-processing systems from studies of lateralization of function in the cerebral hemispheres (e.g., Nebes, 1974).

Evidence that some visual processing at the perceptual level may be (propositionally?) guided was reported by Ross (1976). Using stereograms that change at random, he found that the visual perceptual system generates depth and motion information from combinations of visual input and some kind of pre-existing visual record. Shapes constructed by the visual system from the combination of random-dot stimulus patterns are more idealized than real shapes. They are, "idealized conceptions, imposed on the external flow of visual information by something within the visual system" (p. 86). On the other hand, Shepard (1976), in the most recent of a series of studies of mental rotation of geometric figures, found congruence between data for mental rotation and data for stimulus-induced apparent rotation. He maintained this result cannot be accounted for by sequential, propositionally-based processing. Cooper and Shepard (1976) presented evidence that subjects determine whether a visually presented image of a hand is a left or right hand by moving a mental "phantom" of one of their own hands into the portrayed position and by then comparing its imagined appearance against the appearance of the externally presented hand. This study suggested that the identification of "isomeric" objects is accomplished by a sequence of analog mental transformations and holistic matches.

The increasing evidence for lateralization of imagery and verbal processing in different hemispheres, with its implications for instructional theory, reviewed by Wittrock, et al., (1975) and by Rigney and Lutz (1975), suggests that, although there can be a propositional form for both verbal and imagery processing that simplifies the cognitive scientist's task of constructing semantic memory models with computer programs, there nevertheless are interrelated dual-processing systems, in the two sides of the cerebrum which together comprise more processing capacity than either system alone, and that this duality plays an important role in determining cognitive styles of learning and in increasing the different kinds of processing resources that could be brought to bear during learning. Research on lateralization of function, using split-brain preparations, or unilateral lesions (Milner, 1974; Sperry, 1974; Cuenod, 1974) has been focused primarily on identifying special functions of each hemisphere. Obviously, in the normal brain, the commissures are intact and there are no lesions. In the normal brain, does processing control alternate between hemispheres, depending on the task, or are the special functions of each somehow combined? Broadbent (1974) reviewed research bearing on this question, and concluded that "the two hemispheres must be seen therefore as performing different parts of an integrated performance, rather than completely separate and parallel functions" (p. 31). Literature on the different ways in which this integration might occcur was reviewed by Languis (1976). He summarized this information as follows:

> The interaction between these two processing systems is complex and not fully understood. However, the fact is known that the human nervous system has both inhibitory and facilitatory functions (Hilgard and Bower, 1975) which enables the hemispheres to exhibit complimentary functioning when the hemispheres work integratively (Bogen and Bogen, 1969); selective complimentary functioning, when one hemisphere selectively uses subsystems of the other to solve a problem (Vogel, 1966; Broadbent, 1975); parallel functioning, when each hemisphere works independently on a problem which may later be integrated (Dimond, 1962; Dimond and Beaumont, 1974); independent functioning, when one hemisphere totally inhibits the other to solve the problem (Galin, 1974a); and conflicting functioning, when each hemisphere works alone on the problem and is in conflict with the other in terms of the solution (Galin, 1974b; p. 7).

A study by Gordon and Bogen (1974) is an example of research on lateralization in the neurosciences. These two investigators studied hemispheric lateralization of singing after intracarotid sodium amylobarbitone. It was found that after right carotid injection singing was markedly deficient, whereas speech remained relatively intact. Songs were sung in a monotone, devoid of correct pitch rendering; rhythm was much less affected. The observations indicated a double dissociation; the right hemisphere contributed more for singing, whereas the left demonstrated its usual dominance for speech. They proposed that:

> The dichotomy between language and speech on the one hand, and singing on the other, may be differentiated on a level related to their construction. For example, a sentence, paragraph, phrase or, in short, speech, is composed from several morpheme units which are retrieved from memory according to grammarical rules and are ordered into a specified temporal arrangement. In contrast, songs, melodies, as well as many everyday prosaic passages are remembered and produced as intact wholes. The parts of these units are not pieced together tone by tone, word by word, but rather are recalled all at once as a complete unit. The ability to store and recall intact such large units may be an important aspect of those tasks for which the right hemispheres of most individuals are dominant.

> Although it would be premature at this time to believe that we know in any final way of what appositionality consists, we would like to introduce a preliminary hypothesis based on our observations and those of others that absence versus presence of the dimension of time is instrumental in distinguishing appositionality from propositionality. Previous characterization of the right hemisphere's ability as "spatial" is ill-applied to audible stimuli, unless "spatial" is understood to mean "having no time dimension"! Reliance upon "time" as a principle of organization may better distinguish the left from the right hemisphere: the left is crucially concerned with it, whereas the right is not (p. 733).

Tulving's characterizations of episodic and semantic memories should not be fitted into characterizations of right and left hemisphere functions. It is not yet possible to relate theories of LTS from cognitive science to the evidence of lateralization of cerebral functions from the neurosciences. However, it is interesting that Tulving, and Gordon and Bogen, emphasized time-dependence as a primary difference, in one case between two kinds of LTS, and in the other, between functions of two cerebral hemispheres. Tulving proposed that episodic memory "retrieves and stores information about temporally dated episodes or events, and temporal-spatial relations among these events" (p. 385). Gordon and Bogen suggest that "reliance upon 'time' as a principle of organization may better distinguish the left from the right hemisphere: the left is crucially concerned with it, whereas the right is not" (p. 733).

Motor Memory

There is a third kind of LTS, relating to control over the skeletal muscular system and the vocal chords, for the control of speech and other motor performance, that must be considered here. The variety of skilled performances that human beings can learn must be controlled by some kind of stored information. Much of this skilled performance probably is initiated by information stored in semantic memory, and it is reasonable to presume that information about performance is included in the semantic memory. But, there remains the requirement for something to control the patterns of muscle contractions that are required for speech and for other motor performances. The neuromuscular system is very complex, and includes the cerebellum, a complex organ with a large and highly homogeneous cortex, that sits astride the large ascending and descending columns of the upper spinal cord. The motor system in humans is divided into an upper and lower system, the upper system sending many different tracts to play upon the final common path, the spinal motoneurons, of the lower system. There are many feedback and feedforward loops in the system. All this baffling complexity must require substantial control mechanisms that, in view of the remarkable capabilities of humans to learn skilled performances, must include some form of long term storage, which will be called motor storage in this paper.

There have been fascinating advances in knowledge about the neuromuscular system, tempting excursions into that literature. Many parts of the CNS are involved in the production and control of complex patterns of movements. Kornhuber (1974) described current thinking in the neurosciences about these functional relationships. It is worthwhile reviewing these ideas briefly here, to establish the reason for discussing a motor memory apart from a semantic memory, and to emphasize the importance of these functions of the nervous system for learning, which whatever else it is, is learning to respond appropriately. Kornhuber's summary information-flow diagram for strategic and tactical mechanisms in voluntary actions illustrates the major centers and connections, which it should be noted, include practically all of the CNS. Relevant excerpts from his discussion of the strategy and tactics of actions follow the diagram.

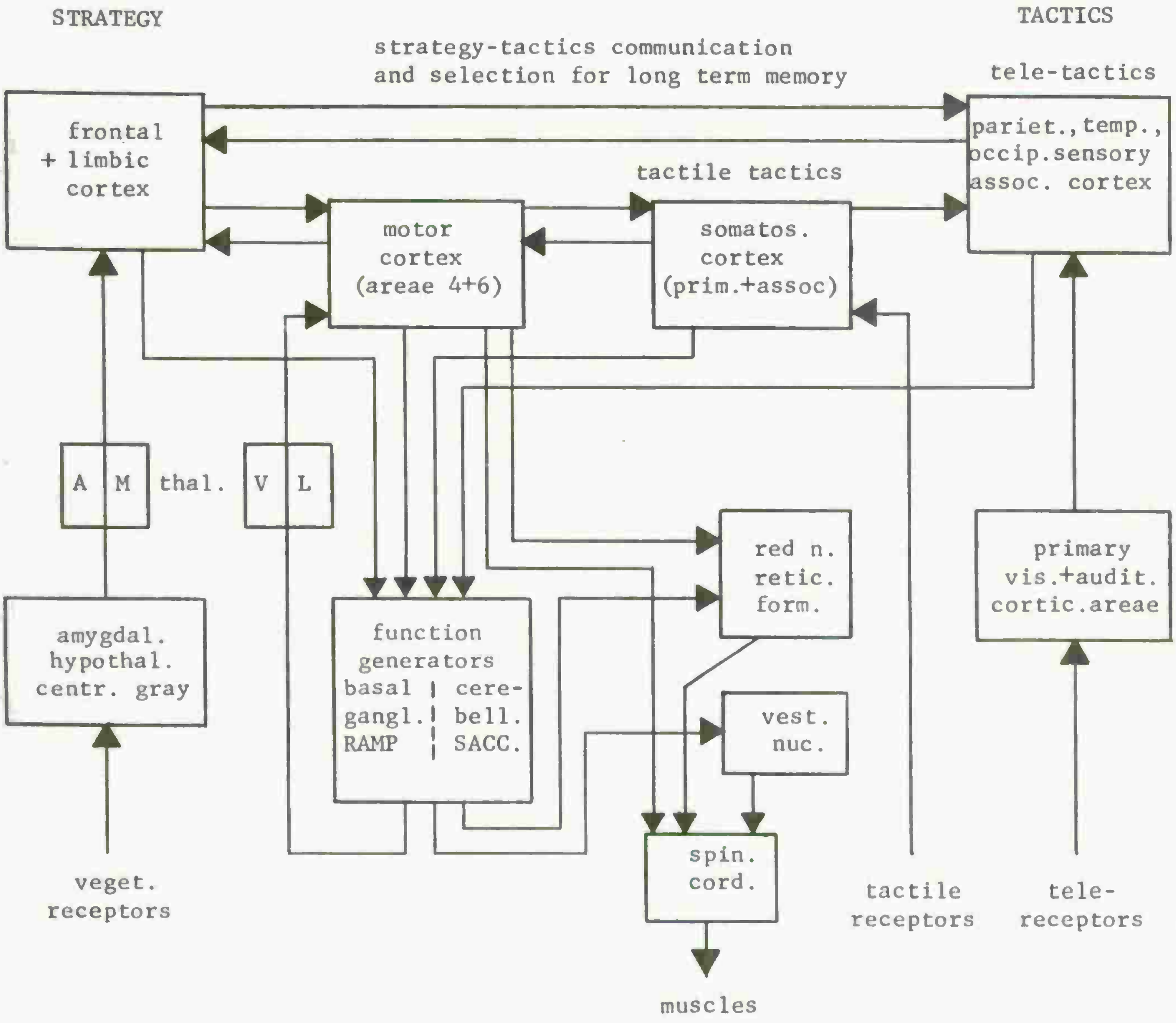

Figure 6. Information flow diagram of strategic and tactical mechanisms in voluntary actions.

