

HUMAN MEMORY STRUCTURES

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ABSTRACT

HUMAN MEMORY STRUCTURES

By

Kenneth Lowell Salzman

This study set out to investigate the nature and form of human memory structures. It was hoped that an understanding of these structures would facilitate the development of computer simulations of human memory. Three models of human memory were proposed and an attempt was made to determine whether these models were related to real memory structures. The task, then, was to differentiate and identify the structures used by individuals. Subjects were asked to memorize spy networks which were presented as lists of message senders and receivers. For each network, the subjects were given a series of timed tasks which required the recall of the network information in different forms. Each subject was also interviewed at the end of the experiment to obtain introspective data. By inspection of the response data, it was found that three distinct memory systems had been used by the subjects. Several assumptions in the original models were found to be inaccurate and revisions of the models were made to correspond with actual memory structures found. The data was grouped according to type of structure used, and the three groups were compared with each other. Several implications for learning and cognitive performance were brought out, and an argument was presented against the stimulus — response explanation of serial learning.

HUMAN MEMORY STRUCTURES

by

Kenneth Lowell Salzman

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This section gives the author a chance to name those who have contributed to the work. I shall use it to delineate the people who, in a sense, co-authored this thesis, for it would not have been accomplished without them.

Dr. John Hunter is in large part responsible for the quality of this work. His advice, experience, and undeniable talent for research and clear thinking were models for me. I have learned much from him and can only begin to express my appreciation for it.

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INTRODUCTION

Increasingly, psychologists study human language in an effort to discover something about the processes involved in the human mind. As a part of this study there have been a large number of attempts made at developing semantic learning machines. These are usually in the form of computer programs which can accept some approximation to the English language as input and, in turn, produce appropriate and correct English sentences as output.

The memory requirements for a semantic learning machine are particularly strong. In basic English there are 850 words, each pair of which is either directly related or indirectly related through other words in one or more ways. Quillian (1968) found that for any given pair of words taken from a sample of only sixty words, there were two or more distinct indirect relationships to be found. Even with a small sampling of words the number of relations, or links, between words is extremely high. To represent full understanding, one must store, in addition to the individual words, the relationships between pairs and groups of words, ultimately amounting to every bit of information and knowledge known to man. To add to the difficulties, each one of these bits of data must be made and kept accessible to the memory user.

The number of bits of information present and the added bits of referencing and locating data needed far exceed the capacities

of every known computer and may exceed the storage capabilities of the human mind as well. Lindsay (1963) has inferred from this that people must develop structures from which bits of information may be inferred, thus foregoing the need to store those bits. How is this done? Perhaps the information is stored in some structure or format that is more efficient than a simple list.

This study was an attempt to probe the question of memory format with the hopes of developing the basis for a model of human memory. In particular two structures will be defined below: the directional and bidirectional "graph". The central question for the empirical work was: Can subjects store information in the form of a bidirectional graph? The following chapter will focus on the definition of structures that are related to graphs and review the various structures that have been studied in computer simulation. The next chapter will review Hayes' (1968) experiment on human memory structure in remembering spy networks. The succeeding chapters will then present the design and results of the present study.

MEMORY STRUCTURES IN COMPUTERS: RELATIONS AND GRAPHS

A memory structure may be defined as a system in which facts or data of some sort are stored and from which these facts may be retrieved. In order to be useful, however, a memory structure must also be reasonably efficient by several criteria. First, it should permit the data to be stored fairly easily. It should not require an extensive encoding unit which would require its own separate memory structure in the form of tables, rules or some other complex system. By requiring such a unit, the form and development of the memory structure becomes secondary to the form of the encoding unit, making the main memory dependent on the development of some "innate" processing unit for its effectiveness. Second, the data should be easily retrievable. Items of information, once stored, should not be made inaccessible through "forgetting" or by virtue of the enormity of the data base which is to be searched. The search itself should not require excessive cues from "outside" sources, nor should it require excessive time to locate the information or to determine that the information is not presently held in memory. The search efficiency is not only a function of the memory structure, but also of the search program or the search process itself. Finally, the information storage should be spatially efficient, permitting the storage of a maximum amount of information in a minimum amount of space. Though this has often been considered purely a hardware

issue in computer models, the technology has now advanced to the point where enormous storage spaces can be put in relatively small machines, thus allowing and requiring more efficient storage procedures if full use of the available space is to be made.

Many writers have noted that the basic unit of understanding in human communication is the sentence. Mathematically most simple sentences are relations between two noun phrases. The relation is the meaning given to the connection between the two noun phrases. There are four parts to such a relational sentence: the first noun phrase, the second noun phrase, an indicator showing that the first phrase is related to the second phrase (without implying that the second is related to the first) and a label describing the type or meaning of the relation. For instance, the sentence "My uncle's best friend despises acts of violence" may be partitioned into noun and verb phrases as (My uncle's best friend) (despises) (acts of violence). The first noun phrase is (My uncle's best friend), the second noun phrase is (acts of violence). The first is related, by this sentence, to the second, but there is no information present concerning the manner in which (acts of violence) are related to (My uncle's best friend) if any such relation exists at all. The nature of the relation is (despises). A sentence of the form, "The house is red" can be rewritten as "The specific house indicated is a red house" and partitioned as (The specific house indicated) (is) (a red house). Similarly, most compound sentences can be separated into multiple sentences of the described form.

Many sentences could be grouped so that all of the sentences in a given group would have the same label attached to the indicator

of the relation. Within such a group the label is redundant. Thus the label could be made an implicit piece of information. Only the other three parts of the sentence would have to be made explicit. One way of doing this is to make a visual diagram of the group of sentences in which each noun phrase is represented by a point in the diagram. If a noun phrase is related to a second noun phrase, an arrow is drawn from the first noun phrase to the second noun phrase to indicate the presence of a relation.

In Figure 1 the noun phrases are geographical locations and the implicit label or meaning for each relation is (is north of). Thus, Figure 1 is a visual representation of a network composed of a group of sentences, each sentence having the form (X) (is north of) (Y) where X and Y are noun phrases. Mathematically, such a

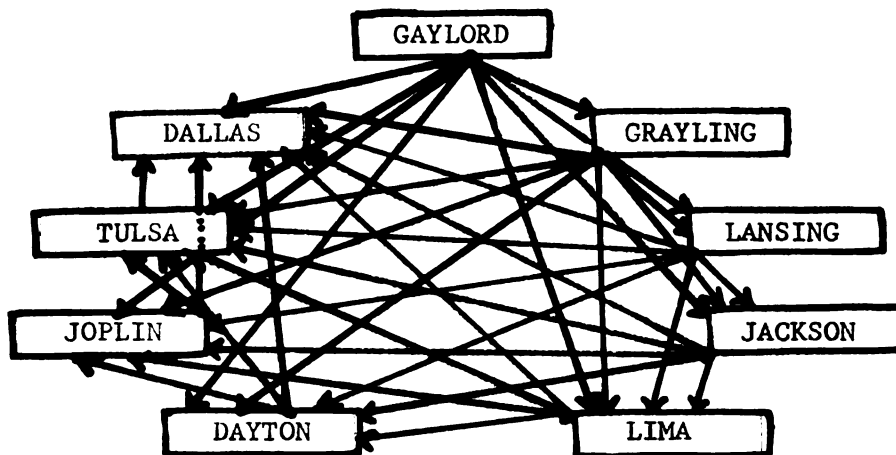


Figure 1. Graph for the Relation (Is North Of)

network is called a "graph". The points representing noun phrases are called "nodes" and the arrows or connections are called "links".

Since most sentences can be written as relations, it is possible to group these sentences as described above and create a graph for each network thus produced. In this way, a large memory structure could be developed to store sentences. As a large number of interrelated nodes, or noun phrases, are introduced to a single network, the number of links required between nodes becomes extremely large. In Figure 1, for example, the nine nodes of the network require thirty-six links in order to completely relate each pair of nodes. It would be useful, in such a situation, to have some means of representing the information with a smaller set of links. One approach is to notice that the label (is north of) for the graph in Figure 1 has the property of "transitivity". That is to say, if A is north of B and B is north of C, then A is north of C. The relation between A and C, then, can be inferred from the relations between A and B, and B and C. Elliott (1965) has defined nine properties, including transitivity, which can be used to make inferences about relations which are not linked directly in the graph. If, in Figure 1, we removed all links which could be inferred from some combination of other links, the resulting graph would look like that shown in Figure 2, which requires only eight links.

In the discussion above, it was assumed that the memory consisted of a multiplicity of "small" graphs, one graph for each relation. Such a system requires an enormous amount of storage space. Is there a way to combine these smaller graphs into a single, more compact structure? A single network could be made which contains

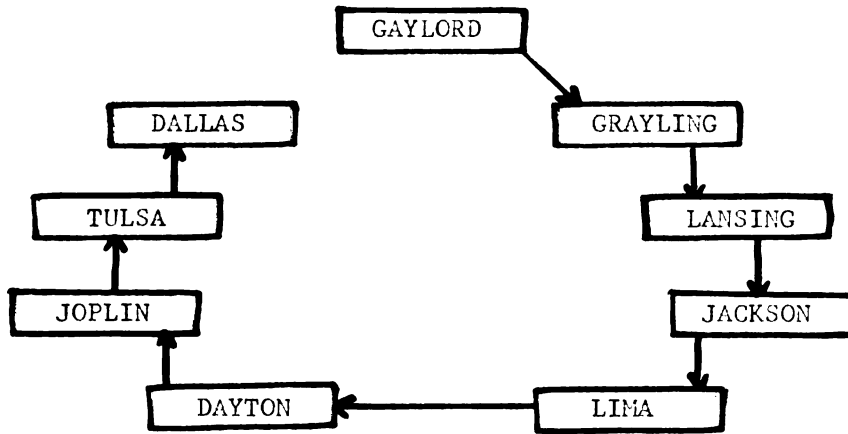


Figure 2. Reduced Graph for the Relation (Is North Of)

all of the nodes and links found in the smaller graphs, but the implicit labels for the links in the smaller graphs must be replaced by explicitly labelled links. These labels must be made explicit by "attaching" the labels to the links themselves.

A graph in which each link is given an explicit label is called a "labelled" graph. A labelled graph structure would require fewer total nodes than the multigraph structure, since no node is listed twice. Furthermore, if two nodes were linked on more than one of the smaller graphs, then the labels from each of these graphs could be collected into a list which could then be "attached" to a single link between the nodes in the labelled graph structure. Thus a set of links with various labels could be replaced by a single link whose label is a list of labels. Furthermore, if the input of data

is clustered, i.e. containing multiple relations from a single node, the labelled graph system allows a more rapid input of this data than does the multigraph system. Multiple relations from a given node require only a single search for that node in a labelled graph, while in a multigraph system the node must be re-located for each new relation listed.

However the most important gain made by reducing the structure to one graph is that new, previously undefined or unconnected relationships can be inferred as quickly as familiar relationships. For example, the question, "Who is your uncle's best friend?" is handled more easily in the labelled graph structure than in the multigraph structure. In the multigraph structure, a "kinship" graph must be accessed to identify the uncle, then a "best friend" graph must be accessed to identify the best friend of the man identified as the uncle. In the labelled graph structure one need only search the set of links to find the uncle, then search the set of links at that node to identify the best friend.

A labelled graph becomes very complex if a great amount of information is stored. Eventually, it becomes advantageous to develop auxiliary devices to aid in the use of the labelled graph. One method of simplification capitalizes on relations dealing with groups of nodes. As an example, consider the group of all men, and the sentence "Men dislike sweet colognes." In a labelled graph, one might locate each node which represents a man and link it to the node (sweet colognes) with the label (dislikes). It would be much simpler if there were a means by which a single link could connect the group of men to the node (sweet colognes). That is, one would

introduce the node (men) to represent the subgraph of the labelled graph whose nodes are men. A link from (men) to (sweet colognes) then implicitly indicates the existence of links from all individual men to (sweet colognes).

A node such as (men), which represents a subgraph of the labelled graph, is called a "hierarchical" node. A labelled graph which has hierarchical nodes is called a "hierarchical" labelled graph. Making use of hierarchical nodes as an auxiliary device will increase the time required to process information, but it greatly reduces the amount of storage space required.

REVIEW OF EXISTING SEMANTIC MODELS

The following is a rapid review of some of the models and systems presently developed or under development which deal with semantic information processing, with an emphasis made on the approach taken towards the memory structure used.

Hunt, Marin and Stone (1966) developed a system aimed at making inductive decisions about set inclusion. The memory space consisted of a $p \times q$ matrix. Each column of the matrix represented a "dimension" or "attribute set"; each row represented an object. The entries in the matrix determined the description of the object by specifying for each object - dimension combination which attribute of that dimension applied to that object (if any). The use of the matrix format, while being expedient for the computer system, may be extremely wasteful in terms of storage space. As each new object or attribute is added to memory, an entire new row or column must be added to the matrix. If every dimension applies to every object, there is no waste. But if (as in human memory) most dimensions apply to only a few objects, then the matrix would soon consist almost entirely of wasted zeroes.

Green's (1963) BASEBALL was developed to answer questions regarding certain statistics related to a season of baseball games. All data was stored in a strict list format where each list contained all the information for a given single game, including items such as month, day, game serial number, teams, and scores. The system

responded to questions by first translating the question into a specifications list having a similar format to the stored lists, then matching the specifications list to the lists in memory until an answer was found. The body of this system was in the processing units which read, translated and sought answers for the questions. Because it was a heavily processor oriented system, this system was inflexible. It could not deal with large amounts of data and it could not learn to answer new questions about the old data.

Simmons' (1963) PROTOSYNTHESIS I was a very ambitious system which aimed at allowing a very wide range of questions in a question - answering machine. He stored the entire Golden Book Encyclopedia into memory. He then developed a reference system for each "content" word. A content word was defined as any word not contained in a list of junction words which consisted of words such as "the", "and", "but", "if", "for", etc. Each content word was given a list of references citing numbers for the volume, article, paragraph and sentence in which the word was found. As a question was read, its content words would be extracted and their reference lists accessed. An answer would consist of those sentences found in which all the content words occurred, i.e. the intersection of the reference lists of all the content words. While this system could, indeed, answer an amazing range of questions, it could only parrot back the sentences it held in memory. This often produced inappropriate responses to questions.

Lindsay's (1963) SAD SAM utilized a kinship graph structure to store statements and respond to questions regarding familial relationships between individuals. Most of the effort in this

study went into parsing the sentences and questions to develop a machine which could read and understand English. Because the memory storage and structure was of only secondary importance, there was a severe limitation of the kinds of facts and hence sentences which could be used. However, the program was able to utilize its memory space effectively, especially by the use of routines which could directly connect graph segments as new information was added. This eliminated inconsistency and "lost" or "misfiled" information.

Quillian (1968) developed a system which was primarily aimed at storing information in the form of definitions. In his model, each word had a "symbolic plane" on which its definition was established by linking the main word, called the "patriarch of the plane", to the various words of the definition. Each subsidiary word, in turn, could be the patriarch of its own plane. In this way, Quillian made maximal use of hierarchical ordering of nodes. The unique functions in Quillian's system were those of comparison and contrast. Although the system demonstrated considerable ability in producing correct sentences as responses, an enormous amount of encoding and processing of information was required prior to its input into the system.

Raphael (1968) combined a labelled graph structure with a logical relations processor to develop a semantic information retrieval system which he called SIR. He defined seven relationships between objects: (equals), (is part of), (is a member of the set), (is owned by), (is to the right of), (is just to the right of), and (single (x)) or "x has exactly one member". Each object was stored and paired with a property set list which contained the adjectives describing

the object. The property set also listed the relations between the object and other objects in memory in the form of relation - object pairs, e.g. (loves, wife). Furthermore, if object A had a relation to object B on its property set list, then object B would have a relation to object A on its property set list, i.e. the converse of the relation of A to B. By using properties such as transitivity, the relations processor then was used to make inferences about the relations between objects not directly related. Thus, the information:

(John is to the right of the chair)
 (Jill is to the right of John)
 (The table is to the right of Jill)

and the question:

(Is the table to the right of the chair Q)

produced an affirmative response. The SIR system is, actually, a complex list structure which simulates a graph structure, but this difference is significant only to the programmer. The use of only seven given relations puts severe limitations on the information that can be stored. There is also a limitation on the kinds of conceptual groupings available to the system.

