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by

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THE CONTROL PROCESSES OF SHORT-TERM MEMORY

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Human memory is divided into a short-term working memory and a long-term permanent memory. Control processes act within the short-term working memory to make decisions and regulate information flow, thereby controlling learning and forgetting.

The system by which information is stored in and retrieved from memory has always been a topic of great interest to psychologists. The English associationists and early experimental psychologists like Wilhelm Wundt, William James, and Ernst Meumann relied upon introspective techniques to generate their theories. Their introspections led them before the turn of the century to divide memory into short-term and long-term components. They discerned a clear difference between thoughts currently present in consciousness and those that could be brought to consciousness after a search of memory that often required considerable effort. For example, this sentence is in your current awareness, but the winner of the 1968 World Series, while probably in memory, requires some effort to retrieve and in fact may not be found at all.

Despite its intuitive attractiveness, the short- versus long-term view of memory was largely discarded when psychology turned to behaviorism which emphasized animal as opposed to human research. The short- versus long-term distinction received little further consideration until the 1950's when a number of psychologists, particularly Donald Broadbent in England, Donald Hebb in Canada, and George Miller in the United States, reintroduced it (see George A. Miller, Information and Memory, Scientific American, 1956, 195 (2), 42-47). The growth of two-process systems was accelerated by the concurrent development of computer models of behavior and mathematical psychology. The two-process viewpoint is now undergoing considerable theoretical development and is the subject of a large research effort. In particular, the short-term memory system, which we will call short-term store (or STS), has achieved a position of pivotal importance. Its importance stems from processes carried out in STS that are under the immediate control of the subject. These control processes govern the flow of information in the memory system; they can be called into play at the subject's discretion, with enormous consequences on performance.

Some control processes are used in many situations by everyone, and others are used only in special circumstances. Rehearsal, an overt or covert repetition of information, is employed in numerous situations: when remembering a phone number until it can be written down, when remembering the names of a group of people to whom you have just been introduced, and when copying a passage from a book, to name a few examples. Coding refers to a class of control processes in which long-term retrieval is enhanced by placing the to-be-remembered information in a context of additional and easily retrievable information. For example, students sometimes learn the twelve cranial nerves with the use of the mnemonic "On Old Olympus' Tiny Top A Finn And German Viewed Some Hops," where the first letter of each word corresponds to the first letter of each nerve. Imaging refers to a control process in which verbal information is remembered through the use of visual images. The ancient Greeks made extensive use of this process. Cicero suggested learning long lists (or speeches) by placing each member of the list in a visual representation of successive rooms of a well-known mansion. A number of other control processes, including decision rules, organizational schemes, retrieval strategies and problem solving techniques, will be encountered in this article. The point to keep in mind is the optional nature of control processes. In contrast to permanent structural components of the memory system, the control processes are selected at the subject's discretion; they may vary, not only with different tasks but even from one encounter with the same task to the next.