The mechanisms of strategy (represented at cortical level in the frontal lobe and cingulate gyrus) as well as the mechanisms of tactics (in the posterior association cortex) have their own access to the motor function generators in cerebellum and basal ganglia. A anterior, M medial, VL ventrolateral thalamus. The communication lines between frontal and sensory association cortex are also important for data selection from short- to long-term memory (see Kornhuber, in Zippel, ed.: Memory and Transfer of Information. Plenum Publishing Company, New York, 1973). The neural mechanisms underlying the strategy of actions (e.g., hypothalamus, amygdala, and orbitofrontal cortex) receive, of course, exteroceptive in addition to vegetative information; the former, however, in a preprocessed format from the sensory association areas; the hypothalamus gets this information indirectly via the cingulate gyrus-hippocampus loop (Kornhuber, 1975, p. 278).

Strategy and tactics in the neural mechanisms of speech: Broca's and Wernicke's aphasia

The findings in aphasia agree with this communication. The frontal aphasia due to lesions of Broca's field is characterized by loss of the drive to speak and of the strategy of speaking: The language of Broca's aphasia is agrammatic and lacks any prosody or speech melody. By contrast, the temporal lobe type of aphasia, due to lesions of Wernicke's field, is characterized by destruction of the lexicalic details, the nouns, in other words, the tactics of speaking. In Broca's aphasia, the nouns are preserved but cannot be activated and organized in sentences. This demonstrates that normally Broca's field acts on Wernicke's. In Wernicke's aphasia the strategy of speaking is preserved and often disinhibited, which results in a lot of meaningless speech; this shows that normally Wernicke's field acts on Broca's as well.

The old view of a corticocortical reflex arc underlying speech from Wernicke's to Broca's field and then via the motor cortex down to the motoneurons is not tenable, because lesions in the cerebellum, basal ganglia, and thalamus are able to produce characteristic speech disorders. Obviously Broca's and Wernicke's fields have direct access to the basal ganglia and (via the pons) to the cerebellum, and the corticocortical interaction between them is probably at least as much in the direction from Broca to Wernicke as back (p. 278).

Shift of the guiding focus during action

If the hand reaches for a pencil, the movement is first guided by visual mechanisms; but if it writes, the movement depends largely on tactile impulses. However, the proportion of the words, the keeping on a straight line, and the finding of the beginning of the next line depend again on visual guidance. In everyday life, the leading focus for the hand often shifts between all the four lobes of the forebrain.

What is in charge of this shift is still partly a matter of speculation. But one point seems clear: It is not a single superhomunculus in the brain, nor is it a single superdrive like Freud's libido. As ethology--the science of animal and human behavior--reveals, man has many drives. And as Sperry's investigations in split-brain patients show, the unity of the human personality depends on many fiber connections (p. 278).

Strategy and tactics of action

If we are hungry, the strategy of our action is to search for food. This strategy is determined by the glucose concentration in the blood and by other factors of the internal milieu, which are centrally sensed in the hypothalamus. The tactics, however, of our search depend on the environment. This is centrally represented in the sensory, primary, and association areas of the occipital, temporal, and parietal lobes, in which the analysis and synthesis of the raw sensory data are performed (p. 267).

Neural mechanisms in the strategy of action

It is known since the experiments of W. R. Hess (1949) that some of the nervous substrates underlying the various drives to act are located in the diencephalon. Hess was able to elicit exploratory behavior, feeding, flight, aggression, vomiting, relaxation, sleep, micturition, and other activities by means of hypothalamic stimulation. Unilateral hypothalamic lesions produce inattention to visual, tactile, and proprioceptive stimuli on the opposite side. Orienting, feeding, or attack behavior to contralateral stimuli is lost for several weeks after lateral hypothalamic lesions. In the clinical literature, the loss of the drives to act is entitled akinetic mutism. The syndrome is characterized by absolute mutism and complete immobility except for the eyes, which are usually kept open and moved in all directions. The lesions that lead to akinetic mutism are bilateral and located in the central gray matter, the hypothalamus, the medial thalamus, or the cingulate gyrus and nearby structures. Lesions of the frontal lobes, to which the hypothalamus via the mediodorsal thalamic nucleus projects, do not result in akinetic mutism, but bilateral lesions of the frontal convexity may cause apathy and reduction of all activities while lesions of the orbital cortex often result in disinhibition of primitive drives. Obviously the needs for homeostasis of the internal milieu and survival of the species are represented in the mesencephalon, the hypothalamus, and the limbic system, and these needs are mediated into action, at least in part, by way of the frontal cortex and the cingulate gyrus.

The frontal cortex has its own access to the cerebellum (via the pontine nuclei), to the basal ganglia, and directly to area 6 of the motor cortex, but we have to imagine that a good deal of influence on behavior occurs via the frontotemporal, frontoparietal, and frontooccipital connections, as well as via fibers from the cingulate gyrus to the lateroposterior thalamus that in turn projects to the parietal lobe. In other words, the

> mechanisms of strategy of action, represented at cortical levels in the frontal and limbic cortex, and the mechanisms of tactics, represented in the temporal and parietal lobes, communicate with each other (p. 277).

Some actions (ballistic and saccadic) are performed so rapidly that they could not be guided by feedback, yet neither, it seems, could they be controlled altogether by motor programs that merely specify a sequence of actions. Kornhuber considered that the cerebellum is the one of two function generators (the basal ganglia being the other) in this system that is responsible for control of rapid movements with regard to timing and duration. He described how it is thought that the cerebellum does this in the following diagram of its timing mechanism, and in the description that follows.

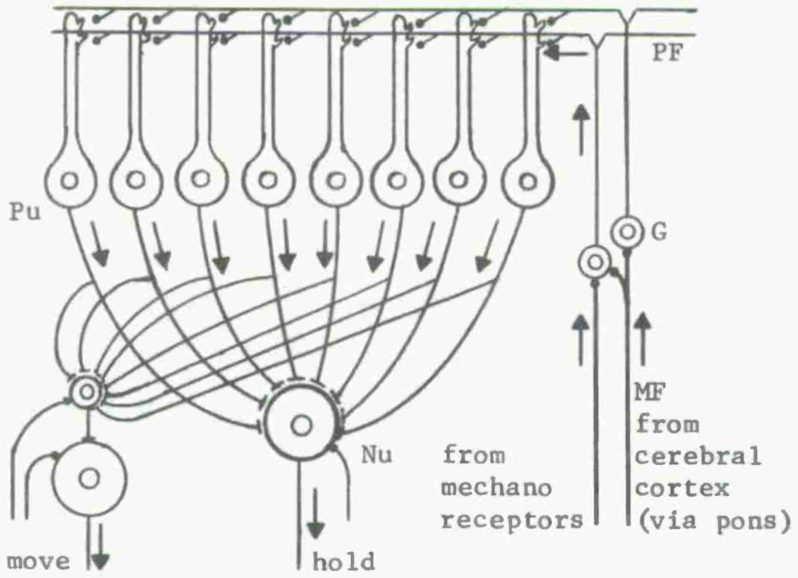

Figure 7. The parallel fiber (PF) delay line in the cerebellar cortex with the convergence of a row of Purkinje cells (Pu) on a neuron of the cerebellar nuclei (Nu). This arrangement acts as a clock, timing the duration of fast preprogrammed movements that are too quick to be regulated continuously (saccadic or ballistic movements). Also, the interval between different fast movements can be timed by this clock. At the granular cells (G) that give rise to the parallel fibers, the afferents converge from the cerebral cortex (via the pons) and from the spinal cord and mechanoreceptors. The inhibitory action of the Purkinje cell output stops the holding function of a hold neuron and disinhibits (by means of an inhibitory interneuron) a move neuron. (From Kornhuber, 1971b; p. 271.)