Elliott (1965) developed a system which was similar to SIR, but considerably more powerful. His system, GRAIS, used a label - linked graph format structure. The labels or relations could be defined at will by the user. Relations were processed by GRAIS according to combinations of nine relational properties developed by Elliott. These properties are defined in Table 1 which also contains examples. Elliott noted that there are only thirty-two logically consistent combinations of these nine properties and

Table 1

Elliott's Nine Properties of Relations

In each case, R represents a binary relation between the elements x and y , i.e. if R is the relation (is larger than), then Rxy is read as x (is larger than) y .

PROPERTY	DEFINITION	EXAMPLE
p-reflexive	Rxy implies Rxx and Ryy	(is as large as)
irreflexive	Rxy implies Rxx is not true	(is larger than)
p-symmetric	$x \neq y$ and Rxy implies Ryx	(is as large as)
asymmetric	Rxy implies Ryx is untrue	(is larger than)
p-transitive	Rxy and Ryz implies Rxz	(is larger than)
one-follower	Rxy and Rxz implies $y=z$	(was sired by)
one-leader	Rxy and Rzy implies $x=z$	(sired)
noregrowth	Rxy implies no set of z_i exists such that $Rxz_1, Rz_1z_2, \dots, Rz_ny$ are all true	(immediately follows)
unlooped	Rxy implies no set of z_i exists such that $Ryz_1, Rz_1z_2, \dots, Rz_nx$ are all true	(is larger than)

GRAIS contains a set of processing algorithms for each such combination. Once the properties of the relation were specified, GRAIS used the designated algorithm set each time it needed to process a sentence involving that relation. In particular GRAIS would use these properties to eliminate redundant storage. For any given combination of properties, GRAIS could remove links between nodes which could be inferred from other bits of information in memory.

A new relation could also be defined as the converse of a relation that was already defined. For example, the relation (is north of) has the properties: irreflexive, asymmetrical, transitive and unlooped. The relation (is south of) could then be defined as the converse of (is north of). The GRAIS system would deduce its properties to be: irreflexive, asymmetrical, transitive and unlooped. A new relation could also be defined in terms of two or more other relations. Thus, (is between) could be defined by a statement like "A (is between) B and C if (A (is north of) B and A (is south of) C)". Not every newly defined relation need be a relation between two nouns. Elliott would also permit a "property" relation such as (is the largest state) or (has managerial responsibilities).

GRAIS is limited only by the lack of hierarchical nodes. In GRAIS, all group or conceptual relations could be handled only through the relations processor which required extra time and information in order to process them. However, even without the hierarchical nodes, GRAIS proved to be extremely efficient, flexible and easy to use, demonstrating the potential utility of a graph format as a memory structure.

BASIC EXPERIMENTAL PROBLEM, APPROACH AND METHOD

This study was an attempt to find a subject - task combination which would result in the use and detection of bidirectional graphs. Presumably, a subject could be identified as either an associative processor or bidirectional graph processor by his performance in a sufficiently complex problem solving task. Hayes' (1966) spy problem was chosen as a reasonable task base.

Hayes Experiment

Hayes conducted a series of experiments on human problem solving. In the experiments, the subjects were asked to learn a network of spies in which each spy could pass information on to other spies in the network. The network was presented as a connection list, such as that in Figure 3, in which each entry gives the name of a spy who can send a message followed by the name of a spy who can receive a message from that sender. The subjects' task was to get a message from a given sender, or starter, through the network to a given receiver, or target. This process can be represented as tracing a path from the starter name through connected names to the target name.

Hayes chose this problem because it had three qualities:

- ...a) the spy problems are homogeneous in that the various steps are all of the same kind and approximately the same difficulty.
- b) the information necessary for the solution of a spy

SHOWER → CLERK
 DROUGHT → HILL
 LARYNX → BETH
 ADJECTIVE → SHOWER
 HILL → HORSE
 BEEF → LARYNX
 DROUGHT → KEVIN
 SHOWER → BEEF
 LARYNX → DROUGHT
 BEEF → TAFT
 ADJECTIVE → PARCHESI

Figure 3. Hayes' Connection List

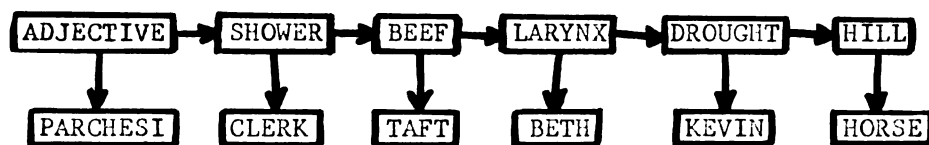


Figure 4. Graph of Hayes' Connection List

problem is contained in the connection list which is under the E's control. In most puzzles, on the other hand, the S is expected to supply information beyond that contained in the puzzle statement.

c) the spy problems are modular in that one can construct a spy problem of any length and any number of blind alleys...

In each of his six experiments, Hayes used a spy network represented by a connected list. In those of concern below, the networks were essentially a straight line set of nodes with branches of length zero, one or two nodes at each of the nodes on the line. The network given in Figure 3 is shown in Figure 4. The principal feature of these networks is that errors result in simple one step blind alleys.

The subjects showed two methods for recalling the link pairs. For the most part, the subjects seemed to use a direct access of the necessary information. By this it is meant that they simply recalled the pair they needed without any conscious effort in finding it. In fifty-five out of the 3200 steps overall, however, the subjects reverted to a list searching method, in which they vocally or subvocally recited the list until the needed pair was encountered. Reciting the list proved to be about ten times slower than the direct access method.

Hayes also found that the speed of traverse, the time required to report one step, increased as the number of steps left to go decreased. Furthermore, if intermediate goals were used, the speed accelerated to the subgoal, then dropped sharply, increasing once more as the next goal grew nearer.

Hayes explained the acceleration in terms of two planning behaviors. In local planning, the subject scans ahead one or two

steps from the node he had just vocalized before naming the next node. Subjects who used this strategy could avoid reporting many of the blind alleys. In remote planning the subject works backwards from the goal as he is solving the problem, thus preparing the end of the chain first. In a line - like network such as that in Figure 4, a subject who uses remote planning never encounters a blind alley! In a later experiment, Hayes varied the presentation format of the connection list; instead of a list of pairs, Hayes used lists in which all receivers (one or two) were given in the same entry, i.e. "Shower passes to Clerk, Deef". He found that subjects using this format took much less time to produce solutions than subjects using the simple list of pairs.

Hayes also noted that subjects tended to retrieve the two connections of a given spy in the order in which they were found on the connection list. He interpreted this as the result of some kind of unconscious list search in which the left hand column of the connection list was the list being searched. This implies, however, that the direct access process is, in fact, a list searching process and not a direct accessing at all. Thus Hayes ultimately hedged as to whether subjects were actually using direct access methods or list searching methods in their solutions to his problems.

Models of Human Memory in the Hayes Experiment

How might subjects have stored the spy network in Hayes' experiment? Hayes considered two structures which will be referred to below as the list structure and the associative structure. After these are presented, a third structure will be discussed:

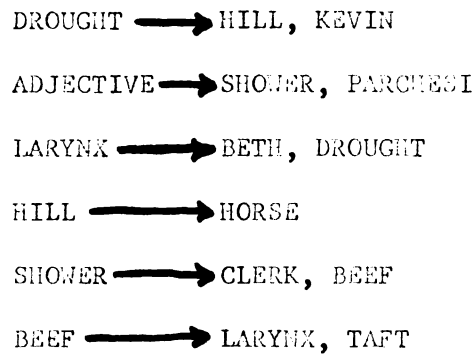


Figure 5. Hayes' Revised Connection List

the bidirectional graph.

The list structure is simply the rote memorization of the list of pairs presented by the experimenter. If information about a node is needed, the person using the list structure must scan the list from the beginning until the node is encountered. Suppose the subject had memorized the list shown in Figure 5 and was then asked to get a message from "Shower" to "Horse". Before encountering Shower on the list, the subject would encounter four other nodes. Furthermore, Shower occurs as a receiver in this entry rather than as a sender. Thus the subject must recognize the fact that the first entry is irrelevant and look for another listing for Shower. Finally he comes to the fourth entry (tenth name). He then obtains "Clerk" and "Beef" as possible intermediaries in the message chain.

He would select one, say Clerk, go to the top of the list, and look for an entry listing Clerk as a sender. And so on.

The preceding discussion assumed that the subject was using the local planning strategy to solve the problem. In this case the subject rejects the pair "Hill passes to Horse" when looking for Shower. However, the pair "Hill passes to Horse" might well suggest to the subject that he do some remote planning, i.e. work backwards from the target as well as forward from the starter. An important feature of the list structure is that it is as easy to work backwards as work forwards.

An associative structure assumes that the information is stored so that the nodes in the left hand column of Figure 5 can be directly accessed. That is, using an associative structure, the subject can obtain Shower's receivers, Clerk and Beef, without any recourse to searching a list. Introspectively, the receivers would simply be "elicited" by an internal reference to Shower. Given the problem "Shower to Horse", the subject would consider Shower and immediately be given Clerk and Beef. If he chooses to follow up Beef, then he is immediately given Taft and Larynx. And so on. If he chooses to follow up Clerk (a case not considered by Hayes), then there would be no association. If the subject is confident that he has learned the list, then he can infer the fact that Clerk cannot send a message to anyone (if he believes it) and can then reject Clerk for Beef. Thus a subject who uses an associative structure to store the network can execute the local planning strategy in a fraction of the time taken by a subject using the list structure.

On the other hand, a subject who uses an associative structure would not be "forced" to consider remote planning by being presented with an entry in which the target is a receiver. Furthermore, if the subject wished to try remote planning, then his "direct access" would not be functional since it is the sender who is unknown. Thus should the subject wish to know who passes to Horse, the associative processor would have to access spy after spy until the node Hill was accessed (since Hill passes to Horse). The associative processor would have no information available with which to locate the needed spy any more quickly than a random search would allow, i.e. no more quickly than scanning the list structure. Thus an associative processor is much faster working forward than it is working backward.

It is important to note that an associative structure is a graph, a unidirectional graph. Each spy would be represented as a node and the arrow from sender to receiver would be stored as an associative bond eliciting the receiver. Furthermore generating a chain of responses is precisely analogous to travelling a path from node to node in a graph.

However this graph structure lacks an important feature of visually drawn graphs. A visually drawn graph can be processed in either direction with equal ease. Thus in a very real sense a visually drawn graph is "bidirectional" and the arrowhead can be thought of as an orientation to a two way link. Can a subject store the spy network as a bidirectional graph? Certainly; the list structure is a bidirectional graph! Any pair is read as a pair and the information can be used backward as easily as forward, the arrow simply serves to label the link between spies as one way or the other.

The central question of the present study can now be stated: Can the subject store the network as a bidirectional graph with direct access? If so, then the subject is using a structure that is directly analagous to searching a visual image of the graph. This thesis began with the hypothesis that this was so and the goal of the empirical study was to find a set of conditions that would induce the subject to store the network as such a graph. For that reason the phrase "bidirectional graph" will be reserved for the case of direct access. A subject who could use a bidirectional graph to store the network could use the local planning strategy as rapidly as a subject using an associative structure. However with a bidirectional graph, remote planning would be as easy as local planning since working backward is as easy as working forward.

Differentiating Structures: the Experimental Tasks

Once the data is stored by the subject, it becomes necessary to obtain some observable measure of the form of his internal storage. By having him solve tasks using the data, the experimenter forces the subject to utilize his storage and retrieval system. By measuring the time required to solve the various tasks and report the solutions, some inferences may be made regarding the form of the subject's storage and processing system. Four such tasks were selected for use in this experiment on the basis of their individual characteristics. These tasks are the forward trace, the reverse trace, the lowest common superior without direct contact, and the elimination of unnecessary nodes.

The forward trace is the traversing of the network from a

given starting node to a given target node. The subject is required to name, in order, the nodes through which the path must go in order to reach the target node. This task provides evidence that the information contained in the network has been stored. In addition, it provides a response time base line for the other tasks. As stated before, both the associative processor and the bidirectional graph processor would access the nodes in the forward direction with the same processis and hence with equal speed. Either would be much faster than a list searcher.

The reverse trace task is defined by asking the subject how to get a message to B from A in that order, i.e. to traverse the network from a target node to a source node and work only backwards. Thus, if A passes to B, a reverse trace would move from B to A. In a spy network, this is the same as finding how a message got to one member from another by examining the source of the message at each step, beginning at the end of the line, until the original source of the message is encountered. If the subject is not "cheating", that is forward tracing from the source node to the target node and reciting the path in reverse order, then he must move step by step in a backwards direction. This poses no problem for the bidirectional graph processor or for the list searcher since they travel backwards through the network as easily as they travel forwards. The associative processor, however, is forced to use the list processor technique of choosing node after node in search of the node linked to the present node for each step of the path. As a result, it is hypothesized that compared to the processing times for forward traces, there will be a sharp rise in processing time on the reverse trace

for associative processors, and no change in processing time on the reverse trace for bidirectional graph processors or list searchers.

If it were possible to have the same subject learn three networks using each of the three structures, then his pattern of times on forward and reverse trace problems would be long - long for list, short - long for associative, and short - short for the bidirectional graph. Thus within a subject, it is easy to differentiate between structures. However, across subjects, the words "short" and "long" reveal their relative character. A subject who uses an associative structure is distinguished by the fact that his performance on the reverse trace task is much poorer than his performance on the forward trace task. A subject whose time was the same forward and backward could be using either a list structure or a bidirectional graph. (Of course those who trust introspective data could always ask the subject which he used.)

There should also be a qualitative difference in the entries in the backwards trace recited by the subject. The bidirectional processor is aware of branches in the reverse direction, i.e. nodes where the spy can receive messages from two or more senders. Thus a subject who uses a bidirectional graph could escape being stuck in a closed circular path. The associative processor, however, is aware of only one backward link at a time and can overlook the branch needed to avoid the cycle. Furthermore, the subject using a list structure is also limited to seeing only one backward fork of the branch at a time. Thus the presence of cycles in the protocol of a reverse trace would also distinguish a list structure from a bidirectional graph.

The "lowest common superior without direct contact" task is, as the length of its name implies, the most difficult of the four tasks to explain. Recall that each node in the network passes to other nodes and is passed to by other nodes. For the purpose of this experiment a node, A, is considered to be superior to another node, B, if node A passes to node B. Furthermore, if node A is superior to node B, and node B is superior to node C, then node A is also superior to node C. A node has direct contact with another node if they are linked; a node is a common superior to two other nodes if it is superior to both nodes. The least common superior without direct contact is that node which is linked indirectly to the two given target nodes using the smallest possible number of links. In a family network, if we choose first cousins as the two target nodes, we find that the sibling parents of the cousins are superior but neither is a common superior. The common great-grandparents of the cousins are common superiors without direct contact, but the common grandparents are the lowest common superiors without direct contact. In a spy network, the lowest common superior without direct contact is that person who can most easily transmit information to the two given members of the network while not being in direct contact with either of them. This task has the advantage of requiring that its solution involves either a reverse trace procedure or an extensive and complicated trial and error approach. The "cheating" mentioned in the reverse trace task is prevented by the fact that the "source" node is unknown, and is, in fact, the object of the search. The subject could track the two reverse trace paths from the given target nodes to locate an intersection point (the solution).