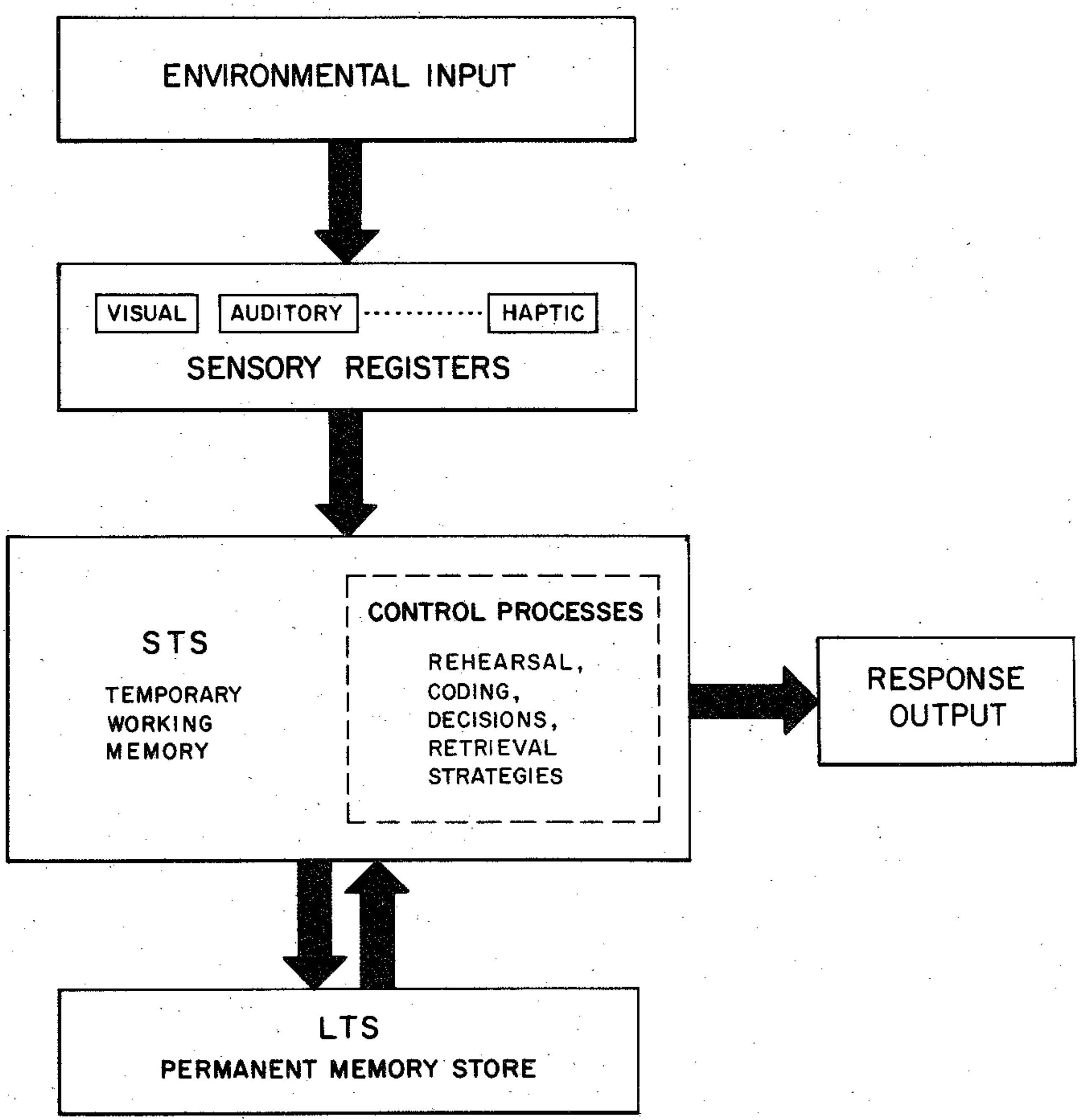
An Outline of the Memory System

We believe that the overall memory system is best described in terms of the flow of information into and out of STS and the subject's control of this flow. Before describing the system it is helpful to introduce terminology with which to discuss information flow. All phases of memory are assumed to consist of small units of information which are associatively related. Any set of information units that are closely interrelated will be termed an "image" or "trace" (thus "image" does not necessarily imply a visual representation). If the pair "TKM - 4" is presented for memory, the image stored might include the size of the card on which the pair is printed, the type of print, the sound of the various symbols, the semantic codes, and numerous other units of information.

The basic phases of the memory system and the types of information flow are illustrated in Figure 1. Information from the environment is accepted and processed by the sensory registers in the various sensory

Figure Caption

Figure 1. Information flow in the memory system. Environmental information is processed by sensory registers in the various physical modalities and entered into short-term store (STS). The information remains temporarily in STS, the length of stay depending on control processes. While information remains in STS it may be copied into long-term store (LTS). While information remains in STS, information in LTS associated with it may also be activated and entered in STS. Thus, if a picture of a triangle is presented, this visual information is processed and entered into STS. Then, since the verbal name "triangle" is associated with this visual information in LTS, this verbal label is also entered into STS.