Timing of rapid movements by the short time clock of the cerebellar cortex

My belief, that the cerebellum does not merely regulate movements which have been programmed and initiated by the cortex, but that the cerebellum is necessary for the design of rapid movements prior to their initiation--movements that are preprogrammed because they are too fast to be regulated continuously by feedback--this belief originated in the observation of dysmetria of saccadic eye movements due to atrophy of the cerebellar cortex (Kornhuber, 1968). Fast saccadic, ballistic eye movements are the only active eye movements we have. The smooth pursuit movements depend on a moving stimulus. To understand the cerebellar dysmetria of saccadic eye movements, we must know that saccadic eye movements are too fast to be regulated continuously by visual feedback. The course of a saccadic eye movement in time follows automatically out of its present angle and cannot be changed at will. The velocity of the saccade is a function of its amplitude. The angle to be moved is measured by the visual system prior to onset of movement. Within the visual association cortex of the forebrain, the angle to be moved is obviously represented as spatial data; it is probably coded in the connections of a nerve cell column, because the information transmission for length depends only on the endpoints and not a line connecting them (Bechinger, et al., 1972). For the eye movement, however, these spatial data must be translated into time-namely, into the duration of the burst of high-frequency action potentials in the oculomotor nuclei since the size of the saccadic eye movement depends entirely on that duration and not on impulse frequency; extraocular motor neurons always fire at the highest possible rate during the saccades except during very small saccades (Schiller, 1970; Fuchs and Luschei, 1970). (For a discussion of the conflicting evidence, given by Robinson; 1970, see Kornhuber, 1971a). The duration of saccadic eye movements (Robinson, 1964) as well as of oculomotor unit burst (Schiller, 1970; Fuchs and Luschei, 1970) is linearly related to the amplitude of the saccades (p. 269).

The inability of the brain to generate saccadic eye movements of normal size in cases of cerebellar cortical atrophy shows that the cerebellar cortex participates in preprogramming the course of the saccade by determining its duration. How does the cerebellum do this? Probably it does it by means of the arrangement of the parallel fibers and the Purkinje cells--a structure unique in the nervous system. I believe we should imagine that the axons of a row of Purkinje cells converge onto a common neuron in the cerebellar nuclei, as shown in Figure 7. As long as the action potentials travel in the parallel fibers, a neuron in the cerebellar nuclei will be inhibited or (by means of an inhibitory interneuron) disinhibited. The duration of the travel of an action potential depends on diameter and length of the fiber. With a fiber length up to 5 mm and conduction velocities down to 0.05 m/sec movements up to 100 msec are possible.

The neurons in the cerebellar nuclei involved in timing saccadic eye movement then project directly or via an interneuron to the oculomotor nuclei in the brainstem that innervate the extraocular muscles, while those responsible for timing fast hand movements are connected via the thalamus to the motor cortex. The parallel fibers of the cerebellar cortex as a delay line with the ability to transform spatial into temporal patterns was the conclusion reached independently by Braitenberg (Braitenberg and Atwood, 1958; Braitenberg, 1961), based on purely anatomical groupings. Unfortunately, Braitenberg's ingenious papers, which have often been quoted for anatomical facts, have been largely disregarded in the subsequent discussions with regard to functional interpretation, perhaps because of the lack of two additional concepts: First, discontinuous (saccadic) timing, and second, preprogramming of fast movements by the cerebellum prior to their onset (p. 271).

The functions of the peripheral afferents to the cerebellar cortex and the temporal coordination of fast movements

This brings us to the question of the function of the peripheral afferents to the cerebellum, coming from receptors in skin, joints, muscles, and perhaps from spinal motor centers monitoring their activity.

If the cerebellar cortex is a clock, preprogramming the duration of fast movements, why does this clock or step generator need these afferents from peripheral receptors and spinal events? Obviously the function of these afferents cannot be to provide negative feedback in a continuous servoregulation. If we consider the more important cerebellocortical mechanism (the granular cells with their parallel fibers connected to a row of Purkinje cells), the influence of the spinal input could be: First, the timing of the start of the parallel fiber volley, and second, the selection of the correct set of granular cells.

Timing the start of the next movement by reafferent signals from the preceding movement, in other words the temporal coordination of successive rapid movements, is certainly important for actions like writing or speaking or playing the piano or (in birds) flying. The activity of many small birds consists mainly of rapid movements that are too fast to be regulated continuously by sensory feedback. When a bird winds through the branches of trees, survival depends on temporal coordination of rapid movements. It is perhaps because of this that birds have such a large cerebellum. Adiadochokinesis, the slowing down and dysmetria of hand writing and hesitant, slow type of speech, are signs of cerebellocortical disturbance in man. It is, of course, easier to use internal feedback from preceding motor actions or reafferent sensory signals for the timing of successive movements than to construct an exact temporal superprogram that takes care of the start of each single movement component independent of the occurrence of the the preceding and following movements. We might therefore imagine

> that, while the sequential program of movements is provided by the cerebral cortex, the exact timing depends on reafferent volleys, converging with the messages from the forebrain at the granular cells of the cerebellar cortex.
>
> Another function of the afferents to the cerebellar cortex from mechanoreceptors might be to participate in the selection of the correct granular cells, which is a function of choice or decision making. The energies needed (and this means, in the case of maximal force, the duration needed) for movements of different starting positions are different. For instance, saccadic eye movements from the midposition to a lateral position have a longer duration than saccades from the lateral to the midposition. The selection of granular cells is, of course, mainly a task for the afferents from the cerebral cortex (via the pontine nuclei). In addition, however, afferents from mechanoreceptors should have an influence on the selection of granular cells in order to take into account the starting position of the limb to be moved.
>
> By contrast, the afferents to the cerebellar nuclei from the mechanoreceptors provide negative feedback for the continuous hold regulation (p. 273).

Motor memory, then is much more than passive storage of "motor programs" somewhere. Although it may be, as Kornhuber suggests, that initial tactical information is stored in columns of neurons in the cerebral cortex, long term storage must include the information necessary to regenerate the patterns of spatio-temporal activity in this extraordinary system that are necessary for repeatable performances, and the extraordinary complexity of these regenerative processes must account for the great amounts of practice required for learning and for maintaining highly skilled performances. This is in contrast to the relatively rapid rate of acquisition of semantic information. One does not have to reread a textbook four hours a day for 10 years to extract meaning from it, yet this kind of arduous practice schedule seems to be common among Olympic figure skaters and concert pianists.

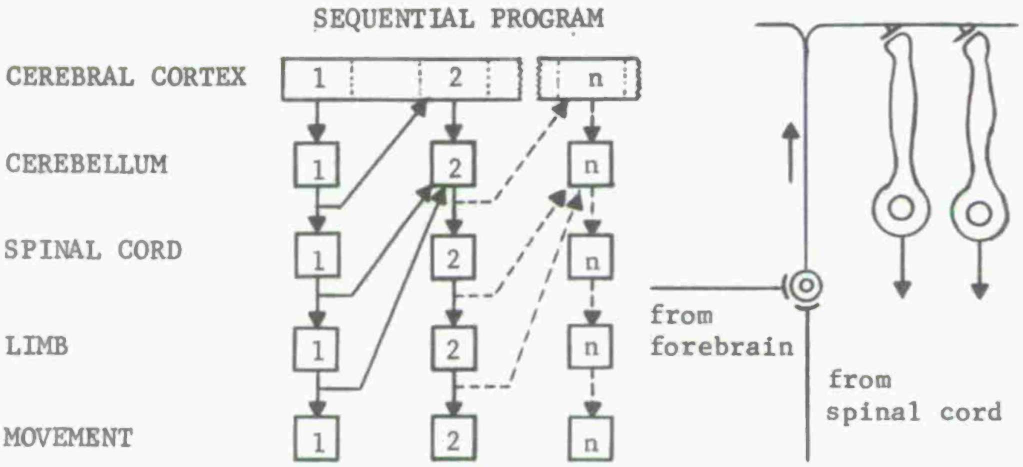

Figure 8. Timing of a series of rapid movements by reafferent volleys.

Instead of constructing an exact temporal superprogram that could start each single component of movement independent of the occurrence and timing of the preceding movement, the cerebral cortex probably provides only a sequential program with specification of direction, extent, etc., and the cerebellum takes care of the timing, using reafferent signals from lower centers or receptors. (Kornhuber, H. H. p. 273)

The question of where the information for controlling patterns of muscle contractions is stored at present has two answers. From Kornhuber's description of the motor system, it might be inferred that the necessary information is stored in the cerebral cortex, distributed spatially in cellular columns, and that this spatial information is translated into temporal patterns by the cerebellum, the short-time clock. The parallel fibers of the cerebellar cortex act as delay lines that, by reason of their passage through the regularly spaced Purkinje cells, transform spatial into temporal pattern outputs from the cerebellar system. Since limbs may be in different positions and different degrees of tension or may be contracting with different amounts of force from one repetition to the next of a skilled motor activity, exact timing in the temporal sequence, according to Kornhuber, is provided by reafferent signals from the lower motor system (Figure 8).

Another view, which is not yet accepted by Kornhuber and others, was expressed by Albus (1973) and by Albus and Evans (1976). This is that the cerebellar cortex, which is remarkably homogeneous in structure and contains a remarkable number of granule cells, is the site of acquisition and long term storage of fine-grained motor control patterns, or templates.

The cerebellum is thought by these theorists to acquire appropriate motor system control patterns by an error-correction system in which climbing fibers adjust synaptic weights until the output of Purkinje cells match data carried by the climbing fibers (Figure 9). Generalization from acquisition trials is possible because of the one-to-many connections in the addressing structure:

It, of course, is obvious that if mossy fiber address lines are essentially analog in nature, there exists an enormous number of possible addresses. If we assume that there are N mossy fiber address lines, and a mossy fiber can carry an analog signal with 50 distinguishable values of pulse frequency, then we have 50^N possible addresses. If we consider that each square millimeter of granular layer has approximately 5×10^4 mossy fibers entering it, we clearly have a potentially enormous number of addresses. However, one must remember that if the world is subjected to a state-space analysis, there exists an equally enormous number of possible states of the world. Mossy fiber input from sensory receptors in the limbs are essentially reporting the state of the limbs. Since people and animals are able to cope with the infinity of possible states in the real world, it is clear that somehow these states are grouped into a manageable number of sets of states. States within such groupings are for all practical purposes equivalent. So too, the virtual infinity of possible mossy fiber addresses are grouped into sets of essentially equivalent addresses. The grouping is accomplished by the granular layer, which performs a transformation such that if two mossy fiber addresses are within an equivalent group, the same pattern of parallel fiber outputs will occur.