Or the subject could use trial and error, i.e. choose nodes one by one, forward trace to each of the target nodes while counting the number of steps taken, compare the total steps taken from the current test node to the number of steps taken from the previous test node, choose the smaller of these, store it for comparison with the next test node, and continue until all of the nodes have been tried. It was hoped that the trial and error procedure would be so horrible as to coerce the subject into seeking a better method.

By requiring a reverse trace as the only simple alternative, this task should also show a faster time to solution for a bidirectional graph processor than for an associative processor. In addition, the need to retain more information to keep one's place in the reverse traces from both target nodes would seem likely to cause more interference with an associative processor, since he must go through more steps to perform a reverse trace than would a bidirectional graph processor.

The "elimination of unnecessary nodes" task consists of the identification of the nodes in the network which can be removed without impairing the communications between the remaining nodes. In the networks used in the present study every spy could ultimately get a message to every other spy. The subjects' task was to find any spy who could be removed from the network without impairing the capacity of the network for total communication. How can such a spy be characterized? Consider a test case as a sender and look at his receivers. If he is the only sender for any of his receivers, then he cannot be eliminated from the network. Thus an eliminable spy must be a second sender for each of his receivers. Now consider

the test case as a receiver and look at his senders. If he is the only receiver for one of his senders, then he cannot be eliminated from the network. Thus an eliminable spy must be a second receiver for each of his senders. Thus the potentially eliminable spies could be found by either working forward from spies with two receivers or by working backward from spies with two senders. In the networks used in the present study, any spy who satisfied both requirements could be eliminated. Obviously, being able to readily count the number of links from other nodes is of enormous benefit in solving this task. Therefore the bidirectional graph processor should be much faster than a subject using either of the other structures.

THE PILOT STUDIES

Basic Strategy

The subject was given four problems. In each problem he learned a spy network whose structure was identical to the structure in Figure 6. In the first problem the spy names were one digit numbers, in the second the names were letters, in the third they were colors, and in the fourth problem they were ordinary first names. Each problem session began with the presentation of a network which the subject was asked to learn.

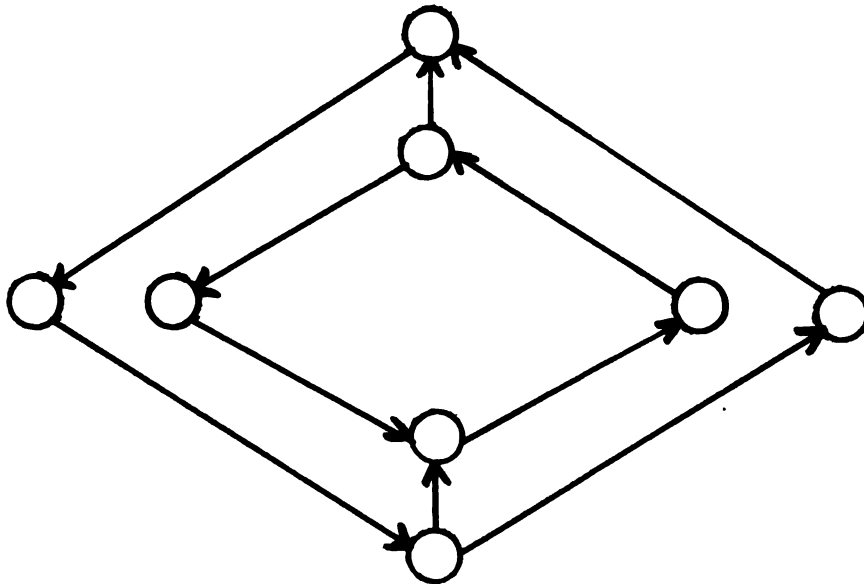
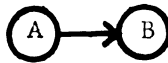


Figure 6. Eight Node Spy Network

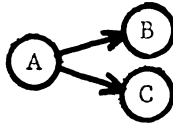
The association:



was presented as the sentence:

A passes to B.

Similarly, the association:



was presented as the sentence:

A passes to B, C.

The network was defined by a set of such sentences, or entries, where each spy in the network had one entry in which he was listed as a sender followed by the name or names of his receivers.

For reasons which seemed plausible at the time, two formats were used in the presentation of the network information. In the "isolated entry" format, the subject was given an apparatus which restricted the subject's view of the information to one entry at a time. In the "bunched" format, all of the entries were presented at once on less than one half of a standard three-by-five index card. The two formats were alternated, each format being used for two of the four problems.

At the conclusion of the final problem session, the subject was given a brief interview to determine his method of storing and using the network information.

Pilot Studies

The subject was given instructions similar to those below:

The information which will be presented to you will describe a spy network. Each of the spies in the network will have a code name and will be able to pass a message on to one or more other spies in the network. The information,

then, consists of the names of the spies and the names of the spies each one can pass a message to. For two spies, X and Y, the information might be, "X passes to Y," which means that spy X can give a message to spy Y but not that spy Y can give a message to spy X. In other words, messages can only go one way in the spy network. You are asked to memorize each network. When you have memorized a network, you will be asked several questions about the network, after which we will go on to the next one.

The subject was then given the information to study until he "knew the network". The learning test was a paired association task. The subject was given the senders in a random order and instructed to name the receivers of each in turn. The learning criterion was the subject's ability to errorlessly name all the receivers three consecutive times. After learning the network, the subject was then given the four experimental tasks.

The First Pilot Study

Subject A had very little trouble in performing the forward and reverse trace tasks, but had great difficulty in solving the other two tasks. In doing the forward traces, the subject went from node to node until a branch was encountered. According to her report, she then checked ahead two steps on one of the branches. If the end was not then readily reached, she tried the other branch. Thus, the subject used forward scanning only when she reached a branch.

The reverse traces were handled similarly, but the use of forward scanning to follow only correct branches was not reported.

The lowest common superior task seemed to present enormous difficulties. In the first two problems, the subject was unable to find a correct solution. In the last two problems, the subject resorted to the trial and error method, selecting a node at random

and testing its link sets to see if the target nodes were reached quickly. The elimination of unnecessary nodes also proved difficult. The subject failed to find a correct response in the first problem, and offered many incorrect responses in the second and third problems. Finally, she used a process of extensive checking and rechecking of each answer before making a response.

The interview which followed the experiment focussed on the presence or absence of some cognitive structure representing any or all of the spy networks used, since such a structure seemed to be a critical factor in determining the presence of bidirectional graph processing. Subject A reported no such structure, showing surprise at the fact that all four networks had used the same structure. Some additional questions were asked concerning the processes involved in solving the tasks, but several difficulties encountered in the experimental method combined with the absence of cognitive structures, hence the apparent lack of bidirectional graph processing, tended to reduce the experimenter's interest in this subject. Consequently, little additional information was gathered.

Subject B spent a great deal of time trying to develop a mnemonic memory system to learn the networks. As a result, the learning periods were longer than for the first subject. This subject reported finding the "isolated entry" format easier to memorize than the "bunched" format and the words used as spy names easier to recall than letters and numbers. In the forward trace tasks, the second subject went from node to node, occasionally reciting the whole network in order to locate the "next" node. If a branch was

encountered, the subject mentally traced ahead several steps on each branch before choosing which branch to take.

The subject performed the reverse trace task one step at a time, becoming stuck in a four step cycle at one point by not recalling an alternative branch. After several cycles the subject did realize that the other branch existed and quickly finished the trace.

In the lowest common superior task, the subject generally reverse traced one step from each of the target nodes, then turned to trial and error to seek a node which could quickly reach the two given target nodes. In the second problem, however, the subject misunderstood the directions and sought the alphabetically lowest node which was superior to both of the target nodes. This confusion was subsequently cleared up. The elimination tasks proved too complicated in the first two problems. In the last two problems she resorted to the trial and error process, looking for spies whose receivers could receive from other senders. This process seemed to be very confusing, and she made many incorrect responses.

Once again the interview was aimed at revealing the presence of cognitive structures representing the spy networks, and again such structures could not be found. Subject B was unable to clarify any of the processes she used to solve tasks and both she and the experimenter were tired after the two hours required to run the experiment. As a result, the interview session was again terminated without having revealed much additional information.

Several difficulties with this experimental method seemed readily apparent. Subjects found the tasks to be more complicated

and difficult than had been anticipated by the experimenter. Furthermore, the time required to run a single subject through the entire experiment ranged from over one hour to a little over two hours. This led to noticeable fatigue on the subject's part by the third or fourth problem. These two difficulties were somewhat disheartening for the experimenter as well.

Another problem was that of coping with incorrect responses to a task. It appeared as though the subject could not only forget some relationships, but create new ones as well. In an effort to curb this tendency, the subject was permitted to refer occasionally to the information card, but continuous use of the card was strongly discouraged. This gave rise to a dependency on the use of the card on the part of the subject which no amount of discouragement seemed able to remove.

The Second Pilot Study

The memory network used was again the eight node network in Figure 6. In order to reduce the running time of the experiment, the subject was given only two problems instead of four. The sets of node labels used were the color and name sets, since these seemed to be the easiest of the four to work with. The isolated format card apparatus was eliminated and the subject was simply given the card itself. The subject was given much the same instructions as in the first pilot; in addition, the four tasks were described and explained to the subject prior to the first network. This was done to reduce the confusion involved in trying to learn a new task while simultaneously trying to retain the memorized network. It was also

expected that the subject would now be able to retain the network in memory with sufficient accuracy so as to eliminate errors. The criterion for a learned network was again that the subject recall without error all the links from randomly selected nodes until each node had appeared three times. Any hesitation or confusion was, in this pilot, taken as an error in an effort to insure clear memory of the network.

Once again, after the subject had learned the network, the four tasks were presented and the time to solution recorded. The subject was not permitted to use the information cards in the tasks.

Subject C performed the forward trace tasks with ease. He reported checking ahead silently prior to making a response to avoid taking wrong branches. In the reverse trace tasks, the subject gave no such report and appeared to be performing the trace from one node to the next methodically with no checking ahead. This process gave no trouble in the first problem, but resulted in his getting stuck in a cycle in the second problem.

The subject attempted to solve the lowest common superior task without using any reverse tracing in the first problem, and consequently became so confused that the task was terminated before a solution was found. He was then able to solve same task for the second problem, but the use of reverse tracing was neither reported by him nor observed by the experimenter. In the elimination task, the subject decided that the removable spies must be among the four receivers who occurred in pairs. He then randomly picked two names as solutions which turned out to be correct in the first problem, but not in the second.

Upon being asked, Subject C reported no visual image or any other sort of cognitive structure. He strictly denied having thought of the network in terms of a graph, but showed an interest in the idea. The interview session then degressed to a discussion of the concepts involved and no further information was obtained.

Subject D performed the forward trace task step by step, working one step at a time without checking ahead. He also delayed his responses until he had completed the entire trace, forcing him to retain the entire trace in memory. In the reverse trace task, the subject reported trying to solve the trace from both ends towards the middle, which resulted in much confusion and forgetting of the network information.

In the lowest common superior task, the subject used simultaneous reverse traces, but again became very confused, failing to solve the task in one problem and giving several incorrect responses before solving it in the other problem. The subject used the trial and error method to solve the elimination tasks. He again tried to retain all results before responding, resulting in incorrect responses.

Again, the interview session showed no indication of cognitive structures and yielded no additional information concerning the manner in which Subject D did store the network information. Additional questioning about the experimental procedure failed to produce any helpful suggestions.

Several problems still remained in this experimental procedure. The recall of the subject was not one hundred per cent accurate, resulting in verbal errors as the subject reported the process and solution for a task. In the event that a clear error was made, the

experimenter attempted to correct the mistake verbally. This approach, however, was completely unworkable for several reasons such as experimenter interaction in the process, communication time during a timed interval and misunderstood messages on both the subject's and experimenter's parts. However it did prove useful for the experimenter to state whether a solution offered was correct or incorrect. In several such cases, the subject returned immediately to processing and presently returned the correct solution to the task.

The lowest common superior task was still found to be quite difficult, partially due to the fact that several subjects had either misunderstood or misinterpreted the task. More time was spent in making certain that the subject was clear about the nature of this task thereafter. This task still seemed to present great difficulty, having the longest times and greatest number of incorrect responses of all the tasks.

The apparent difficulty of the tasks still resulted in subjects who failed to solve one or more tasks. Therefore, the complexity of the experiment was reduced for the next pilot study.

The Third Pilot Study

The memory network used was the six node network shown in Figure 7. This network is a smaller version of the eight node network used before, but has much the same properties. It was hoped that this reduction in network size would result in less difficulty for the subject in terms of accurate recall. Each subject was given two networks using the letter and the number sets of node labels. These sets were thought to be more abstract than the name and color sets and thus possibly a lesser source of connotative effects on the

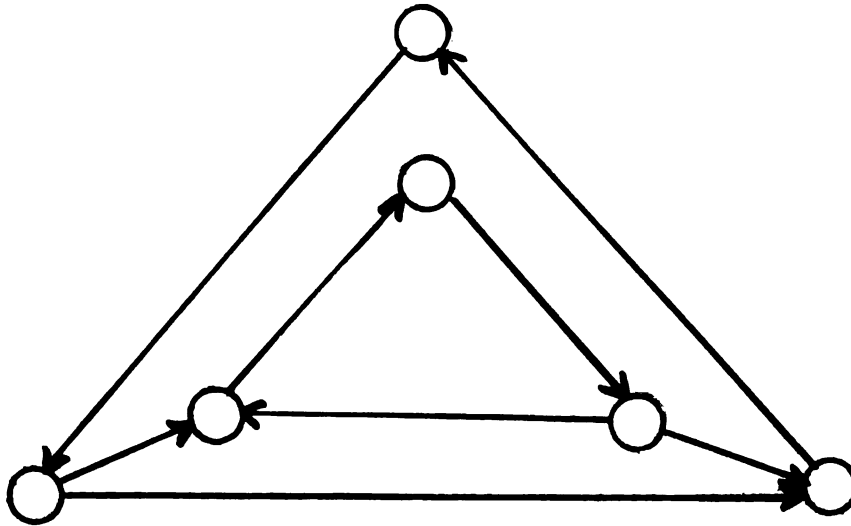


Figure 7. Six Node Spy Network

response time. The isolated entry card was given without the envelope to permit open scanning during the learning periods. The subject was instructed to recite the information out loud during the learning period in hopes of increasing the accuracy of storage and recall by giving the subject muscular and auditory memories of the networks in addition to the visual memory.

The criterion for learning was, again, three consecutive errorless recalls of the entire network in random order. The subject was again tested and timed on all four tasks. To augment the learning procedure during the task phase of the experiment, a review period of thirty seconds duration was made available to the subject upon request. During this period, the subject was given the learning card. If the subject was in the process of solving a task, then the response

timer was stopped.

Two tasks were altered slightly for this network. The lowest common superior task no longer had a unique solution, so either of the two correct responses were accepted. The elimination of unnecessary nodes task was changed so that a node was given to have been eliminated and the task was then to determine the two other nodes which could also be removed and still leave a completely connected network.

Subject E solved the forward trace tasks quickly, giving no indication of checking ahead, yet never taking an incorrect path. She managed to quickly solve the reverse trace in the first problem by working from both ends towards the middle. In the second problem, however, she became confused and was forced to start over, at which point she worked only in the backwards, or reverse, direction. The lowest common superior task and the elimination task were both very quickly and accurately solved.

Subject E was so fast in her performance that it was thought she might prove to be a sought after bidirectional graph processor. In the interview session she was repeatedly questioned concerning the presence of some cognitive analogue of a bidirectional graph structure, but to no avail. No structure of any kind could be reported, and the interview session was terminated. The absence of structure, thought necessary for bidirectional graph processing, was a disappointment. All tasks were done so rapidly that the processes used were not seen.