ENVIRONMENTAL INPUT
VISUAL
AUDITORY
HAPTIC
SENSORY REGISTERS
STS
TEMPORARY
WORKING
MEMORY
CONTROL PROCESSES
REHEARSAL,
CODING,
DECISIONS,
RETRIEVAL
STRATEGIES
RESPONSE
OUTPUT
LTS
PERMANENT MEMORY STORE

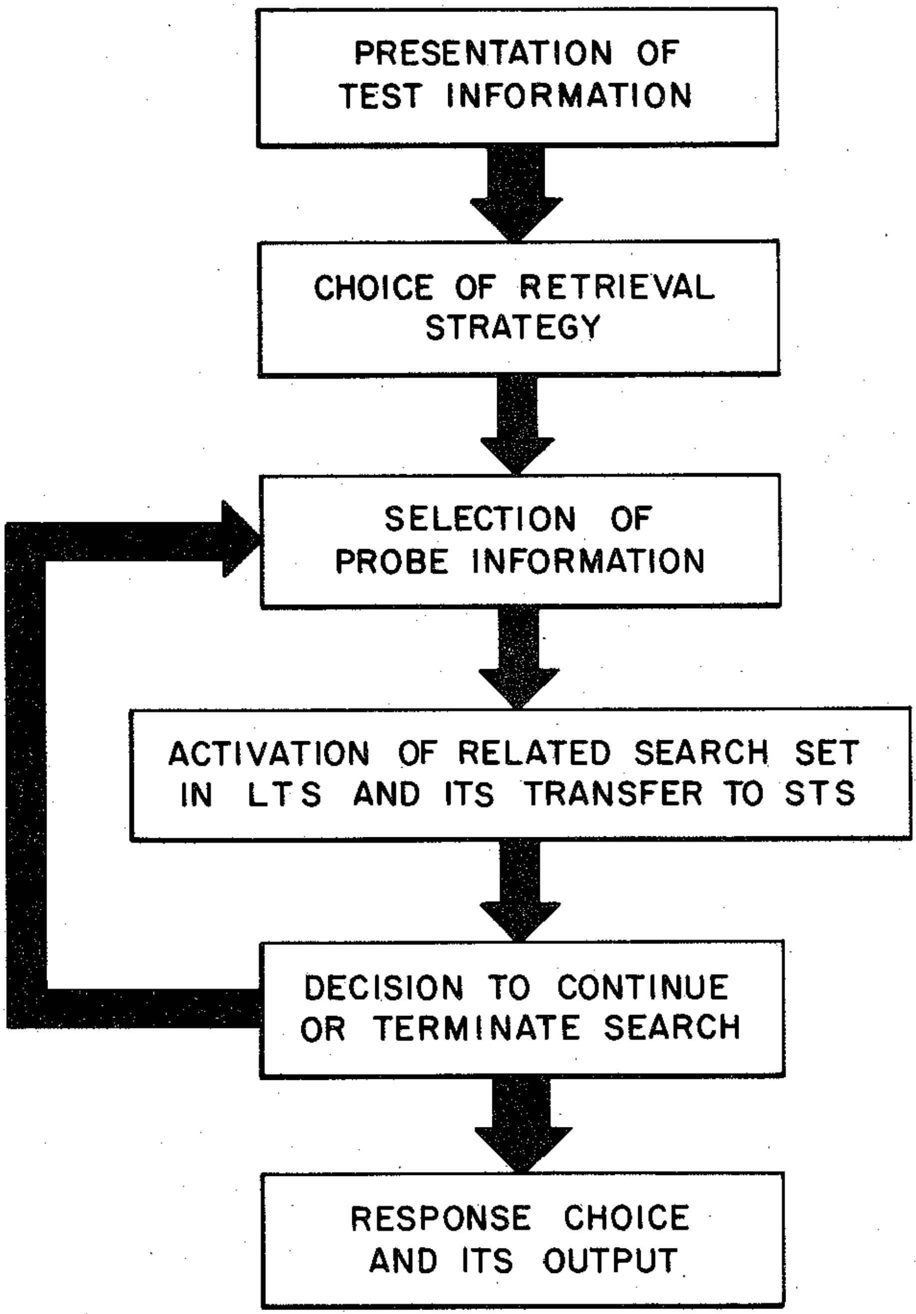
modalities, and entered into STS. Information resides in STS for a period of time that is usually under the control of the subject. By rehearsing one or more items the subject can keep them in STS, but the number that can be maintained in this way is strictly limited. For example, most people can maintain 7 to 9 digits. Once an image is lost from STS, it cannot thereafter be recovered from STS. During the period in which information resides in STS it may be copied into long-term store (or LTS); we shall see that the transfer of information from STS to LTS is highly dependent upon rehearsals of that information in STS. LTS is assumed to be a relatively permanent memory store, from which information is not lost. Information is copied from LTS to STS as well as in the reverse direction; in fact, we assume that during the period an image resides in STS, some information in LTS closely associated with that image will be activated and also entered into STS. Thus information entering STS from the sensory registers will initially be specific to the modality of input, but almost at once close associations from LTS in all modalities will be activated and placed in STS. For example, a word may be presented visually, but immediately after input the articulatory-verbal "name" and associated meanings will be activated from LTS and placed in STS.