The mossy fiber input can be considered a vector

$I = (mf_1, mf_2, mf_3 \ldots mf_N)$ where mf_i is the firing rate of the i-th mossy fiber. We can define similarity between mossy fiber patterns in terms of the Hamming distance H_I input vectors I and I'.

$$H_I = \sum_{i=1}^{N} | mf_i - mf_i' |$$

The mossy fiber input vector I is transformed by the granular layer into a parallel fiber vector $J = (pf_1, pf_2, pf_3 \ldots pf_{100N})$ where pf_i is the firing rate of the i-th parallel fiber.

The theory hypothesizes that at any instant of time only about 1-2% of the pf_i firing rates are non-zero. Thus, the vector J is just a very sparce vector. The principal feature of this transformation is the conversion of mossy fiber patterns in the frequency domain to parallel fiber patterns in the spatial domain. Parallel fibers thus are hypothesized to code information in terms of the specified set of parallel fibers which have non-zero firing rates. We can define a set

$$L = \{ pf_i \mid pf_i \text{ has a non-zero firing rate} \}$$

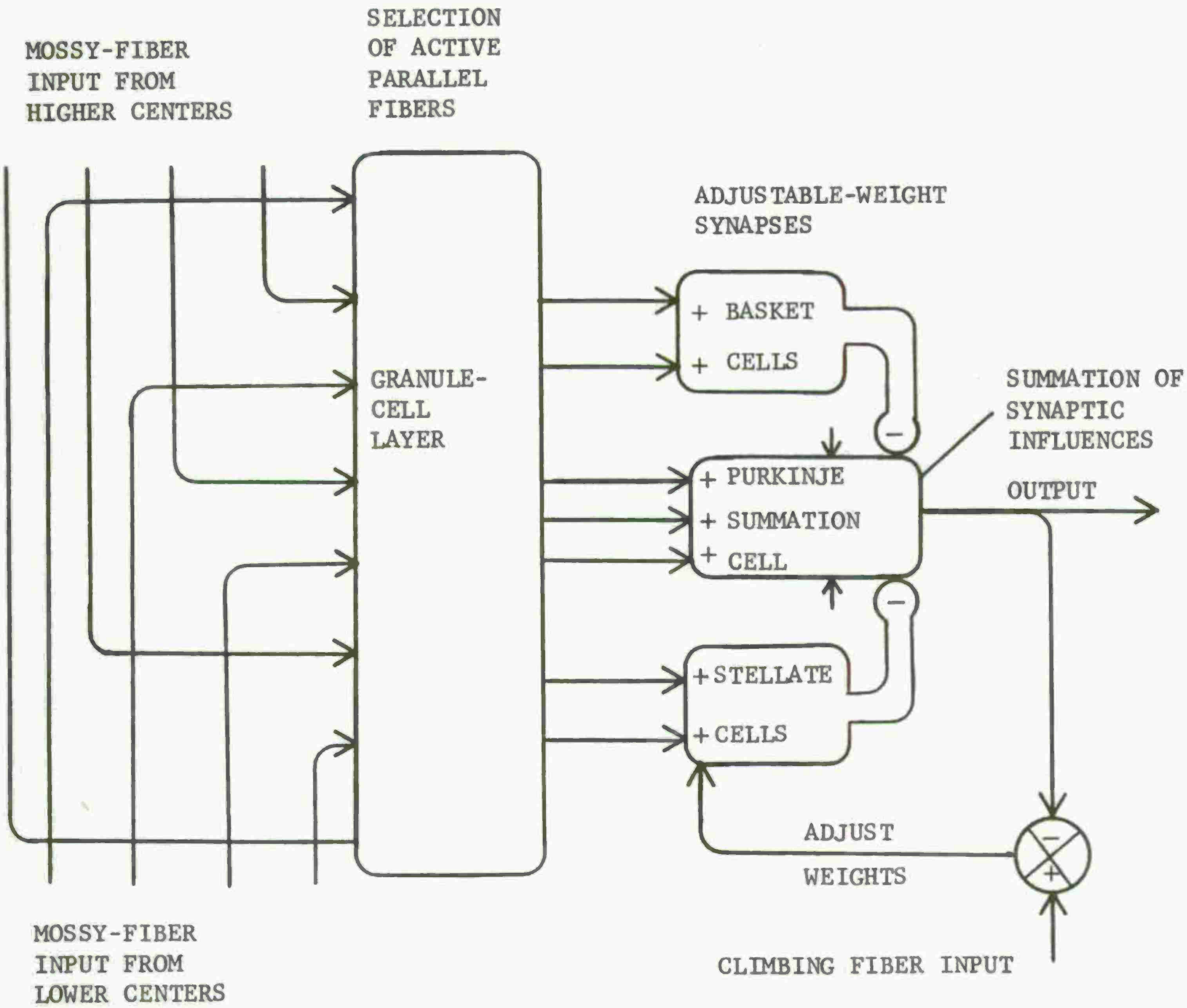

Figure 9. A current conception of the cerebellum as a motor memory. (Albus and Evans, 1976, p. 84).

> We can then represent similarity between two parallel fiber patterns J and J' in terms of the intersection $L \cap L'$. The granular layer is hypothesized to perform such that if H_I is small, $|L \cap L'|$ will be large, and as H_I grows large $|L \cap L'|$ will approach zero. This implies that training for dissimilar tasks (i.e., such that H_I is large) will produce very little interference. Weights adjusted for pattern I will be entirely different for those adjusted for pattern I' because $|L \cap L'|$ is zero. However, for similar patterns, training will generalize. Similar mossy fiber patterns (i.e., H_I small) will cause many or most of the same weights to be adjusted because $|L \cap L'|$ is large. Thus, the cerebellum need not be trained to cope with every possible mossy fiber address corresponding to every possible state of the arm. Instead, training over a small but representative sample of the possible states will suffice. (Albus, 1973, pp. 428-429).

In summary, then, acquisition, retention, and retrieval of information and performance are seen by theorists to depend strongly upon information processing, under voluntary control of the learner, or induced in the learner by externally imposed orienting tasks, and operating within the wired-in framework of the memory system. The processing and storage characteristics of this memory system influence the kinds of cognitive strategies that can be effective during these three stages of learning. Three different kinds of long term stores have been described by theorists: semantic store (verbal and imaginal), episodic store, and motor store. Different kinds of information are acquired by and are retrieved from these stores, and different kinds of cognitive strategies are likely to be effective for facilitating acquisition, retention, and retrieval in each.

Relationships Between Cognitive Strategies and Types of LTS

Some review is appropriate at this point. Basic systems; representational, selectional, and self-directional, are harnessed by orienting tasks in cognitive strategies to make acquisition, retention, and retrieval processes more effective. Representational systems include imagery and language, supplemented by feedback from the neuromuscular and visceral systems. Selectional systems include attention and intention, which can both facilitate and constrain input and its processing in important ways. Self-directional systems include self-programming and self-monitoring.

Cognitive strategies may be applied singly or in combinations. Some instructional strategies could be viewed as methods for exerting external control over cognitive strategies. The Socratic method, discussed earlier, is an example.

Strategies for Acquisition

These are concerned with helping the student build internal knowledge structures that will mediate between stimulus conditions and appropriate responses. The coupling between stimulus conditions and desired responses may be clearly defined, as in training real-time driven operators to perform; or the coupling may be very vague, as in much of education, where acquired information may be only sampled by tests and subsequent behavior may be only weakly influenced by it, if at all.

Cognitive acquisition strategies would be concerned with locating and organizing subject matter, selecting from assembled material that information that is judged to be useful and ignoring the rest, and encoding it by processing operations that effectively transform it for storage in one or more forms of LTS. These strategies are, in effect, transfer operations between some nominal stimulus configurations, say printed text and diagrams in a technical manual, and LTS. The map, as shown in Figure 10, illustrates these relationships.

Types of Subject-Matter		Types of LTS		
		Semantic	Episodic	Motor
INFORMATION	Narratives	E	E	M
	Explanations	E	M	M
	Representations	E	M	M
	Prescriptions	E	E	M
PERFORMANCE	High Semantic/ High Skill	E	E	E
	High Semantic/ Low Skill	E	M	M
	Low Semantic/ High Skill	M	E	E
	Low Semantic/ Low Skill	M	M	M

Figure 10. Tentative LTS Transfer Map for Acquisition Strategies.

The distinctions among different kinds of LTS made in the preceding section will be preserved here, with some additional distinctions and qualifications. Semantic LTS could be divided into imagery and verbal parts even though both may have a propositional base, because there are occasions when mental imagery representations are more important as mediators than verbal representations. The functional and structural topography of mechanical and electronic devices, for example, are efficiently represented by mental images, even though these mental images may be encoded in propositional form. Although there is evidence for three different kinds of LTS; semantic, episodic, and motor, this does not mean that these are independent and isolated entities. In fact, Schank (1975) maintained that semantic and episodic LTS should be combined in what he called conceptual episodic memory. It seems most likely that all forms of LTS are involved to varying degrees in all learning processes. For the present, it may be useful to continue to distinguish among the three types of LTS discussed above. In those cases where acquisition processes must result in additions to, or change in an LTS, if the mediational requirements of content orienting tasks are to be met, an E for elaboration processing is entered in the corresponding cell in the diagram in Figure 10. If it is supposed that a type of LTS only furnishes processing resources to the acquisition processes, an M, for maintenance processing, is entered in the cell. Since processing resources probably are drawn from all the types of LTS by acquisition processes, it will be understood that this also occurs in those cells with E entries. The E signifies that information in this particular LTS is assumed also to be increased by the acquisition processes. This classification is highly speculative, but it may serve a useful purpose in stimulating more thinking about these relationships.