Subject F requested the use of the learning card many times throughout the performances of the tasks. The apparent lack of retention of the material resulted in confusion and erroneous responses in the first presentation. Better retention in the second presentation

reduced both the confusion and the errors. The subject seemed unable to perform the forward trace tasks without the learning card. He then went from one node to the next without checking ahead. The recall of information from memory made the reverse trace time shorter in the second problem. Local planning was not used in either problem. The same marked improvement was shown in both the lowest common superior task and the elimination task, but the processes used remained unchanged. He used a reverse trace approach to the lowest common superior tasks and forward traces on the elimination tasks. Again, no internal structure was reported during the interview.

It seemed clear that neither subject had used a bidirectional graph in this pilot study. Furthermore, the available information regarding the processes used had diminished. The attempts to provide a workable problem set seemed only to lead to a less effective set of results. In addition, the subject seemed to grow dependent on the review card as the experiment progressed. It was decided that the thirty second period was both awkward and ineffective and hence was abandoned. The need for checking and/or review seemed present however, so an alternative was used in the fourth pilot study.

The Fourth Pilot Study

The memory network used was the six node network used in the third pilot study and shown in Figure 7. Each subject was given two networks using the color and the name sets of node labels. These label sets were used to contrast with the label sets in the third pilot study. The isolated entry card was given without the envelope and the subject was asked to recite the information out loud.

The criterion for learning remained the same and each subject

was tested and timed on all four tasks. This time, however, the subject was allowed to retain a review card. This card was similar to the isolated format card, but the entries were spaced more closely together and thus similar to the bunched format card. The subject was permitted to refer to this card at any time. It was felt that the format of this review card would not have much effect upon the structure already stored in memory as long as the subject drew primarily or even largely from memory when accessing information. To this end, the subjects were asked to use the card as little as possible.

Subject G relied heavily on the card and generally seemed unable, or unwilling, to develop any procedures other than trial and error to solve the tasks. She did not check ahead in either the forward or reverse traces and the fact that the entire set of entries was forward links seemed to confuse her performance on the reverse trace task. The subject used trial and error with a great deal of rechecking and reworking in both the lowest common superior task and the elimination task. The major portions of these processes were performed silently and thus not open to observation by the experimenter. The subject reported no internal structure of any kind.

Subject H had better retention of the material and performed the forward trace tasks quickly, using the card only for confirmation. No process was observable at the speed at which this task was performed. The subject experienced some trouble working backwards in the reverse trace tasks, particularly at the branches. The persistent use of the card in this task seemed to add to this trouble. In the lowest common superior tasks, he used a trial and error approach

and became confused upon finding two solutions. In the elimination tasks, he picked two nodes connected to the given node and eliminated all three to see if the resulting network was connected. If not, another pair of nodes was chosen. This method produced quick results in the first presentation and much slower results in the second due to the accuracy of the choice of the first pair. No structure or image was reported by the subject at the end of the experiment.

The dependency which developed on the review cards was very strong. It was so strong, in fact, that one subject was unable to readily access any network information from memory when the card was removed. After a moment the information could be accessed only with some effort, implying that the subject was not using the memory storage during the task phase. Given a choice between accessing from memory and accessing from a card, the subjects invariably chose the card. No suggestion from the experimenter appeared capable of enticing the subject to use the card only for reference and not as a primary source of information.

The Fifth Pilot Study

It had become clear that some serious revision in the experiment was needed. A major difficulty was in the reluctance of the subject to rely on memory and the reluctance of the experimenter to structure, via a single card, the memory and perhaps even the processing mode of the subject. The entire learning procedure was revised in an effort to resolve this conflict.

The spy network used was the original eight node network shown in Figure 6. This time, however, the information was presented on cards, with each entry occupying one card. The subject was given

the cards and introduced to the spy network and the tasks to be performed in the same manner as in earlier pilot studies. In addition, the subject was instructed to hold the cards in a stacked manner, so that only one card could be read at a time, and, in the process of the experiment, to feel free to reorder the cards in any desired manner.

Only one problem was given and only one node label set, the names set, was used due to an anticipated long running time for each trial. The subjects were then given a series of twenty-four forward trace tasks one after the other. The last three of every eight of these were timed. The subjects were then tested and timed on all four tasks used in the earlier pilot studies. As a post test, the subjects were shown an unlabeled diagram of the network and asked to fill in the proper labels from memory, i.e. without using the cards.

By presenting the information on separate cards, it was hoped that the subjects would find it preferable to use their memory rather than search manually through a stack of cards. By allowing the subjects to reorder the cards, it was hoped that the subjects would attempt to develop their own storage structure, either physically on the cards or mentally. The long and tedious series of forward trace tasks was given as further incentive to develop a structure and commit the information to memory. Repeated timing of tasks was used as a further reminder that speed was important, hence a pressure to develop an efficient retrieval system. In general then, it was hoped that this procedure would allow and impel the subject to utilize a storage technique, which could then be measured by the ordering of cards and response time on tasks. The post test would

then give some indication of the extent to which the subject had memorized the network.

Subject I sorted the cards by gender, male names in front and female names in back. As a result, she was forced to do an extensive amount of searching in order to perform forward and reverse trace tasks. In both of these tasks, she did not check ahead and lost her place several times, thus having to start over again. In the lowest common superior task, she made a hasty and incorrect guess then went backwards one step from the given spies. She then searched through her cards for a sender who sent to both of the new spies named. To solve the elimination tasks, she made a search for spies whose receivers had alternate senders and could thus be bypassed. No internal structure was reported, nor was any structure observable in her sorting of the cards except the irrelevant gender distinction.

Subject J had fairly good retention of the material and was able to quickly perform the forward trace task, reportedly checking ahead only one step at a time. It was believed that the subject may have actually checked farther ahead than this, since incorrect branches were never followed. She had great difficulty solving the reverse trace task, tending to reverse the orders of the entries and confusing the direction of the links. She could not explain the process used to perform the lowest common superior task (and indeed she could not solve the task). She hastily gave an incorrect response to the elimination task and then spent a long time double checking her next answer, the correct one, before stating it. Her process in this task was too unclear for her to explain. She reported no internal structures and since she never bothered to

reorder the cards, no conclusion could be drawn from them.

This pilot study resulted in much the same difficulty as had the earlier pilot studies. Incredibly, the subjects still maintained a nearly complete dependence on the cards. The experimental procedure was reported by the subjects to be tedious and there was difficulty in working with the cards, yet they chose to endure this rather than work with the information in memory. If the process reports held little information, the sorting techniques were useless. One subject attempted to use rote memory on the cards in the order given despite suggestions to the contrary. The other subject sorted the cards according to the gender of the first spy mentioned on each card. No list strings or proximity clusters of cards were used. The post test indicated that very little of the information had been committed to long term memory and questioning indicated that no organizational structure or system had been attempted. In general, the data produced by the subjects was inconclusive, largely due to the strength of the subjects' aversion to work with the structure in memory as long as any alternative was present.

At this point, it was decided to abandon any further attempts to revise the experimental procedure in order to develop a workable and informative experiment. Instead, it was considered to be more useful to examine the results of the five pilot studies and determine whether any conclusive information could be drawn from them.

Discussion of the Pilot Studies

Methodological Problems

At this point the results of the pilot studies appeared to be so disheartening that the experiment was actually abandoned for

a time. The very negative tone of the following discussion reflects the fact that it was written at that time.

These pilot studies brought out methodological problems present in this approach to studying the format of human memory systems. The use of a card containing the network information repeatedly led the subject to depend almost entirely on the card, removing the need to memorize information. This behavior can only confuse the data by increasing the effect of the organization of the card itself and by injecting the possibility of some complex serial or even parallel visual processing system. If such a visual system does not exist and no information is retained in memory, then the subject can have no direct accessing of information and should conform to the list processing model. Since the subjects in this study did not conform to this model, there must have been some memory and visual process interaction, but the nature and extent of this interaction cannot be precisely determined.

Response errors, resulting in missing data, were both awkward to handle and hard to avoid. Such errors are thought to be either the result of a misunderstanding of the task involved or of an error in the internal network being used by the subject. The former error was readily remedied through the use of more explicit and complete instructions. The latter error, however, could not be dealt with so easily. If the subject had accurately retained the network in memory, but had randomly erred in the retrieval of the information at some stage of solving the task, then a second attempt at solution would likely be successful. However, the interference posed by the interaction between the stored network and the new learning

resulting from the examination and mental repetition of the error involved became highly significant and awkward to deal with. The experimenter could review the network in order to find the error, but the subject would then be likely to be processing the information to solve the task during the review. The response time data would then have to subtract that portion of the review time not used in solving the task, a piece of information not available to observation. A more difficult problem yet would exist if the retrieval error was a systematic one and likely to occur again, for in that case, the error would be reinforced by the repetition! Finally, the subject's awareness of an error in his stored network would reduce the confidence of the subject in his ability to accurately solve further tasks, and increase his tendency to rely on the original information card given to him.

Fatigue also appeared to have an influence on the subject. There seemed to be a limit to the amount of time the subject could or would spend on the experiment without exhibiting signs of restlessness or inattention. The total time which could be spent without excessive subject fatigue was limited to approximately seventy minutes, the first thirty minutes being without noticeable tiring of the subject. Thus, a learning period of fifteen minutes made the use of four networks quite difficult, yet such a learning period seemed not long enough for effective learning to take place. Thus, the later pilot studies used two, and then finally only one network, in an attempt to increase the time spent in the learning phase of the experiment, in hopes of eliminating the occurrence of errors.

In retrospect, a more effective, and perhaps even more entertaining learning procedure might be to give the subject an information

card and have him perform a single task, such as the elimination task, then begin a paired associate training period and, finally, present him with a series of tasks so that each of the four types of tasks will be replicated. Giving a task first could enhance the learning process by giving the subject some incentive to learn the network in order to handle future tasks. Varying the subsequent tasks might hold the subject's interest in the experiment. It should be noted that the subjects did show improvement in terms of solving the various tasks, which tends to give support to the procedure outlined above. Finally, the use of replications of tasks within the same network could serve to provide a means for dealing with errors, i.e. ignore them. This would reduce the need for the ever - present information card and might result in the elimination of the card dependency problem.

At the conclusion of each set of networks, the subjects were questioned in an effort to determine what kind of structure, or image, of the networks each subject had developed in the course of the experiment. In not one of the subjects was any kind of awareness of structure of any of the networks observed. Not only were no visual images developed, but subjects presented with Figure 6 expressed surprise that the same graph applied to all networks. Further, one subject was unable to fill in a blank network where the links were given but the node names left blank. This is not the response expected of a bidirectional processor.

Throughout this series of pilot studies, the goal was to find a subject - task combination which would exhibit the behaviors expected of a bidirectional graph processor. This bias resulted

in some errors in terms of the experimental procedure. The worst procedure error occurred in the question period which followed each set of networks for a given subject. The questions focussed solely on the presence or absence of a cognitive structure representing any or all of the networks. In so doing, and by displaying Figure 6 and discussing the format concept, the subjects were so distracted from the experiment that they did not volunteer information regarding their own approach to the experiment and its tasks. This information would have been most valuable in understanding the means by which the subject did manipulate the network information. Thus the interview yielded little information to determine the process used by the subjects or the extent to which the card dependency noted earlier interfered with those processes.

There were several indications showing a difference in approach to the forward and reverse trace tasks. First, the subjects rarely took the wrong branch in a forward trace task, but often became stuck in cycles in the reverse trace task. The only means by which a subject could avoid taking incorrect branches would be by tracing ahead of the present position and "checking out" the path ahead of the present point of development of the trace. The subjects then were checking ahead in forward trace tasks, but not in reverse trace tasks. This is precisely the kind of behavior to be expected of associative, or unidirectional graph, processors but not of bidirectional graph processors. Second, most of the subjects were much faster on the forward trace tasks than on the reverse trace tasks. They were slower yet on the lowest common superior tasks. This again suggests an associative processor rather than a

bidirectional graph processor.

Third, the subjects showed considerable difficulty if they attempted to perform both forward and reverse traces to solve a single task. A bidirectional graph processor would show no such effects. To an associative processor however, these represent two very different processes requiring the use of different accessing schemes and "bookkeeping" systems. Thus an associative processor might well exhibit the confusion reported by the subjects.

At this point, then, it seemed logical to conclude that bidirectional graph processors did not, in fact, exist and that such a format was not natural for human memory systems. Indeed this was the conclusion drawn at the time and is still is thought to be true of all but one pilot subject.

The Temporal Data and a Reevaluation

During the black hour when the experiment had been abandoned, the pilot studies were carefully written up and the above evaluative conclusions were drawn. In the process of tightening up the presentation for a final draft, the data were given a "final" long hard look. In particular, the times for each subject on each task were examined in detail. These latencies are presented in Table 2.

An embarrassing event occurred at this point. The data for the first subject of pilot one, which had been overlooked as a result of the extensive methodological difficulties encountered, was given closer inspection. Incredibly, the response times for forward and reverse traces were about equal, as expected of list processors and bidirectional graph processors. In addition, the times were also very fast, as low as thirteen seconds for a reverse trace; thus the

Table 2
Seconds to Response for the Pilot Subjects

TASK	TRIAL	S U B J E C T S									
		A	B	C	D	E	F	G	H	I	J
Forward	1	58	178	32	36	08	101	47	15	55	17
Trace	2	37	39	40	48	10	243	38	09	*	*
	3	21	12	*	*	*	*	*	*	*	*
	4	18	21	*	*	*	*	*	*	*	*
Lowest	1		58	210+	125	38	114	190	150	150	165+
Common	2	260+	348	197	163+	10	34	155	180	*	*
Superior	3	117	48	*	*	*	*	*	*	*	*
	4	95	55	*	*	*	*	*	*	*	*
Reverse	1	50	100	26	180	26	214	113	100	150	180+
Trace	2	34	20	181	132	82	38	65	105	*	*
	3	13	125	*	*	*	*	*	*	*	*
	4	13	54	*	*	*	*	*	*	*	*
Removal	1	120+	240+	10	105	16	390+	87	49	110	80
(Elimin- ation)	2	152	180+	141	117	12	40	95	114	*	*
	3	276	210	*	*	*	*	*	*	*	*
	4	81	267	*	*	*	*	*	*	*	*

* Subjects not given further trials.

relative response pattern was short - short. By all previous criteria, this had to be data from a bidirectional graph processor! Yet it was equally clear that this subject did not have an internal visual image, nor did she report any conscious structure of any kind!

At this point an exacting reevaluation of the first pilot study was made. An examination of the latencies for subjects A and B in Table 2 shows that there was indeed considerable fumbling on the part of both subjects and some rather erratic times as well. However, most of this actually washed out in the first two problems. The data for the third and fourth problems are clean and stable. Were subjects A and B really as "tired" and "fatigued" as had been assumed at the time? Perhaps not. Perhaps what appeared to the experimenter as fatigue was really a lack of animation and expression. And perhaps the lack of exterior expression simply reflected that the subjects were completely focussed on maintaining rapid, efficient, and complicated interior processing!

So it was that at the eleventh hour, with the "abandoned" experiment already written up, the decision was made to revise and pursue the first pilot study.

THE MAIN EXPERIMENT

The following text is concerned with the experiment conducted following the pilot studies. It will consist of a description of the procedure used in the experiment and a description of the responses and approaches used by the subjects tested. The succeeding chapters will contain revisions of the models of human memory along with the conclusions drawn from them.

Method

For the main experiment, an approach similar to the first pilot study was used. Each subject was given four problems, each problem utilizing the same geometric network but with different names for the spies. This was the eight node network used in the first pilot study and shown in Figure 6. In this way, the subjects had time to adjust to the experiment. Prior to the first problem, the subject was told the task set and had each task explained to him until he understood it. For each problem thereafter, he was given the card containing the network information and asked to memorize it. When he felt confident that he had memorized the information, the experimenter began a paired associate testing session during which the subject had to give the receiver or receivers for randomly chosen spies named by the experimenter. This session ended when the subject had given errorless responses for all of the spy names for a total of three consecutive times. The subject was then given

the task set.