Our account of STS and LTS does not require that the two stores necessarily be in different parts of the brain, or involve different physiological structures. It is possible, for example, to view STS simply as a temporary activation of some portion of LTS. The same physiological structures might be involved in both instances, the only distinction being whether or not a given structure is currently activated. Also, in our thinking we tend to equate STS with "consciousness"; the thoughts and information of which we are currently aware can be considered to be part of the current contents of STS. Such a statement lies in the realm of phenomenology, and as stated cannot be scientifically verified. Nevertheless, thinking of STS in this way may help the reader conceptualize the short-term system. Because consciousness is equated with STS, and because control processes are centered in and act through STS, this store is considered to be a "working memory": a store in which decisions are made, problems are solved, and information flow is directed.

Retrieval of information from STS is quite fast and accurate. Experiments by Saul Sternberg at Bell Telephone Laboratories and others have shown that the retrieval time for information in STS such as letters and numbers ranges from 10 to 30 milliseconds per character. The retrieval of information from LTS is considerably more complicated. So much information is contained in LTS that the major problem is finding access to some small subset of this information which contains the desired image. This problem might be likened to the task of locating a particular book in a library. Once the book is located, it may then be scanned in an attempt to recover the desired information. We propose that the subject activates a likely subset of information, places it in STS, and then scans STS for the desired image (which may not be present in the current subset). The retrieval process therefore becomes a search in which various subsets are activated and scanned. The conception is depicted in Figure 2. On the basis of the test query the subject selects a small set of features termed "probe information" and places the probe in STS. The subset of information in LTS closely associated with the probe will then be activated and entered into STS; this subset is termed

Figure Caption

<u>Figure 2.</u> Information flow and decisions during the search of long-term memory. The probe is placed in STS, then information in LTS closely associated with the probe is activated and placed in STS. This set of information is called the "search-set." Before the search-set is lost from STS, the subject draws images from the search-set for examination. If the desired information is not found, the search is either stopped, or recycled to another selection of probe information.