The subject-matter headings require some explanation. Narratives, such as history, describe a stream of events, or episodes, with a time base. Chronological order is of some importance. Narratives, transmitted by word of mouth, probably are the oldest form for communicating information. Explanation refers to the concepts, symbols, and formalisms of science. Representations are descriptions of entities in the world, for example, a radar repeater. They describe structural and functional characteristics of such objects, often using some of the abstractions of science. Prescriptions are lists of action descriptions.

The categories of performance also require some elaboration. The four categories refer to the guidance of performance. Some performances, such as troubleshooting, are guided by a large amount of semantic information but demand low motor skill. The acquisition of low semantic, high motor skill performances may be done principally by practice, without substantial amounts of prior study; where high semantic guidance but low motor skill is involved, the converse might be true. In these terms, storage of information in motor LTS is assumed to occur as a consequence of repetition and feedback in the motor system.

Speech, writing, and singing are governed by highly complex rules and codes that have evolved over very long periods of time and that are heavily dependent on semantic LTS. Swimming and running are performances that place substantial demands on motor LTS but that are not governed by complex rules and codes, and thus may not depend so heavily on semantic memory. Motor LTS must be able to control vocal chords, trunk, limbs, and hands, with great precision. Other performances are composed of simple motions that do not require much skill, and that can readily be learned by anyone who can follow a simple list of instructions.

Strategies for Retention

Strategies for improving retention of storage in LTS would take into account what is known about the courses and causes of forgetting. For at least some kinds of material, the course of forgetting seems to be quite rapid for a short time after acquisition, and then the forgetting curve levels off. A major cause of forgetting, under these circumstances, is usually accepted to be retroactive inhibition. Subsequent experiences interfere in some way with the learned material, possibly disrupting response systems upon which retrieval processes depend more than interfering with storage processes, thus making information inaccessible rather than obliterating it. Proactive interference interferes with retention of subsequently learned material, insofar as this can be tested by retrieval tasks, by response competition. These two major kinds of interference have been thoroughly investigated in verbal learning laboratories. Other known causes and their different effects, such as traumas and aging, have been studied clinically (e.g., Talland and Waugh, 1969). That other, unknown causes, also exist is a strong possibility.

Strategies for improving retention also should be sensitive to what is to be retained. Retention of semantic information may involve different processes, at least in part, than retention of episodic information, and each of these may involve different processes than retention of programs for motor skills. Retention also is influenced by the characteristics of prior acquisition episodes. The effectiveness of acquisition strategies is sometimes measured as a function of delay before retrieval.

These conditions suggest that different strategies for retention might be necessary, although the position could be taken that avoiding interfering and disrupting conditions and refreshing storage by appropriate reacquisition or review activities are the general strategies. Since there may be fundamental differences in storage processes in long term memory for semantic information, for episodic information, and for information to guide motor performances, a tentative storage maintenance map for retention strategies is given in Figure 11.

Kinds of LTS	Retention Interval	
	Short	Long
Semantic	A	M
Episodic	A	M
Motor	A	M

Figure 11. Tentative storage maintenance map for retention strategies.

The A in the map refers to avoidance of interfering or distracting conditions over short retention intervals. The M refers to maintenance level processing to refresh storage. Maintenance of information in LTS over long retention intervals, ready for rapid retrieval, would require some form of reacquisition strategies, which probably would differ depending on the type of LTS.

Strategies for Retrieval

Intuitively, a variety of retrieval strategies would be possible, depending on where retrieval occurs in the other two stages of learning and on the type of content that is involved. Retrieval of verbal material would call for different strategies than retrieval of motor performances, etc. An important fundamental distinction is between retrieval processes in recognition and retrieval processes in recall. Recognition clearly is a more sensitive measure of whether or not something is stored in LTS, as well as being particularly appropriate for testing for storage of non-verbal materials, which may be difficult to characterize by recall procedures. Another fundamental distinction is between verbatim and paraphrase, or inferential recall. The vast bulk of verbal learning research has been concerned with verbatim recall of isolated items, and thus, in Tulving's terms, has been studies of episodic memory; whereas semantic memory is of pre-eminent importance in human learning, and paraphrase recall requiring inferential processes is the most common form of retrieval.

Retrieval strategies have received less attention in the literature than acquisition strategies, probably because the primary emphasis in training and education is on inducing students to acquire information and skills, and because thorough learning seems to insure good recall.

Retrieval often is required during acquisition, and in this sense, is part of acquisition. This retrieval goes on before any lengthy retention interval, and is strongly supported by immediate cues in the acquition situation and, on occasion, by knowledge of results.

What about retrieval separated from initial acquisition by a long retention interval? Here, effective retrieval still may depend on the circumstances of acquisition as well as on other world knowledge in semantic memory. For example, if the student reorganized information in a memorable way during acquisition, retrieval is likely to be more effective than if he did not. Retrieving the height of Mt. Fujiyama, 12,365 feet, might be facilitated by remembering that there are 12 months and 365 days in a year.

Orienting tasks requiring retrieval from LTS must include information about what is to be retrieved, to insure that retrieval processes search for the right information. Recognition tasks contain most of the cues that were present in the acquisition situation. Recall tasks can be designed with varying degrees of richness of cues from the acquisition situation. According to this view, richness of cues for retrieval is a function of the number and kinds of cues that were stored in LTS during acquisition that also are present in the specifications of the retrieval orienting tasks, or that are generated as a consequence of performing the retrieval orienting tasks. Gentner's study, reviewed above, indicates that, in retrieval during acquisition, cues for recall at first come from the episodic structure of the subject matter, then later, with more acquisition, are generated by the learner from the semantic structure that is developing in LTS. The concept of cue richness relates to semantic network theories of LTS. There seem to be at least three parameters involved; number of effective entry points into semantic memory provided by cues in the retrieval orienting tasks, the nearness of these entry points to the knowledge structures that must be retrieved, and the scope of the information that the orienting task requires be retrieved. All of these are worthy matters for investigation.

Although cue richness could vary from extremely high for recognition tasks to extremely low for free recall tasks, the characteristics of the subject matter and of the job tasks the student is being taught influence, in some cases, the variations in cue richness that can be designed into retrieval orienting tasks. The job tasks may themselves contain retrieval cues. There always are environmental cues in job situations that facilitate retrieval, and in many jobs, sources of detailed technical information are provided. These greatly reduce the overall requirements for storage in and retrieval of information from LTS.

Since retrieval may occur during acquisition or during retention stages of learning, retrieval strategies may be tentatively mapped with these two stages, as shown in Figure 12.

Types of LTS	Stages of Learning	
	Acquisition	Retention
Semantic	L	H
Episodic	L	H
Motor	L	H

Figure 12. Retrieval mapped with stages of learning and types of LTS.

In the figure, L signifies low expenditure of processing capacity, H indicates high expenditure. The thought is that retrieval during acquisition is likely to require less processing capacity because the information is more readily available, having been freshly stored. After longer intervals between acquisition and retrieval, more processing capacity would be required, even to the extent of reconstructing the information from other related information. The notion of expended processing capacity is used here instead of Deep, Elaboration (E) and Maintenance (M) processing, or Type II and Type I processing, used in the transfer map for acquisition strategies. Acquisition strategies also require an expenditure of processing capacity, as Griffith demonstrated, although it is not necessarily always true that deep processing requires more processing capacity than maintenance processing (Craik and Tulving, 1976).

Retrieval during acquisition usually is employed, as discussed earlier, to obtain feedback about the states of acquisition, so that subsequent instruction can be scheduled more effectively. This feedback information is used in feedback loops in the instructional system, as knowledge of results for the student, and as part of the student's sufficient history to be used for adaptive control (Figure 1). In addition, the processes of retrieval can influence the process of acquisition.

Responding also influences in another way the kind of information that is acquired. The distinction, often made in technical training, between "nice to know" and "need to know" is made on this basis. In this sense, the job task contains the retrieval orienting task which, in turn, determines the information that is to be acquired to enable performing the job task. It is fair to say that in most military technical training today, the attempt is made to determine content by proceeding backwards from training objectives based on observable performances.

Retrieval after long retention intervals may have the objectives of providing feedback about how much is retained, or of practicing earlier learned responses, or of accessing information stored in LTS now needed for some other reason. If a substantial amount of forgetting has occurred during the retention interval before the retrieval episode, then an effective retrieval strategy must be different than if retrieval occurs during acquisition. Whereas some form of directed recall may be the basic retrieval strategy during acquisition, relearning may be the basic strategy for retrieval after substantial forgetting. That something still is stored in LTS is, of course, demonstrated by the fewer trails required to relearn than were required for original learning. What is still stored in LTS even after retrieval other than relearning fails, is not clear. It seems, on the basis of everyday experience, that the finer details are forgotten first, leaving more general impressions. But it could be that the finer details just become inaccessible sooner.

The notion of cue richness, developed above, might be invoked as a bridging concept between retrieval during acquisition and retrieval during retention. It could be assumed that higher cue richness, even to the point of supplying all the original material, would be required in retrieval strategies after greater amounts of forgetting have occurred. This may be of some use as a variable in retrieval strategies, although the "tip-of-the-tongue" phenomenon, and repressive amnesias indicate that retrieval processes sometimes are temporarily blocked. At these times, the richness of retrieval cues might be immaterial. Retrograde amnesia, produced by traumas, in which most events over some interval stretching backwards in time from the time of the trauma are forgotten temporarily, illustrates this, although presumably episodic memory is affected more than is semantic memory (Williams, 1969).