The task set now consisted of a forward trace task involving all eight nodes, a forward trace task involving only six nodes, a lowest common superior task, a reverse trace task involving all eight nodes, a reverse trace task involving six nodes, and the elimination of unnecessary nodes task. The protocols were recorded, as was the response time for each task and the total time required for each problem, including memorization and testing time.

The procedures and performances on the lowest common superior task and the eliminations task seemed to be of little value in terms of determining the internal structure of the memory in the pilot studies. The primary purpose in retaining these tasks was to space apart the forward and reverse trace tasks. Also it was feared that removing these tasks might produce very different results for some unknown reason pertaining to the adjustment to the experiment over problems. For these reasons, the discussions of the subjects' treatments of the lowest common superior task and the elimination task will not be included unless some aspect of the data appears directly relevant to the determination of internal structure.

At the conclusion of the fourth and last problem, the subject was "de-briefed" in an extensive interview period. During this period, the subject was asked many questions in order to determine the presence or absence of internal visual structures or analogues thereof, the presence of conscious storage formats of any other kind, the process used to memorize the information, the processes used in solving the tasks, including the method used for retrieval of information in forward and reverse directions, and the means

used to avoid or break out of forward and reverse trace cycles, and finally, any other information or comments which the subjects wished to volunteer.

Subjects

A total of nine subjects were used, at which point enough data had been collected to serve as the basis for a new set of models of human memory storage.

All of the subjects were from eighteen to thirty years of age. Two were undergraduates at Michigan State University, one a graduate student's wife and the remaining six subjects were graduate students at Michigan State University. Of these, the data for both undergraduates and one graduate is questionable, to varying degrees, as these subjects failed to complete all four problems of the experiment.

Results

Subject 1 was a male undergraduate. He showed great difficulty in memorizing the information and reported that he usually had difficulty in rote learning. During the testing sessions, he would seem to have all of the information correctly stored, then he would forget some entries and reverse directions on others, prolonging the testing sessions extensively. He reported using mnemonics, addition tricks and other memorization gimmicks to aid him, but they seemed to the experimenter to produce interference rather than act as learning aids. In general, the devices he used were all purely associative, i.e. they connected two spy names but gave no hint as to the direction in which the messages were passed. Consequently,

his protocol had repeated uses of reversed links which had to be corrected by the experimenter.

The subject performed forward trace tasks methodically, proceeding one step at a time until a branch was reached. He would then choose one branch until it reached a spy already named or the end of the trace. In the first two problems, his response times were fairly good, but increased sharply in the third problem. This was apparently due to the fact that the subject had, in the third problem, tried to prepare for the reverse trace tasks during the memorization period. As a result, his recall of the forward trace links was much poorer and more error - ridden than before.

In the reverse trace tasks, the subject seemed to have two constant problems. In the first place, he repeatedly began performing forward traces in the middle of a reverse trace process, and had to be reminded to work backwards. The second difficulty was his inability to locate a branch in the backwards direction. Thus he could not find a point at which he could exit from a cycle. These two problems, combined with poor recall, resulted in quite long response times despite cues, prods and even forgotten pieces of information given to him by the experimenter. Such assistance was only provided when it was clear that the subject would be unable to solve the task without such aid.

The experiment was terminated after the third problem, since the elapsed time had already exceeded two hours and appeared likely to run on interminably.

In addition to the information presented above, the subject reported no visual image of the spy network, or any analogue thereof.

Furthermore, he stated that he had not generally stored the information in a list form, but he was unable to describe the manner in which information was stored.

Subject 2 was also a male undergraduate. He displayed an even greater inability to retain the network information than had the first subject. The first problem required forty minutes to run. After thirty minutes more, the testing session for the second problem had still not been concluded and looked as if it would not conclude at all. The experiment was terminated at this point and the subject interviewed. This too was to little avail, since the subject seemed aware only of how difficult the tasks were and how poor he was at this form of exercise. In terms of his response times, he did the forward trace tasks in a reasonable length of time, about fifty seconds, but failed to complete either of the reverse trace tasks. As only one problem was completed, the scores for this subject were considered inconclusive since no replications were made.

For the remaining subjects, a more stringent selection procedure was used. Subjects were chosen on the basis of intelligence as indicated by advanced academic achievement or personal knowledge held by the experimenter or both. The object of such a procedure was to avoid subjects who might prove to be unable to complete all four problems in a little over two hours. Periods of greater duration proved extremely fatiguing to both subject and experimenter.

Subject 3 was a male graduate student in physical education. After explaining the task set to him, the experimenter gave the subject the information card for the first problem. The subject then memorized the network silently, as he preferred. After having

done this fairly quickly, the testing session was begun, at which point a difficulty was discovered. The subject had misunderstood the directions and had performed the elimination task during the memorization period! He had then only memorized the resulting six node network. He was able to re-introduce the removed nodes to his memory of the network, but he was able thereafter to immediately identify the removable nodes, rendering the elimination task ineffective.

The subject performed the forward traces directly, reciting the spy names in order with only one error in the first problem. In the fourth problem, a doubt as to whether he was on the right path towards the end of the eight node trace resulted in his restarting the trace from the beginning. As the end of the trace neared, the response time for each step shortened greatly, producing the kind of acceleration to completion described by Hayes. The subject reported that this was due to his checking the path ahead of his response. As the end was reached, he would simply recite the rest of the path. Thus, no "remote planning" was used.

The reverse trace tasks were handled with equal ease, equal time, and equal process according to his report. He made no distinction between forward and reverse tracing and seemed unaffected by branches in either direction. Moreover, he showed the same pattern of acceleration to completion in reverse tracing as he had shown in forward tracing.

Several additional facts were noted prior to the interview session. In the second problem the subject experienced some proactive interference, an event not seen in any of the earlier experiments. In the third problem, he remarked on the fact that the networks all

appeared to have the same structure. He even considered pairing the new spy names with their counterparts in the other networks as an aid to memorization, but rejected the idea as too difficult. On the basis of this observation of his, he identified the lowest common superior in the third and fourth problems without going through his searching process, referring to this approach as "cheating". He knew their identities by their locations in the network. In the fourth problem, he commented that one of the spies "didn't belong". When asked about this, he replied that the spy was extraneous to the system and had to be fitted in awkwardly. A final note was that the elapsed time for the entire experiment was just slightly over one hour. Clearly, this subject was something new.

The interview session confirmed what had been suspected. The subject did have an internal structure. It was not visual in nature, in that he did not "look" at it, but he could and did draw the structure as it would appear if it were a visual image. In other words, the subject described exactly the possession of a non-visual bidirectional graph structure. He added that this was common for him and not an unusual artifact of, for instance, the misunderstanding in the first problem which was noted above.

The lack of visual imagery in a bidirectional graph processor was puzzling at first, since no alternative form of a graph structure seemed available. How, for instance, could the subject describe and even draw the graph structure without visualizing it? An alternative model was developed and confirmed in a follow up interview with this subject. Instead of representing the graph structure as a visual image, the subject represented the structure as a motor image. A

motor image, in this sense, is a representation wherein the size, shape and location of the object is described in terms of the movement required to reach it. In this way, the nodes of a graph structure are given hypothetical physical locations in space and can be identified and recalled in terms of their locations. For this subject, the nodes were located within his head, apparently just behind his forehead, where they could be "reached" but not seen. Motor imagery, then, is seen as an alternative to visual imagery, providing some kind of non-verbal representation of a bidirectional graph structure.

The one discrepancy between this subject and the model of a bidirectional graph processor was in his response times. The times for forward and reverse traces were equal, as predicted, but they were not as fast as they "should have been". His long forward trace times were never less than thirty-five seconds. This was fast, but Subject A of the first pilot study turned in times of twenty-one and eighteen seconds for the same trace. Times as low as nine seconds had been recorded in the pilot studies. The model of the bidirectional graph processor obviously needed revision. More subjects were needed now to either locate another such processor or else establish their relative rarity.

Subject 4 was a male doctoral student in education. He spent a great deal of time trying to find the "key" to the information in problems one and two. After very extensive manipulation of the order of entries, he began memorizing the network according to the patterns he had developed. In the first problem, this consisted of a highly complicated system grouping the numbers into small groups thus:

(1,2,3) (4,5,6) (7,8)

and then storing a very complex semi-algebraic algorithm which determines the receiver for any given spy. In the second problem, he merely reordered the list of senders to alphabetical order and then memorized the resulting list of receivers.

The result of this preparation was mainly confusion and hesitation. After almost two hours, he had completed only two of the four problems. He asked to be excused due to fatigue and other commitments, and the experiment was terminated. As a result of having only two scores per task for this subject, it is difficult to determine accurate mean response times for him.

In the longer forward traces, his forward times were fairly high, but his times for the longer reverse traces were fully twice as high. In the shorter traces, however, the times for the first problem were roughly equal while for the second problem they had the same relationship as had the longer trace times. It is believed that the good performance on the first shorter traces was the result of the subject's ability to develop an efficient system for the first problem, and his inability to do so for the second. In all of the trace tasks, the subject began working step by step from one node to the next without planning ahead. If the path became too long, or if a branch was found or a spy was named twice, he would begin to try to build the path from the other end, thus starting at the second spy given and working towards the first. After one step, however, he would abandon the effort as it proved too confusing. The reverse trace tasks seemed to be more difficult, as the experimenter had to remind the subject of the direction of the trace several times. Another factor which added to the difficulty was the subject's

tendency to confuse associations, either by reversing their order or by producing incorrect links by using an incorrect step in either his algorithm in the first problem or in his double list structure in the second problem. In all other respects, he performed the forward and reverse trace tasks in an identical fashion.

The subject reported no visual image or similar such structure. He was not able to add any additional information during the interview session as he did not seem to have a clear idea of how he developed either the processes he used to solve the trace tasks or the systems he used to store the information.

Subject 5 was the wife of a graduate student. She showed quite a contrast to the preceeding subject. She began by expressing a doubt as to whether she could memorize the information on the card. She then began reading the entries. In the fourth time through the reading, she was not looking at the card, but reciting the information from memory. As she continued reciting the list, the speed of recitation increased. By the eighth or ninth time through the card, she was reciting the list as fast as she could speak. She then became silent and apparently continued "rehearsing" the information several more times before asking for the testing session. The paired associate testing session, in turn, was completed rapidly without error. This pattern held true for all four problems. The subject showed no differential response to the different code names used for spies, memorizing each list as if it were no more or less difficult than the others.

In performing the forward trace tasks, she went step by step until a branch was encountered. She would then choose one branch,

apparently at random, and try it. In the interview session, however, it was revealed that she actually checked several steps ahead very rapidly and, if she was taking the wrong branch, she would correct herself before she made a response. The speed with which this checking ahead was accomplished was remarkable. In three out of the four long forward trace tasks her response times were under fifteen seconds and in the short forward trace tasks was as low as six seconds. In none of these tasks was an incorrect branch reported on the protocol. Another interesting feature was that her responses also showed the acceleration at the finish described by Hayes. Once again, as with Subject 3, this was due to a checking ahead of the present position and not an independent preparation of the last steps of the trace.

The reverse trace task seemed to present some difficulties in the first problem. The long trace was slowed down due to a confused association and the short trace contained a reverse cycle from which she had some difficulty locating the exit branch. In the second problem, she solved the long trace rapidly, but again took an incorrect branch on the short trace, this time locating it readily and taking the correct path. In the third problem she reported an increase in her ability to perform reverse traces and showed an acceleration to the finish for the shorter trace, finishing in nine seconds. She stated that the acceleration was not due to her checking ahead but rather to the fact that her tracing went faster than she could speak. In the fourth problem, she again hit a reverse branch, this time at the very end of the long trace, and started the trace over to find the error. The second time through the trace, she "saw" the branch and solved the task. Each of these two times through the network her response time

was about twenty seconds. Her response times on the forward and reverse traces were nearly equal except for those in which an incorrect reverse branch was taken. In all traces the response times were very fast, and the total time to run all four problems was only one hour.

In the interview session, she reported no visual or non-visual image or structure and referred instead to a process whereby she can recall part of an entry directly if the rest of it is given. Thus "Jane ____" elicits "____ passes to Ted" and "____ passes to Jane" elicits "Ron". She also reported that reverse branches were harder for her to detect than forward branches and that she did not use any checking ahead in the performance of reverse trace tasks. Thus from all indications, she was simply a very fast list processor.

Subject 6 was a male graduate student in psychology. Immediately on seeing the information card, he stated that he would have to visualize the network or else he would be unable to memorize it at all. He then spent about twenty minutes in silence doing this. In the second problem, his first reaction to the information card was, "Oh boy, retroactive interference" which was followed by "Hmm, isomorphisms!" It took only ten minutes for him to memorize the second network, and nine and six minutes for the third and fourth problems, respectively. The testing sessions for each problem went rapidly and without error, indicating that he had memorized the information quite effectively.

This subject did both the forward and reverse trace tasks very rapidly with few errors. The subject's forward and reverse trace response times were nearly equal, he showed no differential ability to perform either and he reported that the procedure he used was the

same for all traces.

While working the traces, he uttered occasional phrases such as "I can't get up there, can I," and "I keep misplacing those two," interspersed in the process. His verbalization of the forward trace itself was also unique. Subjects made responses of the form, "A passes to B, B to C, C to D." In contrast, this subject's responses were of the form, "A to B to C to D," in a continuous chaining of the nodes. It was as if the information was not stored in the form of entries, as on the information card, but rather as some linked network or graph.

This was confirmed in the interview session. His procedure for solving a trace problem consisted of "picturing" the portion of the network containing the given spy and "looking ahead" to the spies linked to or from that spy. Incorrect branches were not taken since each trace was reported as either "spiralling in" or "spiralling out", and the correct path was thus indicated.

The elimination task was solved by his removing the spies not on the "major square" of his internal network. These spies were removed by the subject in under five seconds in all but the first problem.

The subject completed all four problems in one hour twenty-five minutes, after which the interview session was begun. In this session, he reported that he did, in fact, have a visual image of sorts for the spy network. On further questioning, several aspects of this image were revealed. The whole network was not "visible", i.e. capable of being "seen" or "read", at one time. A sense of the whole image was present, but did not yield any information until it was "looked at". The picture called forth by "looking" at the image was fleeting, lasting

only a few moments and containing only one or two nodes and all of the links to or from those nodes. The image, then, was a latent image which could be used only a part at a time, but which could be accessed at will. When the image was not accessed, there was no sense of its presence and none of the network information was immediately available. The description of this structure seemed similar to that of Subject 3, but with a greater emphasis on the visual imagery present. Thus Subject 6 appears to be a direct visual bidirectional processor.

Subject 7 was a female graduate student in psychology. She memorized each network in less than five minutes and sped through the testing sessions without error. In the process of memorizing each network, she would break up the information card into three sections, top, middle, and bottom. She would then read the information twice in each of the following orders: the top, bottom and middle sections, the bottom, top and middle sections, the top, middle and bottom sections, and the bottom, middle and top sections. After eight readings of the whole network, then, she would have the information memorized. Towards the end of this process, her recitation became slurred, with the end of one spy name merged into the beginning of the next, as if the vocalization process was lagging behind her mental process.

She performed forward trace tasks one step at a time until a branch was encountered. She would then pick one path and track ahead verbally one or two steps. If no solution or cycle was found, she would then return to the branch and take the other path. Her forward trace times were about thirty seconds, for all of her forward traces, whether long or short. Her speech sounded methodical and steady, as if she were grinding out the process bit by bit.