PRESENTATION OF TEST INFORMATION
CHOICE OF RETRIEVAL STRATEGY
SELECTION OF PROBE INFORMATION
ACTIVATION OF RELATED SEARCH SET IN LTS AND ITS TRANSFER TO STS
DECISION TO CONTINUE OR TERMINATE SEARCH
RESPONSE CHOICE AND ITS OUTPUT

the "search-set." The subject selects from the search-set some image, which is then examined. The information extracted from the selected image is utilized for a decision: has the desired information been found? If so, the search is terminated. Even if the information has not been found, termination may occur if the subject decides continuation is unlikely to be productive. If the search does continue, the subject begins the next cycle of the search by selecting a probe once again. This may or may not be the same probe used on the preceding cycle, depending upon the subject's strategy. For example, the subject may be asked to search for states of the United States starting with the letter M. He may do so by generating states at random and checking their first letter (in which case the same probe information may be used on each search cycle) or he may generate successive states in a regular geographic order (in which case the probe information is systematically changed from one cycle to the next). It can be shown that strategies in which the probe information is systematically changed will more often result in successful retrieval, but will take longer to do so than alternative "random" strategies. Note that the Freudian concept of repressed memories would be handled in this framework by an inability of the subject to generate an appropriate probe.

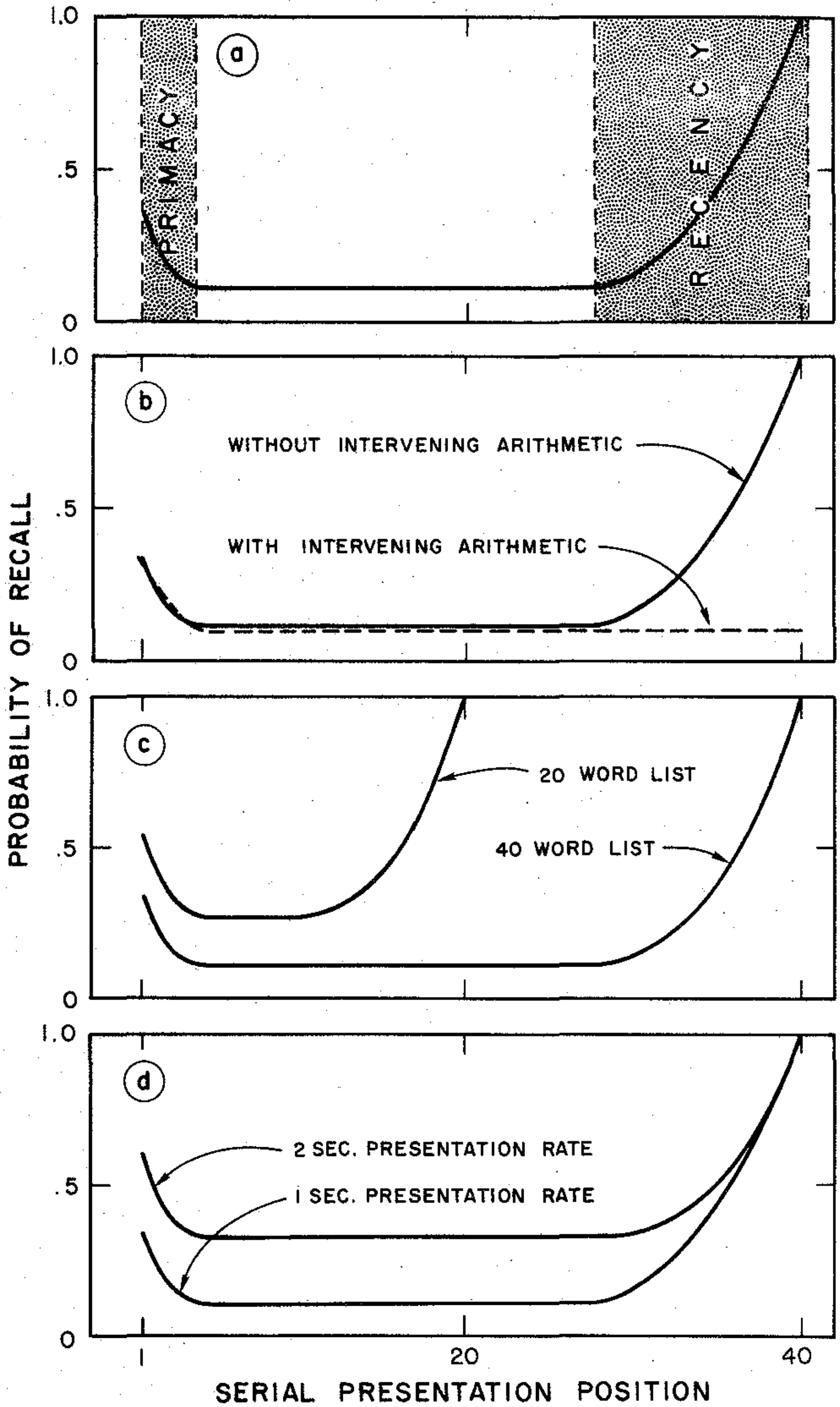
The Effects of Rehearsal

The reader has undoubtedly noticed that this theory portrays the memory system almost entirely in terms of the operations of STS. This is quite intentional. In our view, information storage and retrieval is best described in terms of the flow of information through STS, and in terms of the subject's control of the flow. One of the most important of these control processes is rehearsal; rehearsal is an overt or covert repetition of information that either increases its momentary strength in STS or otherwise delays its loss. Some examples have been mentioned earlier; other uses of rehearsal occur during the taking of lecture notes or during the act of performing mental arithmetic. Rehearsal can be shown not only to maintain information in STS but also to control transfer from STS to LTS. We will present several experiments concerned with an analysis of the rehearsal process.