IV. THE STRUCTURE OF COGNITIVE STRATEGIES

The premise of this report is that it may be possible to improve the effectiveness of students as learners by gaining better control over the kinds of information processing they do while acquiring, retaining, and retrieving information and performance. This control might be achieved either through teaching the students more effective processing strategies, or through real-time monitoring of their processing, although the feasibility of the latter remains to be demonstrated (Rigney, 1976). The teaching might be done by describing particularly effective processing operations to the students and instructing them in how to use these operations, or by so arranging conditions in the learning environment that students are forced to use the desired kinds of processing operations, without explicitly describing these operations to them. The latter is a standard way of teaching students content. In mathematics, for example, students are given problems so designed that they are forced to perform the operations and use the concepts it is desired that they learn, in order to get the right answers.

Orienting tasks are the principal means of controlling the student's processing operations, although they must be combined with subject-matter that is to be processed, and the subject-matter often also contains embedded orienting tasks at lower semantic levels, which it is assumed the student already understands. This use of orienting tasks is clearly illustrated by innumerable studies of memory and cognition in the verbal learning laboratory. For example, Mandler and Worden (1973) described examples of semantic processing without permanent storage; processing during shadowing, reading stories to children while not attending, and skilled typists copying manuscripts. They suggested the following explanation for this phenomenon:

> It is now possible to suggest the locus of the typist, parent, and shared-attention effects. The semantic organization of the primary task is apparently adequate at the time of input to produce a reasonable level of semantic processing. However, as time passes or intervening tasks intrude, the semantic organization is lost. As a result, recall drops to very low levels and synonym confusions appear. The semantic organization of the material, which is present to some degree immediately following presentation, disappears over time. The present data do not differentiate between 2 hypotheses, whether the organization is not stored permanently at input or whether the degree of semantic organization that is performed at the time of input is set at the (low) level required by the task. The latter case suggests the reasonable argument that task requirements set the degree of organization of material at the time of input. In any case, we conclude that shadowers, typists, and parents operate with the required semantic organization at the time of input, but fail to remember the contents at a later time because the organization was not adequately stored or only superficially performed (p. 282).

Categories of Orienting Tasks

Orienting tasks are familiar ingredients in the incidental learning paradigm of the verbal learning laboratory, where they serve as an important means for implementing experimental variables. Thus, in Griffith's study, reviewed above, one experimental group was told to construct sentences in which the to-be-learned paired associates were embedded. The other experimental group was told to repeat sentences with embedded paired-associates supplied by the experimenter. These instructions were orienting tasks. Instructions to the student, then, constitute one form of orienting task. Instructions often are given at the beginning of a session in which a number of items are to be processed in the same way. Thus, Griffith's students learned not one, but a series of paired associates by processing them according to the same instruction. This form of orienting task exerts fairly weak control over the desired cognitive processing operations. Students instructed to construct their own sentences in which to embed paired associates may or may not do that all the time. Students instructed to form mental images with embedded paired associates could use some other processing operations if they chose. Post-session questioning usually reveals that a fraction of the students admit they did not follow instructions any, some, or all the time. In these cases, students are following their own self-instructions. It seems likely that instructions calling for bizarre, complicated, or highly effortful processing operations would run a higher risk of being abandoned by students in favor of more familiar, simpler, or easier self-instructions. This is a serious weakness in the instruction form of orienting tasks. A remedy is to require the student to reproduce processing operations. Students instructed to form mental images can be instructed to draw these images. Students instructed to generate sentences with embedded paired-associates can be required to write the sentences. This adds time to the processing. Thinking is quicker than thinking plus drawing or writing. It also adds the motor response systems to the cognitive processing, and this changes the processing operations; drawing is not equivalent to imaging, writing is not equivalent to mentally generating sentences.

Questions are a second form of orienting tasks. Since questions do call for answers, they are the pre-eminent type of orienting task used in teaching content. In one form or another, they are used to teach everything from science and mathematics to history and English literature (Bloom, Hasting, and Madaus, 1971). As orienting tasks for cognitive strategies, they must be designed to require that desired kinds of processing resources be used in order to answer them. Questions are more readily used as the orienting task part of embedded cognitive strategies, where the processing that the question elicits in the student is not identified by him as a cognitive strategy. A recent example of this usage in the verbal learning laboratory was reported by Craik and Tulving (1976), in their study of depth of processing and the retention of words in episodic memory:

> "Subjects were induced to process words to different depth by answering various questions about the words. For example, shallow encodings were achieved by asking questions about typescript; intermediate levels of encoding were accomplished by asking questions about rhymes; deep levels were induced by asking whether the word would fit into a given category or sentence frame. After the encoding phase was completed, subjects were unexpectedly given a recall or recognition test for the words. In general, deeper encodings took longer to accomplish and were associated with higher levels of performance on the subsequent memory test. Also, questions leading to positive responses were associated with higher retention levels than questions leading to negative responses, at least at deeper levels of encoding." (p. 268).

There is great current interest in question-answering instructional systems, in which the student also can ask questions of the system. The thought is that this will allow the student to pursue his curiosity about a topic, acquiring answers to questions he really wants to have answered. When natural language processing really becomes feasible, the instructional bandwith of these systems might become sufficiently greater to make them more powerful than simpler, cafeteria-style interactive systems.

Processing Resources for Cognitive Strategies

In learning content, a context of prior world knowledge in which the to-be-learned content can be embedded and which contains already learned processing operations is the major resource. For learning to learn, retain and retrieve information and performance, the emphasis is on more effective utilization of representational, selectional, and self-directional processes.

Representational Processes

These represent important features of the external and internal worlds. They include sensors, intermediate, and higher level representational systems. Most of the processing that goes on in these systems is not available to consciousness or to voluntary control, and probably is parallel processing. In fact, in view of recent theories of semantic memory noted above, it could be said that parallel processing is characteristic both of the peripheral parts and of the higher centers of neural representational systems. The pre-eminent representational tools that are available to consciousness and to voluntary control are language and imagery. These two resources are almost inextricably intertwined. Language has the remarkable property that it can evoke rich imagery under certain circumstances, so that reading a novel can be a rich imaginal experience, full of scenes and characters and events that move through consciousness as dreamlike images. The fact that dreams are composed of images rather than text and that very few dreamers talk in their sleep probably has some implications for how language and imagery are related, leading to the speculation, encouraged by apparent developmental changes in sleep and in imaging capability, that imagery is the more primitive of the two great representational systems. In very young infants (Nova, 1976), a very high proportion of sleep is REM sleep. In adults, dreaming occurs predominantly during REM sleep.

Coupling these representational systems to learning and memory with orienting tasks depends, on the one hand, on common experience, and on the other, on increasing the knowledge of the roles of these representational processes in learning and memory that is beginning to be accumulated by cognitive scientists. Thus, it is not possible here to give definitive prescriptions for the most effective use of these processing resources for this purpose. Observations from learning assistance centers and studies of recruit capabilities (Duffy, 1975), suggest that the capability to use language effectively for reading, writing, or speaking is less than universally distributed among people. One of the important requirements must be to increase this capability, and thus, to increase these basic processing resources that are available for use in learning. It is interesting, in this regard, that there are remedial reading clinics but not, apparently "remedial imaging" clinics. Both Bower (1972) and Wittrock (1975) remarked on the remarkable bias in education toward the language system, and suggested that the capability to image, relatively strong in children, is later neglected.

The ways in which language can be used for more effective learning and remembering seem to be primarily as follows. If acquisition is a problem of relating something new to something old, language can be used for the relational operations, which would include analogy and metaphor, existential affirmatives, and universal affirmatives, as well as description, reorganization, and inference. The fundamental requirements for cognitive strategies is that the student actively use language as a learning tool rather than passively processing whatever lesson materials come his way. He should be shown how to use these relational operations to facilitate understanding during acquisition. Retrieval, the search of LTS for information not immediately available, seems to involve using language to probe LTS in different ways, to reconstruct from fragments, or to construct by inference.

Although imagery currently is being very actively explored as a cognitive strategy, most of the investigators tend to use fairly simple subject-matter, such as paired associates. In addition to providing an embedding and relational context during acquisition, mental imaging seems to be useful for reconstructing episodes during which material was acquired, and for creating imaginary episodes in which performances can be reviewed, as a way of checking on the level of acquisition as well as refreshing memory during retention. During this rehearsal of performance, language is a useful tool for self-instructions, e.g., for talking oneself through a series of movements a step at a time.

Selectional Processes: Attention

Selective attention is conceived as a conscious capability that can be focused on a broad range of internal and external events and processes. It evidently is a necessary constituent of deep, or elaborative processing, and evidently has limited capacity. Its roles as a processing resource in cognitive strategies are not confined to deep processing; selecting material not to process may be an even more important function. It has been reported (Personal Communication) by the Stanford Learning Assistance Center that one of the most common deficiencies of students is the inability to select the important passages from textual material, such as a book or a scientific journal article rather than plowing through the whole thing, word for word. Learning how to do this seems to be an important preprocessing use of selective attention. Indeed, a good part of a professional's knowledge of his area may consist of knowing where and how to access technical information quickly, rather than knowing the information itself.