In the reverse trace tasks, she had some difficulty coping with reverse branches. In three of the four long reverse trace tasks, she stalled at the next to the last step. At that point in the trace there is a branch which goes either to the end of the trace or to a node encountered near the beginning of the trace. In the three instances, she apparently saw only the incorrect branch, stopped, and proceeded to start over from the beginning of the trace, carefully checking all possible paths along the way. Consequently, her reverse trace times for one time she did not take the wrong final step is very different from the three times that she did. When she did not make this error, her time was thirty-five seconds, about the same as her forward trace times. In the shorter reverse traces, these errors occurred less frequently and seemed to create less confusion. In many of the reverse traces, both long and short, her responses would include both senders in a reverse branch. Thus, if "B passes to D" and "G passes to D, E" her reverse trace protocol might include "..., D from C or E,...". In the interview she explained that when she noticed the reverse branches she tagged the spies who received from two senders, thus making herself aware of the reverse branch. Apparently, however, the procedure was not completely effective, as she did sometimes fail to recognize the alternate path of a branch, as detailed above.

In any task which required the development of a procedure, particularly the elimination task, she seemed to have a relatively large amount of confusion and many delays, though still completing the tasks in under two minutes. In the interview session, she stated that she was very poor at "abstracting" but very good at rote

memorization. She reported no internal structure for the networks but went into length describing the method used to memorize the information. As noted above this procedure was that of a redundant list processor. She was able to complete all four problems in fifty-one minutes, the fastest time recorded.

Subject 8 was a female graduate student in psychology. She stated at the outset that she hated memorization. She tried to develop gimmicks, tricks or mnemonics for the systems, having by far the greatest trouble with the last problem which used names as labels for the spies. She mentioned that the problems would be easier to handle "if I were the mental imagery type, but I'm not." She expressed a desire to use a pencil and paper to draw the network, but this was rejected by the experimenter. She considered developing internal structures, but rejected the idea as involving far too much time and effort. She also recognized the similarity between the networks, but avoided investigating this because it seemed more likely to confuse her than help her.

During the testing sessions, she would begin with many errors and then quickly increase her accuracy until it met the criterion of three consecutive runs through the network. She reported that the testing session was actually serving as a learning session for her, and that it was more effective than her own memorization.

She performed the forward trace tasks one step at a time, accessing the next spy from the last one in the trace. At branches, she picked one path and followed it until it hit the end or until it cycled, when she would return and take the other path. Her times were fairly fast, with the exception of the fourth long trace in which

she became very confused with the names involved.

She reported performing the reverse traces in the same manner, but that the reverse branches were harder to detect and the reversing of links was somewhat confusing. Her protocols, however, seemed to indicate that the reverse traces were very confusing to her. If a cycle was encountered, she restarted the entire trace. Also, in the process of performing a reverse trace, she often reversed the directions of links. As a result, her response times for reverse traces were considerably longer than those for forward traces. The total time required to work through all four problems was over two hours.

Subject 9 was a male graduate student in psychology. His approach to memorization of the information was one of developing tricks for memory and for his own personal entertainment as well. He found the memory tasks to be dull and uninteresting and so had to "liven them up" for himself. In this process, he tried out many different recitation rhythms and patterns, probably in hopes of finding one which would make the learning easier. He decided to memorize the network in a string, beginning with a sender who did not receive and ending with a receiver who did not send. When he discovered that the network was circular he laughed and jokingly accused the experimenter of making things hard for him. The memorization sessions were quite long, during which time the subject finally ended up learning the network purely as a list of pairs of names. The testing sessions were quite long for two of the problems and were never rapidly finished in any of the problems.

The subject performed the forward traces step by step, stating that the name of the next spy in the network would simply pop into

his head as he said the last one. When a branch was encountered, he would silently track ahead several steps until he could determine the correct path. His responses did not include recognition of branches, although he never took an incorrect one. His response times in the forward trace tasks were fairly consistent, ranging from as fast as seventeen seconds for a short trace to as long as thirty-two seconds for a long trace.

The reverse trace tasks presented more difficulty. He reported that a process was used similar to the forward trace process, but that the name of the next spy took longer to recall. He frequently only recognized that there had been a reverse branch when he found himself in a cycle. If he did recognize a branch when he came to it, he would arbitrarily choose one path and verbally continue on it until it succeeded or failed. Those times that he failed to recognize the branching point, he had a very hard time working out the solution. His response times for the reverse trace tasks were much longer than those for the forward trace tasks ranging from a low of thirty-one seconds for a short reverse trace to over three minutes for a long reverse trace.

Completing all four problems took two hours and twenty minutes. No internal structure was reported and very little additional information was presented in the interview session. The subject seemed quite tired from the experiment and stated that he had found it generally pretty hard. All the data is consistent with the assumption that this subject was using an associative storage scheme.

THE TEMPORAL DATA AND THE MODELS

The Classification of Individual Subjects

Three models of human memory are to be considered: list, associative, and bidirectional graph structures. The data for input to memory is a list of entries which describes completely a spy network. That entry consists of a "sentence" of the form "A passes to H" where "A" represents a spy who is able to pass a message to the spy named "H".

A person using a list structure would simply rote memorize the information on the card. To retrieve the information, the subject would have to scan the whole list until the entry needed was encountered. Since the English phrase "A passes to B" includes "B receives from A" there would be no inherent differential effect for this subject in doing either a forward trace task or a reverse trace task. However, the subject must be careful about reverse branches. That is, a forward branch is represented by a single entry, i.e. "H passes to C, B", making both alternative paths immediately visible. A reverse branch, on the other hand, is represented by two entries, each of which has the same spy as receiver, i.e. "B passes to D" and "G passes to D, E". Such a reverse branch from spy "D" is not readily seen, and only one of the alternatives, "G" and "B", might be retrieved at any given time by a list processor.

A person using an associative structure would store the

information in such a way that the name or names of receivers of one spy are accessed directly when the sender's name is used as a "cue" for the recall. Thus the entry "A passes to H" would be recalled from memory when the subject concentrated on the name "A". Concentrating on the name "H" similarly elicits the entry "H passes to C, B", not "H receives from A". In a forward trace task, each receiver's name would be directly accessed from the mention of the sender's name. In a reverse trace task, however, the associative processor would have to conduct a search of his entire memory to find the sender's name when given only the name of the receiver. Reverse branches would pose even greater problems for associative processors than for list processors. Thus for an associative processor, reverse trace tasks would take far more time than would forward trace tasks.

A person using a bidirectional graph structure would store the information in such a way that accessing a spy's name would produce a memory of the links to and from that spy. That is, accessing the name "H" would produce "H receives from A and B, and passes to D and E". Thus a bidirectional graph processor would perform forward and reverse trace tasks equally easily.

If these models of human memory represent actual structures, then it is possible to distinguish the subjects using one structure from the subjects using another. There are several criteria. First of all there is the hypothesis that the response times for forward and reverse traces should be short - short for bidirectional graph processors, short - long for associative processors and long - long for list processors. The results from pilot studies, however, seemed to indicate that the pattern for list processors might also be

short - short. If this is the case, additional criteria will be needed to differentiate the graph processors from the list processors.

One extreme possibility capitalizes on the fact that the graph processor creates a graph structure for the information in each spy network while the list processor uses the information as it is given. This graph is structurally identical for each problem and one might expect that a bidirectional graph processor would notice that fact (and hence mention it in his interview) and capitalize on it. In particular, one might hope that the learning time would decrease from problem to problem. For the list processors, learning one network should have little effect on learning subsequent networks since the information is already presented in an optimal list form. Thus there should be little decrease in learning time for the list processor.

Table 3 shows the task times for each subject in the main experiment. From Table 3, it can readily be seen that Subjects 1, 4, 8, and 9 all had reverse trace response times far longer than their forward trace response times. Indeed, their average reverse trace response time ranged from two to three times as large as the average forward trace response time. In addition, these subjects reported no visual or motor images. Thus, these subjects fit the criteria for using an associative memory structure. All subjects in this group had considerable difficulty in memorizing the information. Each took over two hours for the entire experiment.

Subject 2 also appeared to fit in this category, having relatively long reverse trace times, no visual or motor images and needing a great deal of time and effort to memorize the networks. The

Table 3

Times (in Minutes:Seconds) for Subjects in the Main Experiment

TASK	TRIAL	S U B J E C T								
		3	6	5	7	8	9	1	4	2
Learning	1	21:09	24:01	3:12	5:42	23:32	24:00	25:29	22:29	23:31
	2	11:12	14:11	2:52	4:18	11:03	14:18	25:07	43:57	*
	3	9:23	14:20	4:08	5:00	15:40	16:52	38:56	*	*
	4	6:06	11:00	3:20	4:49	28:40	20:18	*	*	*
Forward	1	1:12	:46	:15	:31	1:40	:22	1:05	3:04	:52
Trace	2	:41	:18	:30	:28	:35	:29	1:02	2:36	*
(8 node chain)	3	:35	:16	:13	:30	:40	:21	2:07	*	*
	4	1:01	:16	:13	:32	2:36	:32	*	*	*
Reverse	1	1:07	:35	:34	1:17	3:24	3:02	5:48	6:00	5:16
Trace	2	:47	:34	:17	1:31	3:45	1:08	3:41	5:55	*
(8 node chain)	3	:45	:30	:20	:35	1:47	:52	4:07	*	*
	4	3:47	:26	:45	2:10	1:57	2:47	*	*	*
Forward	1	:37	:27	:09	:26	:31	:24	:47	:42	:50
Trace	2	:15	:13	:21	:28	:28	:28	:34	1:45	*
(6 node chain)	3	:20	:13	:07	:29	:20	:21	1:21	*	*
	4	:31	:26	:06	:32	:38	:17	*	*	*
Reverse	1	:22	:23	1:00	:57	2:51	:31	2:21	:57	6:30
Trace	2	:12	:16	:32	:36	3:03	2:24	5:30	4:00	*
(6 node chain)	3	:17	:10	:09	:42	:27	1:08	2:58	*	*
	4	:30	:16	:12	:30	1:20	:45	*	*	*
Elimination	1	:00#	3:35	:32	:47	2:19	5:06	4:22	:18	:57
	2	:00#	:08	:37	1:51	5:06	3:08	2:35	:47	*
	3	:00#	:04	:25	1:25	4:26	1:32	1:43	*	*
	4	:00#	:03	:14	1:10	4:19	1:25	*	*	*
Lowest	1	3:55	1:13	:14	2:50	:43	6:35	:45	:57	6:30
Common	2	2:52	:20	:15	:32	6:00	1:05	2:31	4:00	*
Superior	3	:40	:28	:38	:19	1:40	1:54	:48	*	*
	4	:05	:20	:10	:17	:30	3:56	*	*	*
Total	1	29:00	30:00	6:00	13:00	35:00	40:00	40:00	55:00	41:00
Elapsed	2	16:00	16:00	5:00	13:00	30:00	23:00	40:00	65:00	*
Time	3	12:00	17:00	6:00	12:00	25:00	23:00	52:00	*	*
	4	12:00	13:00	5:00	13:00	40:00	30:00	*	*	*
Sex of Subject		M	M	F	F	F	M	M	M	M

* Subject did not finish experiment due to overly long time needed.

Subject performed task during learning period.

classification of this subject is tentative, since he did not complete the experiment and thus had only one set of response times.

What about the four subjects whose forward and reverse trace times were roughly equal? Subjects 3 and 6 both reported some kind of visual or quasi-visual internal structure, while neither Subject 5 nor Subject 7 reported any such structure. However, this could be due to poor introspection on the part of Subjects 5 and 7. Subjects 3 and 6 both were able to learn the network information faster for the later problems than for the earlier ones; they both recognized and counted on the observed similarities between the four spy networks. Subjects 5 and 7, on the other hand, required the same amount of time to learn the network information for each of the four problems, and made no mention of the similarity between the networks. Thus, Subjects 3 and 6 seemed to treat the networks as similar, and applied the structures and insights made in one problem to the succeeding problems. Subjects 5 and 7 seemed to treat each network individually, considering each a new problem entirely. This seems sufficient to categorize Subjects 3 and 6 as bidirectional graph processors, and to categorize Subjects 5 and 7 as list processors.

Finally, can Subject A of the pilot studies now be classified? She exhibited very fast, equal response times for both forward and reverse traces, suggesting that she was either a bidirectional graph processor or a list processor. A follow up interview confirmed the fact that she had not used any visual or motor imagery, but had "just memorized" the networks. Consequently, she seems to fit the model of a list processor.

Comparisons of Speed

Table 4 presents the mean response times for each of the three processing groups on each of the tasks. For this table, the subjects were grouped in the following manner: Subjects 3 and 6 were combined as the bidirectional graph processors; Subjects 5 and 7 were combined as the list processors; Subjects 8 and 9 were combined as the associative processors. Subjects 8 and 9 were the only associative processors who completed all four networks. Since completing the task was a function of how rapidly the subjects performed, this means that Subjects 8 and 9 were in effect selected as the fastest of the associative processors. That is, if the other associative processors had completed four problems these means would have been much greater.

The five graphs in Figure 6 show the mean trace times for each group. The first four show that there are virtually no time trends and that the pattern of group differences is essentially identical in six and eight node tasks. Therefore the trace times for six and eight node tasks were averaged with each other and then averaged over time. The resulting means are plotted in Figure 6c. This figure shows only slight differences between groups in forward trace times (and there were no differences at all on the six node tasks). On the other hand, there are considerable differences in reverse trace times with graph processors nearly twice as fast as list processors and associative processors far slower than either.

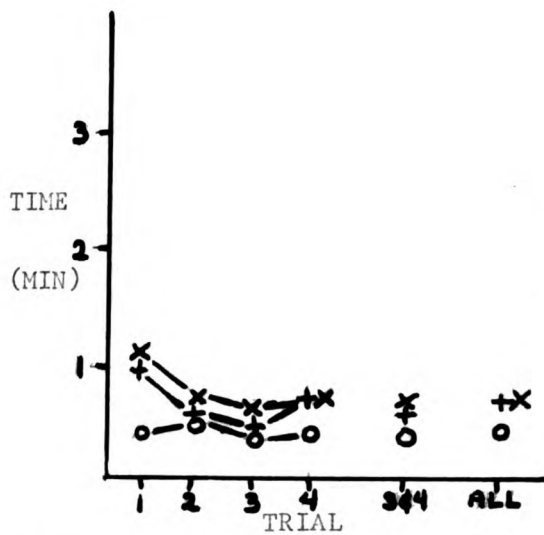
The other facet of Figure 6c worth noting is the differences between tasks within groups. Forward and reverse times are identical for the graph processors and grossly disparate for the associative

Table 4

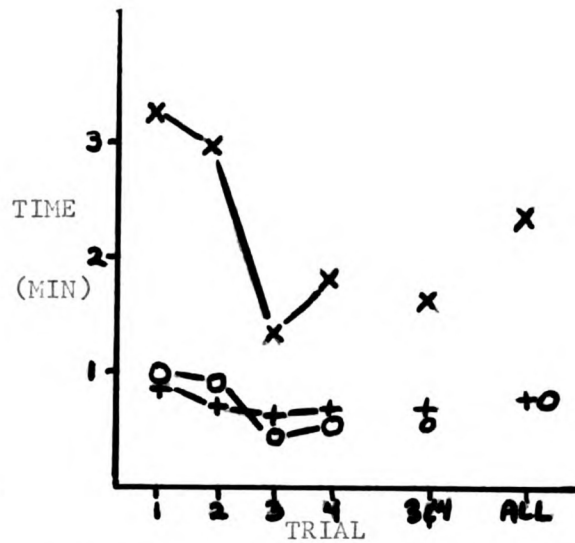
Mean Times for Subjects in the Main Experiment

TASK	TRIAL	GRAPH 3&6	LIST 5&7	ASSOCIATIVE 8&9
Learning	1	22:35	4:27	23:46
	2	12:41	3:35	12:40
	3	11:52	2:34	16:16
	4	8:33	4:00	24:29
	ALL	13:55	3:39	19:13
Forward	1	:59	:23	1:01
Trace	2	:35	:29	:33
(8 node chain)	3	:26	:22	:31
	4	:44	:23	:45*
	ALL	:41	:24	:43
Reverse	1	:51	:56	3:13
Trace	2	:41	:54	2:57
(8 node chain)	3	:38	:28	1:20
	4	:40*	:36*	1:49*
	ALL	:43	:44	2:20
Forward	1	:32	:17	:28
Trace	2	:14	:25	:28
(6 node chain)	3	:17	:18	:21
	4	:29	:19	:28
	ALL	:23	:20	:26
Reverse	1	:23	:59	1:41
Trace	2	:14	:34	2:44
(6 node chain)	3	:14	:26	:48
	4	:23	:21	1:03
	ALL	:19	:35	1:34
Elimin- ation	1	1:48	:40	3:43
	2	:04	1:14	4:07
	3	:02	:55	2:59
	4	:02	:42	2:52
	ALL	:29	:53	3:10
Lowest	1	2:34	1:32	3:39
Common	2	1:36	:24	3:33
Superior	3	:34	:29	1:47
	4	:13	:14	2:13
	ALL	1:14	:40	2:48
Total	1	30:00	10:00	38:00
Elapsed	2	16:00	9:00	27:00
Time	3	15:00	9:00	24:00
	4	13:00	9:00	35:00
	ALL	19:00	9:00	31:00
Total—	1	7:25	5:33	14:14
Learning	2	3:19	5:25	14:20
=Perfor- mance	3	3:08	6:26	7:44
	4	4:27	5:00	10:31
	ALL	4:35	5:36	11:42

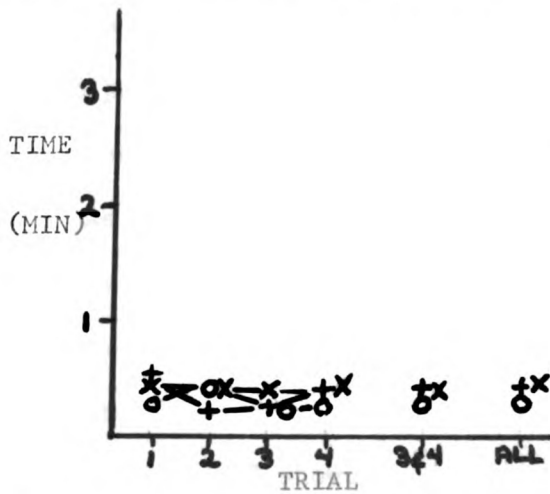
* Estimated average used to compensate for apparently abnormal time.



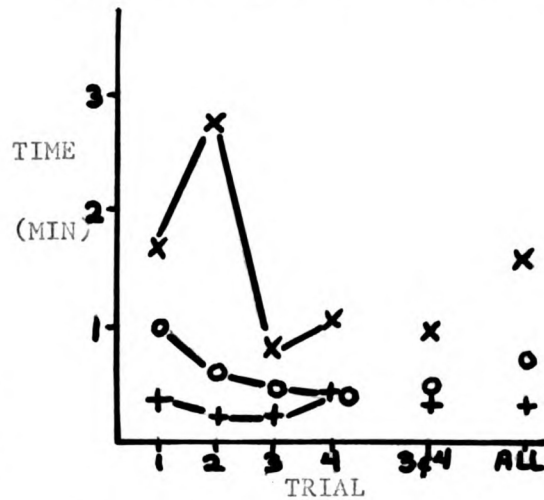
a) Forward Trace (8 node chain)



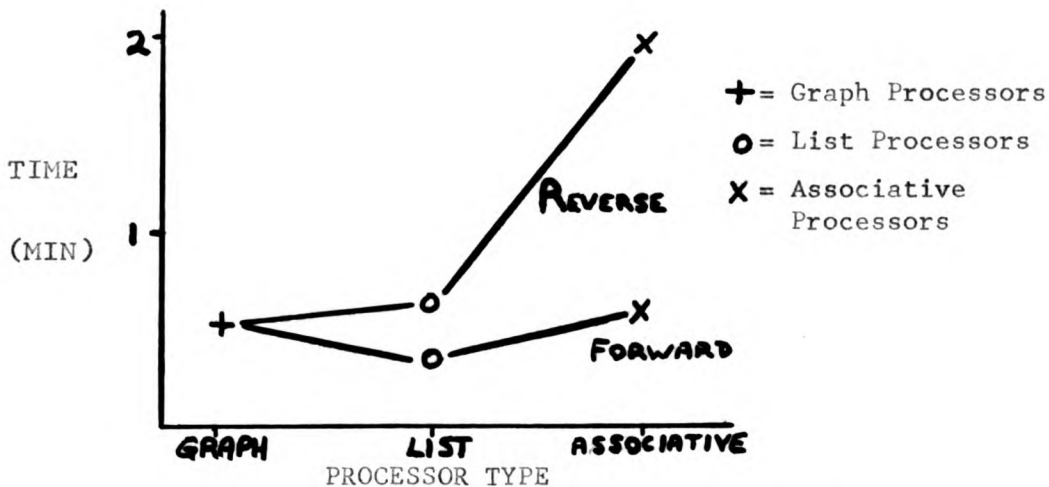
b) Reverse Trace (8 node chain)



c) Forward Trace (6 node chain)



d) Reverse Trace (6 node chain)



e) Mean Trace Times as a Function of Processor Type

Figure 8. Mean Trace Times for the Three Processing Types

processors. However the times are not identical for the list processors. Instead, reverse trace times are more than twice as long as forward trace times for the list processors. Inspection of the protocols suggests that this time difference was produced by the failure to detect branches in the reverse trace rather than a difference in processing time per se.

Figure 9 shows the average time to solve the lowest common superior task. All three groups show marked improvement over time. Initially the list processors were much faster than the graph processors who were much faster than the associative processors. By the third problem, the graph processors had become as fast as the list processors. On the other hand, the difference between these groups and the associative processors actually increased over problems, particularly if the times are viewed relatively. On the fourth problem, the associative processors took over eight times as long as the other two groups.

Figure 10 shows a sharp differentiation between the three groups in the time taken to eliminate "unnecessary" spies. The associative processors were initially very slow and showed little improvement. The list processors started out the fastest, but showed no improvement over problems. In contrast, the graph processors were intermediate to the other groups on the first problem, but shrank to essentially zero times on the last three problems. This is consistent with their verbal reports that they learned the structural characteristics of eliminable spies on the first problem and then recognized them thereafter.

Figure 11 shows the time spent learning the networks. The list

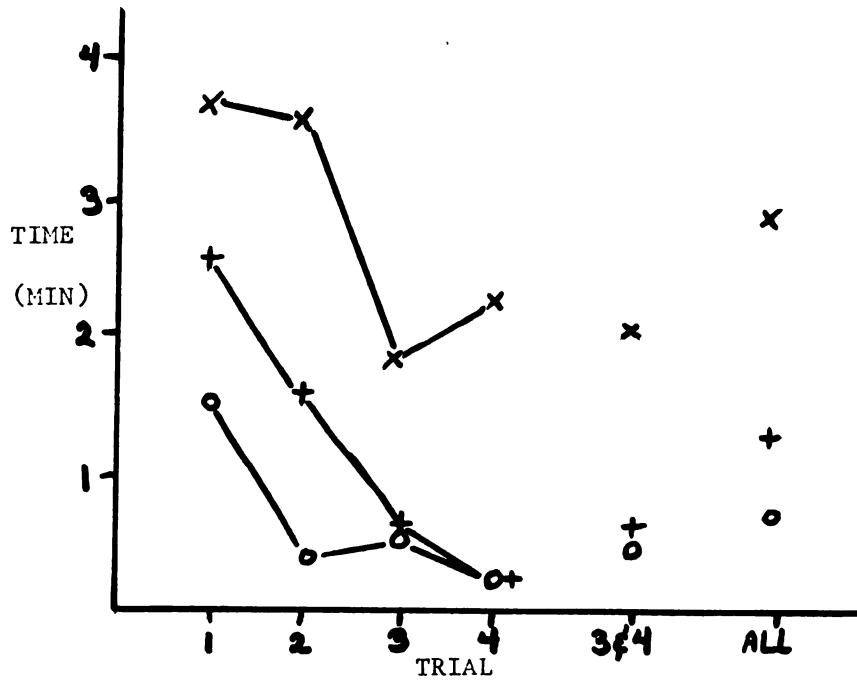


Figure 9. Average Times to Complete the Lowest Common Superior Task.

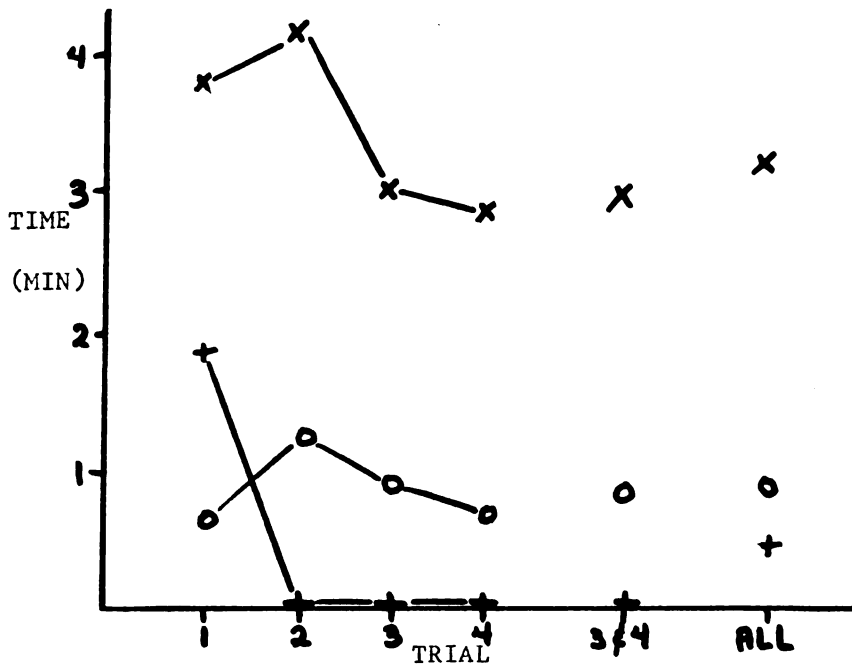


Figure 10. Average Times to Complete the Elimination Task.

processors started out far faster than the other groups and maintained the same speed. The other groups took over twenty minutes to learn the first network, but dropped to about half that on the second problem. The graph processors continued to drop in time over the third and fourth problems, but the associative processors got worse! Furthermore this pattern is identical for both associative processors. The explanation of this puzzling finding is clouded by the fact that three potential factors are confounded for this group: task differences, proactive interference, and fatigue.

Figure 12 shows the total time spent in the six tasks for each problem. As was true during the learning period, the list processors start out fast but show no improvement. The graph processors start out slower than the list processors on the first problem, but they improve so much on the second problem that they then become the fastest group. The associative processors show a dramatic improvement on the third problem, but regress somewhat on the fourth. This pattern stands in sharp contrast to the learning pattern for the third problem and is much weaker even for the fourth. Thus if there were fatigue or proactive interference effects on performance, they did not show up until the fourth problem.

Figure 13 shows the total time spent on each problem (i.e. the sum of the graphs in Figures 11 and 12). Again the list processors start out fast but show no improvement. The graph processors start out three times slower than the list processors, but by the fourth problem they have dramatically narrowed the gap to a percentage difference of thirty points. And they were still dropping when the experiment was terminated. The associative processors started out slow, but also showed

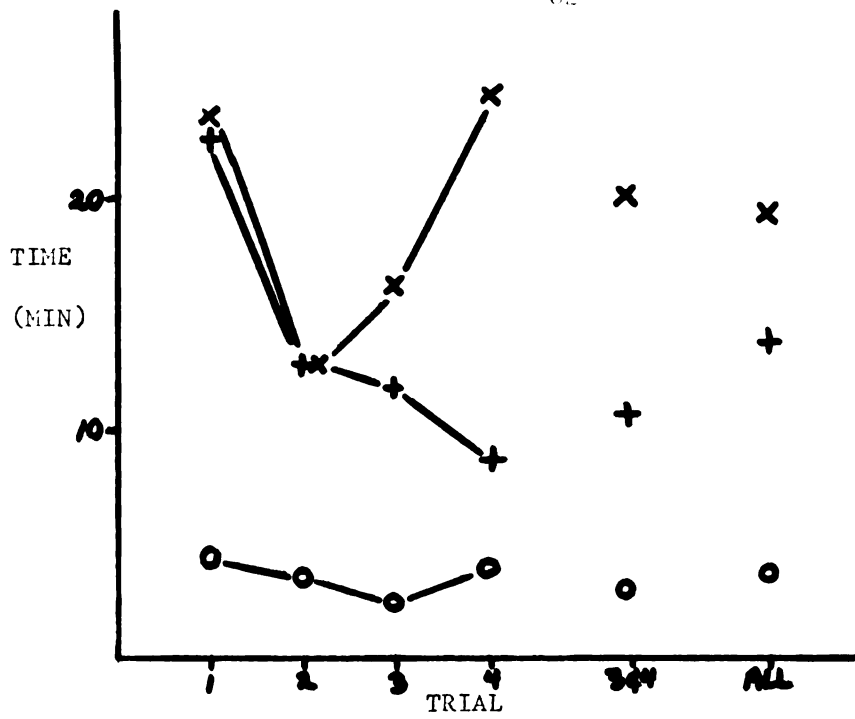


Figure 11. Average Times Spent Learning the Networks.

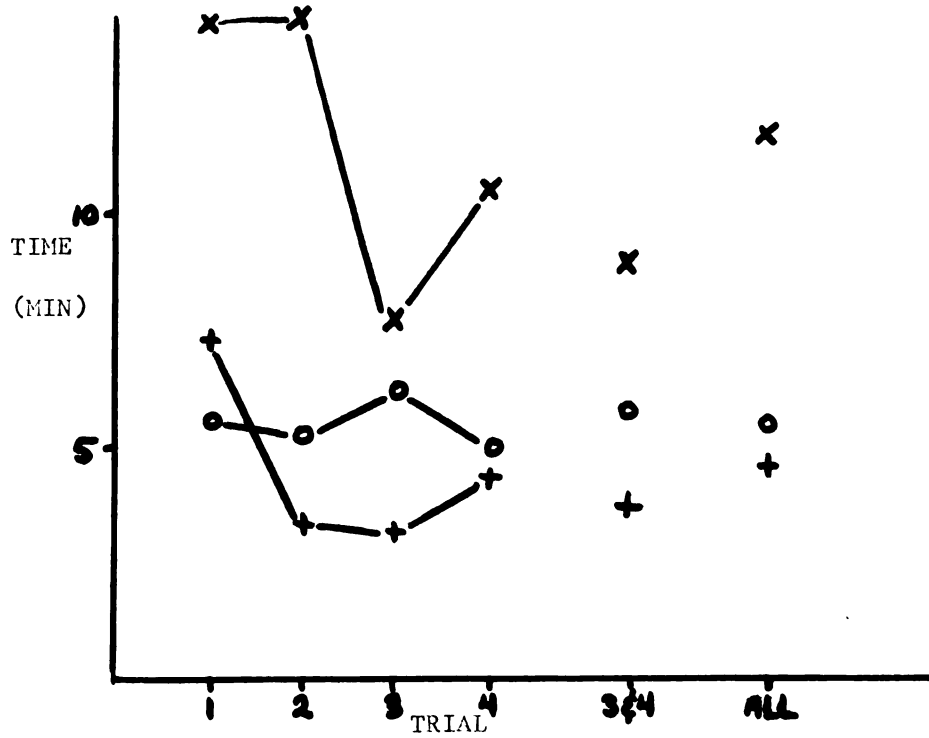


Figure 12. Average Times Spent Performing the Tasks.

strong improvement over the first three problems. However, they took nearly as long on the fourth problem as they took on the first.