Once the preprocessing selection of information has taken place, the attentional requirements of deep processing for acquisition must be met. The student must concentrate, as the saying goes, on what he is trying to learn, despite external and internal distractions. In this respect, attention is analogous to a priority interrupt system. Minimizing external distractions is largely a matter of designing the environment. Minimizing internal distractions is a problem for cognitive strategies. It may be that self-generated distractions are the primary source of inefficient learning. The stream of consciousness may be less a stream than a bubbling cauldron where all sorts of odds and ends continually surface to interfere with the task of learning, as suggested by a figure from Kahneman (1973, p. 18). Methods that could be taught to the student for controlling internal distractions must have a high payoff in improved learning efficiency. Self-discipline and concentration are well known words in the lexicon of education and training. Methods for accomplishing these are less well-known, but would seem to depend either on self-instructions or biocybernetic techniques. The latter require neurophysiological or electro physiological indicators, which at best are crude. Pupillary dilation first suggested by Hess and Polt (1964) as an indicator of mental effort, has been studied in many contexts, with positive results. There is a correspondence between cognitive load and pupillary dilation. Kahneman (1973) reviewed evidence for pupillary dilation both as a between-tasks and as a within-tasks indicator of changing cognitive loading:

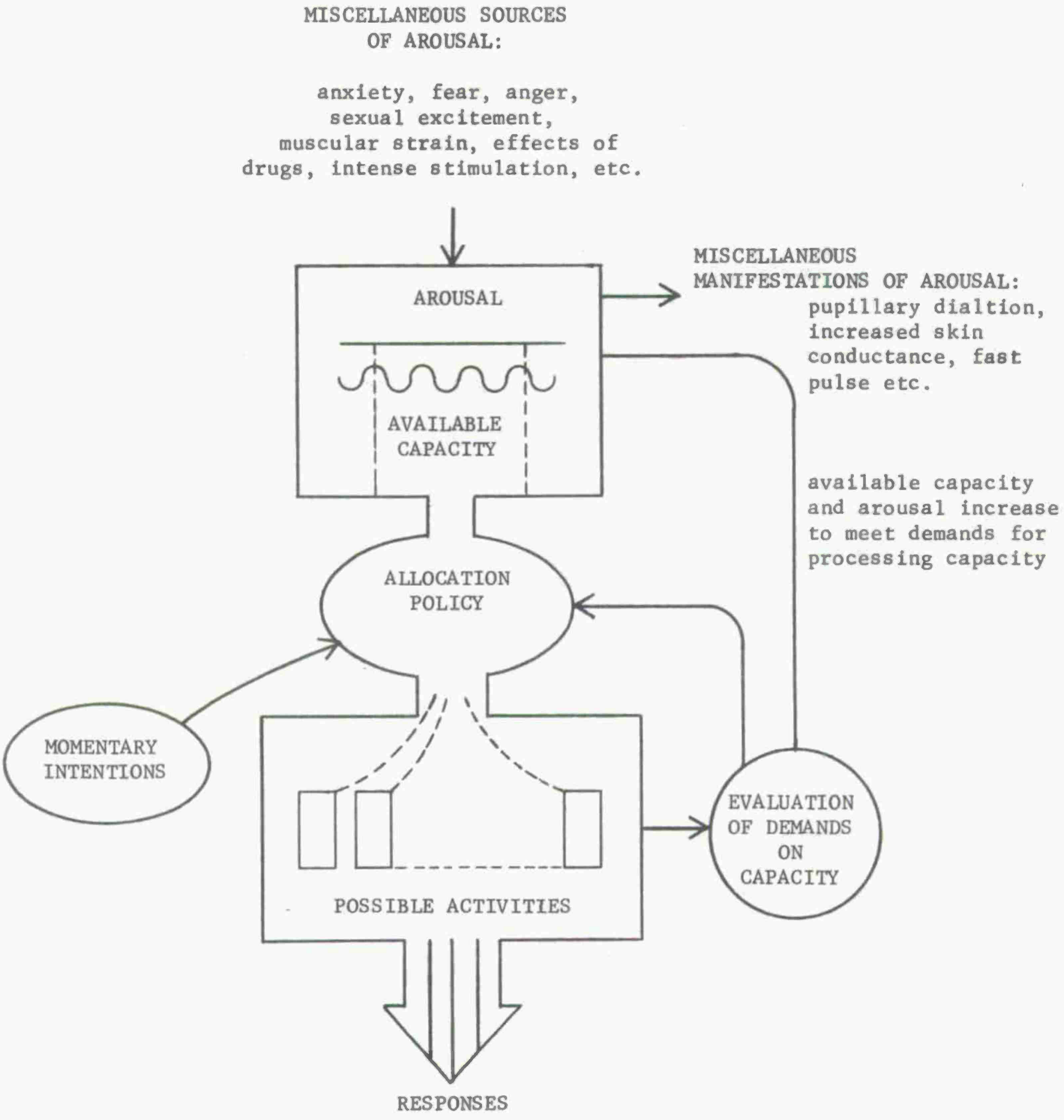

Figure 13. Effort and other determinants of arousal.
(Kahneman, 1973, P. 18).

The claim that pupillary dilations indicate mental effort was made by Hess and Polt (1964); Hess, (1965), who observed a striking correspondence between the difficulty of mental arithmetic problems and the magnitude of the dilation during the solution period. The correspondence between cognitive load and pupillary dilation was later confirmed in many contexts: 1. Arithmetic (Bradshaw, 1968b, Payne, Perry & Harasymin, 1968). 2. Short-term memory tasks of varying load (Kahneman & Beatty, 1966). 3. Pitch discrimination of varying difficulties (Kahneman & Beatty, 1967). 4. Standard tests of "concentration" (Bradshaw, 1968a). 5. Sentence comprehension (Wright & Kahneman, 1971). 6. Paired-associate learning (Colman & Paivio, 1970; Kahneman & Peavler, 1969). 7. Imagery tasks with abstract and with concrete words (Paivio & Simpson, 1966, 1968; Simpson & Paivio, 1968). 8. And the emission of a freely selected motor response instead of an instructed response (Simpson & Hale, 1969). In all these situations, the amount of dilation increases with task demand or difficulty. The relation between attention and pupillary dilation is maintained even in the absence of specific task instructions: Libby, Lacey, and Lacey (1973) observed dilations of the pupil when the subject merely looked at pictures. The largest dilation occurred while looking at "interesting" and "attention-getting" pictures. Pratt (1970) also observed that the pupillary dilation varied with the unpredictability of random shapes to which subjects were exposed. Evidently, complex and interesting pictures, like difficult tasks, attract attention and demand a relatively large investment of effort.

The second test of an adequate measure of effort is within-task sensitivity. Several studies have confirmed the suggestion (Hess, 1965) that the size of the pupil at any time during performance reflects the subject's momentary involvement in the task. Indeed, the fidelity of the pupil response permits a second-by-second analysis of task-load and effort. Kahneman and Beatty (1966), for example, showed that the presentation of each successive digit in a short-term memory task is accompanied by a dilation of the pupil. The increase in pupil diameter corresponds to the increasing rate of rehearsal which is imposed by the presentation of the additional digit. This pattern of rehearsal can be altered by presenting the items in several groups, separated by pauses. Then, a brief dilation of the pupil occurs after the presentation of each group, corresponding to the spurt of rehearsal during each pause (Kahneman, Onuska & Wolman, 1968). Finally, when a subject is informed that he needs no longer retain the digits he has heard, his pupil briefly dilates, then constricts, as he ceases to rehearse (Johnson, 1971, p. 1911).

The pupillary dilation is a relatively fast response, and major dilations can occur within one second after the presentation of a demanding stimulus. Thus, Beatty and Kahneman (1966) showed that the pupil dilates about 10 percent of base diameter during the first second following the presentation of a familiar

> name, when the subject must respond by the appropriate telephone number. Similarly, in a pitch discrimination task, the diameter of the pupil reaches a maximum within one second of the presentation of the critical tone; the size of the pupil at that time faithfully reflects the difficulty of the discrimination (Kahneman & Beatty, 1967). When subjects are required to produce an image that corresponds to a particular word, pupil diameter reaches its maximal value faster with concrete than with abstract words (Colman & Paivio, 1969; Paivio & Simpson, 1968; Simpson, Molloy, Hale & Climan, 1968). A plausible explanation of this finding is that the visual image is produced sooner for concrete than for abstract words (p. 20).
>
> To further test the validity of the pupillary measure of effort, a behavioral measure of spare capacity was introduced. Subjects were required to perform two tasks simultaneously. The primary task involved the transformation of a digit string: the subject heard a series of four digits (e.g., 3916) at a rate of one digit/second, and he was instructed to pause for a second, then to respond with a transform of that series (4027), adding 1 to each digit of the original set. In addition, the subjects performed a secondary task. In one experiment (Kahneman, Beatty & Pollack, 1967), a series of letters was flashed in quick succession, and the subjects monitored the display for the occurrence of a "K." In another experiment (Kahneman, 1970), the subjects were briefly shown a single letter, which was to be reported after the completion of the digit-transformation task. The payoff structure in these experiments was designed to ensure priority for the digit-transformation task: the subject was paid for the visual task only if he had performed the transformation task adequately (p. 20).

Thus, pupillary dilation might be considered as an indicator to be monitored and transformed into some kind of signal to the subject in a biofeedback paradigm.

Currently, there also is interest in the possible usefulness of cortical potentials as electrophysiological indicators that could be used to improve concentration. Theta-band activity has been associated with signal detection performance in a radar task (Beatty, Greenberg, Deibler, and O'Hanlon, 1974). This is a classical vigilance task, in distinction to cognitive information processing tasks that are of interest here. Gopher (1976) and others have reported on plans to monitor on-going EEG of aviators to identify arousal states while flying that might be undesirable, and that might be avoided by providing feedback to the aviator. North and Gopher (1976) described a study of the multidimensional aspects of attention in flying. This is, of course, a real time task that calls for flexibility in allocating attention to different tasks and the ability to cope with divided attention, or to timeshare attention among several requirements, rather than concentrate all attention capacity on one kind of cognitive processing. The feasibility of using biocybernetic techniques to teach students to concentrate, or conversely, to reduce internal distractions, remains to be demonstrated.