Figure 14 brings out a fact which is not evident in the previous figures. Since total time is cumulative across problems, the different groups did not learn the later networks at the same time. Since this is very important for the fatigue hypothesis, Figure 14 shows the time spent learning each network as a function of the accumulated time spent in the experiment at the beginning of the learning period. This reveals some sharp differences between the groups. The graph processors were learning their third network at a time when the list processors had completed the entire experiment, and the associative processors learned the fourth network at a time when the graph processors would have been finished with the entire experiment. Thus it is entirely possible that fatigue effects on the fourth problem would appear for the associative processor without appearing for the graph processor. This could also be true for the third problem.

The Subjects' Self Evaluations

The graph processors approached this experiment as a challenge or puzzle, showing obvious enjoyment in "solving" the networks. Their confidence and joy stand in stark contrast to the reactions of the other subjects.

The associative processors, in general, showed a phenomenon of being torn between the other two processing methods. It was as if they felt that they should (but could not) utilize one or the other method (and they were fairly specific as to how they would use the alternative processing style). Consequently, they made, at most, only half-hearted

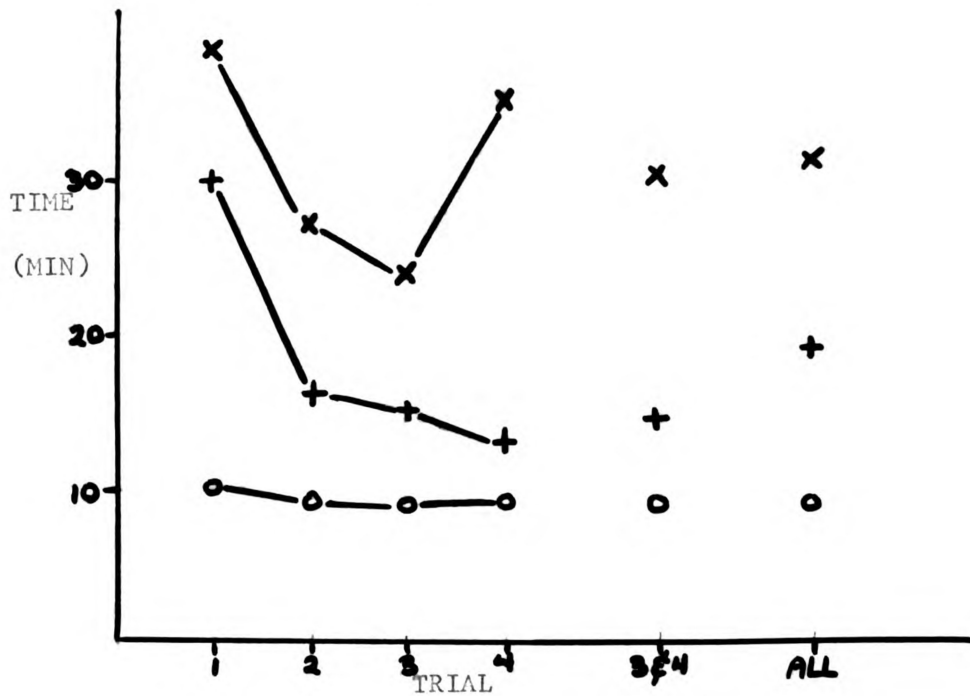


Figure 13. Total Time Spent on Each Problem.

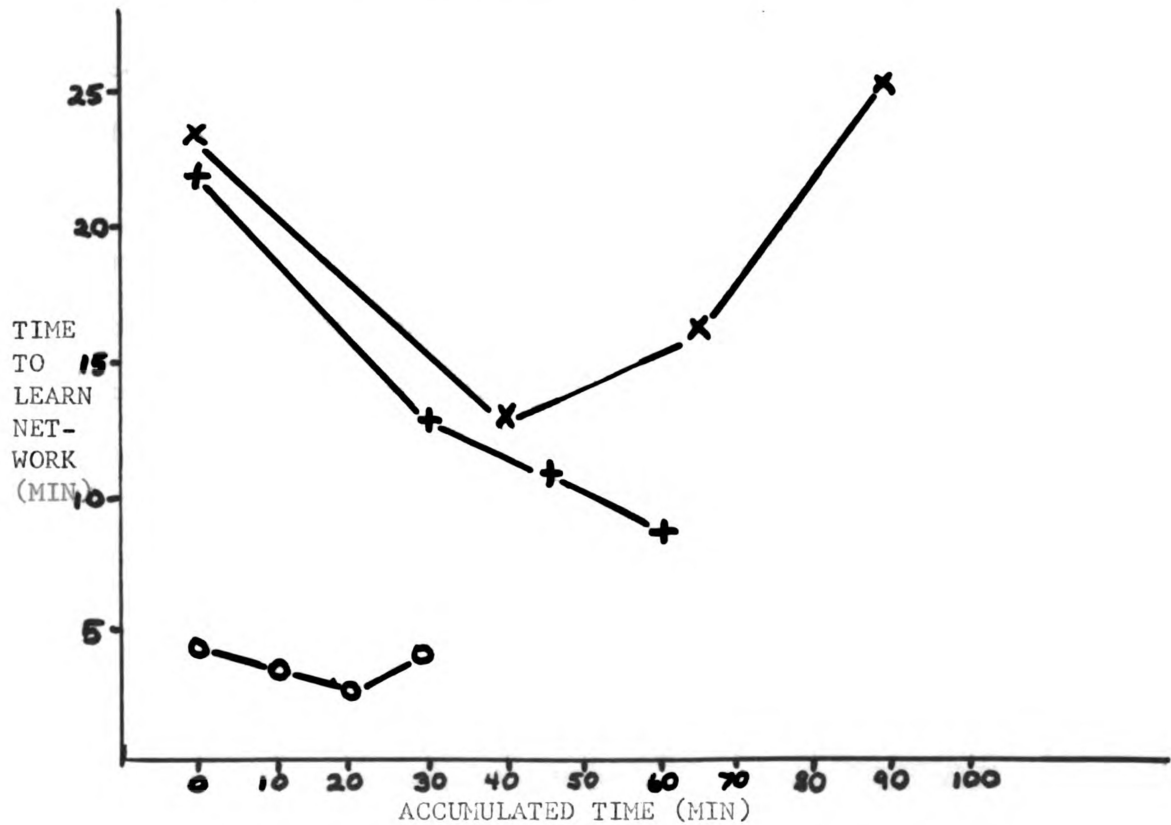


Figure 14. Time Spent Learning the Network as a Function of the Accumulated Amount of Time in the Experiment at the Beginning of the Learning Period.

attempts at an alternative before returning to the associative method. The associative processors were the only ones who considered using a different method. Whether the cause of this is flexibility, ambivalence, or a realization that the associative method was a poor one is unknown.

In all three of the list processors (including Subject A of the pilot studies) there appeared a feeling of guilt or shame for using this processing method. All stated that, from early school years, they felt as though they were "cheating" because they had to count on their fingers, memorize equations by rote without understanding them, etc. That is, they generally used methods which seemed clumsy and inelegant. The fact that these methods proved effective did not change the feelings involved. It was a curious feature of the most efficient processors that they felt ashamed of their method of processing, even after being told of its effectiveness.

Finally, a last observation was made regarding the list processors and the graph processors. For what it is worth, it was noted that both of the efficient and ashamed list processors were females, while both of the less efficient, organization-seeking graph processors were males.

DISCUSSION

Hayes

Hayes noted that his subjects often had steady response times for each step of a trace until the goal, or end node, was approached. Then there was an increase in response times as if the subject had rehearsed the last segment of the trace. From this, Hayes concluded that subjects perform a reverse trace from the goal node during the process of performing a forward trace. He called this action "remote planning". Similar increases in the speed of later responses were found in the present study. However not a single subject reported remote planning! Instead, subjects reported that their responses tended to lag behind the actual point of the search, allowing them to search ahead in the trace. When the goal node was reached in the search process, the search process was stopped, leaving the response process to catch up. Without the need to keep a silent search going, the subjects could recite the steps of the trace more rapidly, producing the observed acceleration of response times.

Hayes also distinguished between "direct accessing" and "list searching", stating that the former was far faster than the latter. His process definition of "direct access" was an associative response. Thus the original prediction in this study was that associative processors would have dramatically rapid forward trace times while list processors would be slow. The exact opposite was true.

Associative processors were slow and halting while list processors were fast and smooth. How could this reversal have occurred? First it should be noted that both graph processors and list processors stated that their inner search was too fast to report verbally. Thus much of what Hayes believed to be direct accessing may have been very fast list processing. On the other hand, the sub-vocal "list searching" Hayes described may actually have been some very slow associative processors directly accessing one after another of the weak associations in search of a needed link. This would have been particularly acute if a few associative processors actually tried remote planning!

Processing Speed and Learning

The three models of human memory structures, as originally described, predicted most of the results obtained. Specifically, the short - short response pattern for the bidirectional graph processors and the short - long response pattern for the associative processors occurred as expected. Also the graph processors did indeed capitalize on their perception of structure to achieve striking efficiency on the lowest common superior and elimination tasks. On the other hand, the models failed to predict the low level of efficiency of the associative processors and the high level of efficiency of the list processors. The long - long response pattern for the list processors did not occur. Instead, the list processors turned in the shortest total elapsed times of all. It was, in fact, the associative processors who produced very long total elapsed times for this experiment. As a consequence of the list processors' great speed, there was also a failure in the prediction that the forward and

reverse trace times would be equal. The list processing time was so fast that the difference in search time produced by missing the reverse branches was as large as the time required for an entire forward trace!

The original model of the associative processor made extensive use of the direct access concept, describing the associative process as a series of direct accesses. This model assumed that a paired associate, once placed in memory, would have and maintain a high association strength without the need for additional practice. Thus the second half of the pair would be available instantly each time the first half was used to access it. In the experiment, however, the associative subjects showed forgetting and reversing of links as well as a relatively slow accessing time. Whereas the graph and list processors were typically performing the forward trace steps faster than they could report them, the associative processors repeatedly exhibited silences in their reports because the next step in the trace had not yet been accessed.

A second error in expectations was in the learning data. For several centuries, memory has been thought to be associative. Thus one would assume that the associative processors would be the quickest learners. This prediction is even farther from reality than the prediction of fast forward traces. At their fastest, it took the best associative processors three and a half times as long to learn a network as did the equally practised graph and list processors.

On the other hand, the speed of the list searching process is many times faster than expected, far faster than any vocalization process. If subjects 5, 7, and A are indeed list processors, then the

data in Table 3 show that a list processor can scan the entire list several times in the period required for an associative processor's recall of a single forward connection!

Why is list processing so much faster than associative processing? Perhaps the key is in how the two kinds of subjects conceive of the information that defines the network. The associative processor treats each pair as a single item. The list processor thinks of the information as one list and practices that list as a unit. If indeed the learned list is internally stored as a unit, then this has many implications for future recall. If such a list is accessed as a unitary chunk of information, then every time a list structure is rehearsed or searched, each pair within the list structure is practiced. Thus, since the list is searched at least once for each step in a trace, the pairs are practiced much more frequently by list processors than by associative processors.

At a later point in learning, there is another intriguing possibility for a list processor. If a list becomes one chunk of information, then it may be possible that the entire list can be stored in short term memory as one item. Since every pair is on that list, a list processor might thus need only one call to long term memory for an entire forward trace!

On the other hand, the associative processor learns a series of distinct paired associates. Thus the rehearsal of one pair to increase its associative strength will not increase the associative strength for another pair. To the contrary, as the one pair is being rehearsed, the strength of the other is weakened by the forgetting process. Small wonder then that these associations are of a weaker

form and more subject to disruption than those of the list processor.

The preceding discussion exactly reverses classic associationism. Stimulus - response theory has always sought to account for serial (i.e. list) learning as a collection of paired associates. The previous discussion argues that the associative processor is really an inferior list learner. The associative processor makes the mistake of learning a great many short lists where one long list would do.

Graph Processors

Information regarding the bidirectional graph processors helped to clarify two aspects of that approach: the nature of the hypothesized imagery, visual or otherwise, and the relative efficiency of the process. The original model of the graph processor postulated the existence of some analogue of a visual image which would constitute the graph structure. The image developed was not necessarily visual in nature. That is, alternative sensory modes could apparently be used resulting in a motor image instead. For each of the subjects tested, the sensory mode of the image, whether visual or motor, was constant and was reported to be the one generally used.

In the graph processors tested, not only did this structure exist, but the subjects were aware of the structure and actively worked to develop an efficient form for it. Having actively created the form of the image, the graph processors were able to selectively attend to various sections or elements of the structure. In the elimination tasks, they were thus able to temporarily "disregard" the existence of various nodes and then examine the resulting graph structure. Consequently, the graph processors were able to determine

the eliminable nodes with considerable ease.

Contrary to the original expectations, the time required to develop and process the graph structure was not shorter than the time required for the list structure. The formation of the graph structure required considerable time and effort. For the first problem, the graph processors required as much time to learn the information as did the associative processors. However, the graph processors required less and less time to learn each successive network and their final learning rates approached those of the list processors. This improvement was due mostly to the repeated usage of the basic graph structure developed for the first network. That is, the graph structure had some substance apart from the specific spy network to which it was applied. This quality did not appear in either the associative structure or the list structure.

Although the graph structure formed a single block of information as did the list structure, the time needed for a rehearsal of the whole graph structure was longer than that required to rehearse the list structure. As with the list structure, the entire graph structure appeared to be available for access from short term memory once it was recalled from long term, or permanent, memory.

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APPENDIX

APPENDIX A

THE PRESENTATION AND TASK FORMATS

The following are facsimiles of the cards used to present the four networks to the subjects in the main experiment. The cards used were standard unruled three by five cards. Next to each card facsimile is a listing of the tasks in the order in which they were given to the subject.

NETWORK I

1 passes to 8
3 passes to 2
5 passes to 7, 1
8 passes to 6
7 passes to 3
2 passes to 8, 4
6 passes to 5
4 passes to 7

TASKS

1. Forward Trace from 1 to 4
2. Forward Trace from 7 to 5
3. Find the Lowest Common Superior for 8 and 3
4. Reverse Trace from 1 to 4
5. Reverse Trace from 2 to 8
6. Elimination

NETWORK II

B passes to D
F passes to G
H passes to C, B
D passes to A
C passes to F
G passes to D, E
A passes to H
E passes to C

TASKS

1. Forward Trace from B to E
2. Forward Trace from C to H
3. Find the Lowest Common Superior for D and F
4. Reverse Trace from B to E
5. Reverse Trace from G to D
6. Elimination

NETWORK III

BROWN passes to GREEN
 RED passes to GOLD
 WHITE passes to GREY, BROWN
 GREEN passes to BLACK
 GREY passes to RED
 GOLD passes to GREEN, BLUE
 BLACK passes to WHITE
 BLUE passes to GREY

TASKS

1. Forward Trace from BROWN to BLUE
2. Forward Trace from GREY to WHITE
3. Find the Lowest Common Superior
for GREEN and RED
4. Reverse Trace from BROWN to BLUE
5. Reverse Trace from GOLD to GREEN
6. Elimination

NETWORK IV

SUE passes to RON
 BARB passes to CARL
 TED passes to EVE, SUE
 RON passes to JANE
 EVE passes to BARB
 CARL passes to RON, VINCE
 JANE passes to TED
 VINCE passes to EVE

TASKS

1. Forward Trace from SUE to VINCE
2. Forward Trace from EVE to TED
3. Find the Lowest Common Superior
for RON and BARB
4. Reverse Trace from SUE to VINCE
5. Reverse Trace from CARL to RON
6. Elimination

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