Selectional Processes: Intention

In most learning situations, to a very large degree, the individual student decides on the amount of investment he will make in a particular course. The fact that education and training take place in social contexts in which there is an implicit agreement with each student that the student will participate supports individual intentions with social pressures to achieve. Peer competition adds to these pressures. Fear of failure in this context may be a potent driving force that carries many students beyond the point where they would have quit had they been on their own. But the question here is how individual students can be taught to control their own intentional processes so that they can make a strong investment of their processing resources in learning. This seems to be an unploughed field. Indeed, the whole notion of self-discipline seems to be out of step in a manipulative and permissive society, and in the climate of Neo-Freudian, Skinnerian philosophy. The bases of the intentional strategies that might be taught to students would be in knowledge about effective learning processes, learning as a contract with oneself, and self-generated goal structures. As the differences between effective and ineffective cognitive strategies for acquisition, retention, and retrieval become better differentiated, this information should be transmitted to students so that they can deploy their processing resources more effectively on those things they want to learn. Learning anything takes time. Most of the learning with socially valuable outcomes requires years of commitment. These are well-known facts, but they may still not be clearly articulated to students. When a student embarks on this kind of learning he is making a contract with himself to use a large block of his time in an activity that presumably will have worthwhile payoffs for him. He should be taught to relate the payoffs he is looking for with the payoffs society is likely to grant him for completing this contract. What he really is looking for may or may not correspond to society's payoffs, and this may or may not make a difference to him.

The analysis of and generation of goal structures might also be taught to students to assist them in controlling their intentions to learn. The identification of intermediate goals and the paths from them to some top goal would allow organization of the learning task into modules that could be achieved in a step-wise fashion with intermediate successes to reinforce intentions and intermediate resting points before going on.

Goal-descriptive directions, i.e., an embedded cognitive strategy, have been demonstrated to produce substantially higher recall performance on goal-relevant test items, in learning from textual material (Kaplan & Rothkopf, 1974, Rothkoph & Kaplan, 1972). Rothkopf and Billington (1975) have advanced a two-factor model to account for these effects, in which processing effort that has been applied to a particular text element, is generally inversely related to E, which is a preexperiment experience factor associated with a particular text element-test item combination.

The question of interest here is whether students could be taught to develop their own goal-descriptive directions for guiding their learning of some subject matter that would yield similarly positive results. This might be done in response to externally imposed requirements or simply to answer self-generated questions efficiently.

Self-generated questions are considered to be forms of self-generated goals, and may be among the most potent of cognitive strategies, stimulating the learner to search for answers he wants to know. They presumably arise out of curiosity about the world, which results in reducing uncertainty and increasing the possibilities for control over events. Since one question often leads to another, a great deal of what people learn probably results from this process. Critics of the current educational system (e.g., Holt, 1969) assert that it warps or destroys the child's native capacity for learning and creating. Nurturing this native capacity is a fundamental goal of question-answering instructional strategies in general, and of the approach to instruction currently being developed by Papert (1973), Kay (1976), and others. Frase and Schwartz (1975) reported positive effects on recall from prose of both question asking and answering.

The time spans over which these planning activities might be applied would be long for education and short for training. In both cases, the student also makes a contract with the instructional institution, in which he delegates a certain proportion of this planning to the institution. In the case of military training, the nature of this contract is, of course quite different than it is with, say, a university. Bringing all this down to the point of allocation of processing resources on a real-time basis integrates intentional processes with attentional processes, where they can be located, in the Kahneman Model (Figure 13), in the momentary intentions block. These could be conceived as the unfolding outcomes of the longer range planning, which would include the intention to start or not to start learning some large block of material.

Self-Directional Processes

The effective use of representational and selectional processes ultimately depends on the individual's self-directional skills, even though instructional institutions provide highly organized curricula and assume the responsibility for providing other forms of external facilitation of learning, and in early stages of learning the student must rely heavily on this external facilitation. A reasonable view of the functions of the CNS in learning and memory, as pointed out above, is that they are divided into three levels; top level cognitive processes of which the learner can be made aware and which he can learn to control; intermediate-level neural substrate processes which the cognitive processes activate but which cannot be brought under direct, voluntary control; and third-level neural machinery that is assumed to be wired-in by the interaction of genetic and early developmental experiences, apparently is far less plastic than the two higher levels, may be activated by the higher levels, but may be driven by its own internal pacemakers and is locally controlled by its own feedback and feedforward loops.

Some of this lower-level neural machinery may be accessible to external modification by biofeedback techniques, but these are not, as yet, significant in education and training except, possibly for physical therapy. The CNS contains both adaptive and self-organizing features which support the self-directional processes that will be discussed below.

Self-Programming Skills. Cognitive scientists currently are developing interesting theories about different forms of self-programming in long term memory. Some of these were reviewed briefly in an earlier section. A much simpler idea is involved here, that students can learn to organize their processing resources for performing a particular learning task. This organization would occur in anticipation of the task requirements, and later, during the performance of the learning task, in response to local information. Students can, according to this idea, learn self-programming skills for matching their processing resources to learning task-requirements. Anticipatory self-programming, i.e., planning, is common enough in other human affairs, although it is not necessarily a common stage in learning. It would require that the student be able to obtain advanced information about the different processing resources that would be suitable for the occasion. This would require that the student be able to analyze the subject-matter to be learned sufficiently well to do this. This skill might be acquired, with some expert assistance, although the nearest thing to this assistance in current instructional institutions seems to be brief statements of prerequisites for intermediate and advanced courses. What would be needed in addition would be classification of subject-matter by processing resources. Learning self-programming at this stage would be equivalent to learning self-assignment of different orienting tasks as subject matter characteristics changed. Although this possibility seems scarcely to have been considered, there is the evidence described by Kahneman, reviewed above, that pupillary dilation indicates overall level of effort, or allocation of general processing capacity, is adjusted to suit the perceived requirements of changes in information processing tasks.

Self-Monitoring Skills

Most learning of any practical consequence extends over appreciable periods of time and involves sequences of interrelated material and sequences of interrelated actions. Self-monitoring skills are required to identify errors, to keep track of progress, to sense processing overload, to monitor the performance of actions. In initial stages of learning, many of these chores may be done for the student by the instructional system. But, the attainment of proficiency both as a learner and as a performer, using what has been learned, includes the learning and use of self-monitoring skills that will free the learner and performer of dependence on external monitoring.

Some sort of self-monitoring must be done by most people most of the time. It is a requisite for survival. The concept of the self, as an entity distinct from the rest of the perceived world is fundamental to protecting that self from the rest of the world. The awareness of students of what they are doing while they are learning possibly is another individual difference, although tests of self-monitoring skills do not come immediately to mind. The two points of application are in real time to be sure that planned actions are, in fact, now being performed; and in looking back to review what has been done to check for errors. Self-monitoring skills obviously are of great importance where long sequences of operations must be performed in an exact pattern. Many everyday situations involve this: filling out an income tax return form, using a statistical algorithm, flying an airplane, finding a path through a freeway, etc. Self-monitoring requires allocation of attention to the detailed operations of cognitive processing and of performance, and a conception, model, or guide, for how these operations should be done, which in initial stages of learning is supplied by the instructional system, and in the final stages of learning is retrieved from long-term memory, supplemented by extended memories characteristics of the task. It may be that episodic memory is the source of the warning feeling that something is wrong with a just-performed sequence of operations, while semantic memory supplies information about what is wrong. At least, the experience of sensing that an error has been made seems often to precede the identification of what that error was.

V. TECHNIQUES FOR IMPLEMENTATION

Although the immediate effects of cognitive strategies can be and should be investigated by means of small sample, snapshot experiments, longer term effects, and identification of cost benefits in training, require broader scope, longer term studies done in the context of a training or educational system. Although technical training in the Navy is being shifted from so-called lock-step to so-called self-paced Computer Managed Instruction, attrition rates are still relatively high in some of the important courses. And, when students leave these and go to their job assignments, they are likely to encounter documentation that is not in smoothly programmed format; technical manuals are often very heavy going. The cost-benefit gained from teaching students to use cognitive strategies in these contexts could be substantial, and should be investigated. Students who cannot keep up in technical courses, such as basic electricity and electronics, now receive certain kinds of remedial training, most often consisting of repetition of a course module. These remedial requirements are highlighted by attrition rates, and tend to receive a good bit of attention.

But, students who are not doing well in a course are not the only prospects for teaching learning-to-learn techniques. A recent article, Time (1976), described the Learning Assistance Center (LAC) at Stanford. This facility was started in 1972 to help the freshman students, who are said to be among the brightest in the nation, replace slovenly and inefficient study habits acquired in high school with more effective techniques. The LAC now teaches more than 50% of Stanford's 1,500 freshmen, and also is open to upper classmen, graduate students, and faculty. The author of the article noted, apparently with some surprise, that "Stanford considers the courses so valuable that it even gives credit for them."

The Learning Assistance Center appears to be an effective way to implement the teaching of cognitive strategies. Diagnostic measures can be administered and combinations of strategies can be assembled for each student. In the context of military training, it might eventually be fruitful to send all recruits through a LAC before sending them to technical courses, to include LAC diagnostic profiles as part of a person's record, and to provide LAC's at all technical training complexes as well.

A system for supporting research on teaching cognitive strategies is under consideration at this laboratory. Its principal features will be dual interactive displays, the capability for storing and randomly accessing large masses of textual and graphic material, in color or black and white, and the capability for sensing where in these textual and graphic images the student points. This will be the basis for interleaving two levels of instruction and for control over microinteractions with the student. Such a system ultimately should be useful in Learning Assistance Centers, where large numbers of students would be taught to be effective learners.

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