The research in question involves a memory paradigm known as "free recall." Because the experiments to be considered here are based on one or another variation of this paradigm, it will be described in some detail. The situation is analogous to one in which you are asked to name the people present at the last large party you attended. The experimental procedure is extremely simple. A list of random items (usually common English words) is presented to the subject one at a time. Following presentation the subject attempts to recall as many words as possible in any order. Many psychologists have worked with this paradigm and major research efforts have been carried out by Bennet Murdock at the University of Toronto, Endel Tulving at Yale University, and Murray Glanzer at New York University. The result of principal interest is the probability of recalling each item in a list as a function of its serial presentation position. Plotting this function yields a U-shaped curve of the form presented in Figure 3a. The increased probability of recall for the first few words in the list is called the <u>primacy effect</u>; the large increase for the last 8 to 12 words is called the <u>recency effect</u>. There is considerable evidence that the recency effect is due to retrieval

Figure Caption

<u>Figure 3.</u> The probability of recall as a function of serial presentation position for various free recall experiments. In free recall a list of words is sequentially presented to the subject and then he is asked to recall them in any order. (a) The basic serial position curve: the rise on the right is called the recency effect because these words are the most recently presented; the rise on the left is called the primacy effect because these are the first words presented. (b) If an arithmetic task is interpolated between presentation and recall the recency effect disappears but earlier portions of the curve are unaffected. The recency effect thus appears to be due to retrieval from STS, and is eliminated when arithmetic causes the words to be lost from STS. (c) The list length effect demonstrates LTS retrieval failure in free recall. Words in long lists are recalled less well than words in short lists. (d) The time available to rehearse each word affects LTS retrieval: slower presentation results in better recall. The above graphs are idealized, and are based on experiments reported by James Deese, Bennet Murdock, Leo Postman and Murray Glanzer.



a
PRIMACY
RECENCY
b
WITHOUT INTERVENING ARITHMETIC
WITH INTERVENING ARITHMETIC
c
20 WORD LIST
40 WORD LIST
d
2 SEC. PRESENTATION RATE
1 SEC. PRESENTATION RATE
PROBABILITY OF RECALL
1.0
.5
0
1
20
40
SERIAL PRESENTATION POSITION

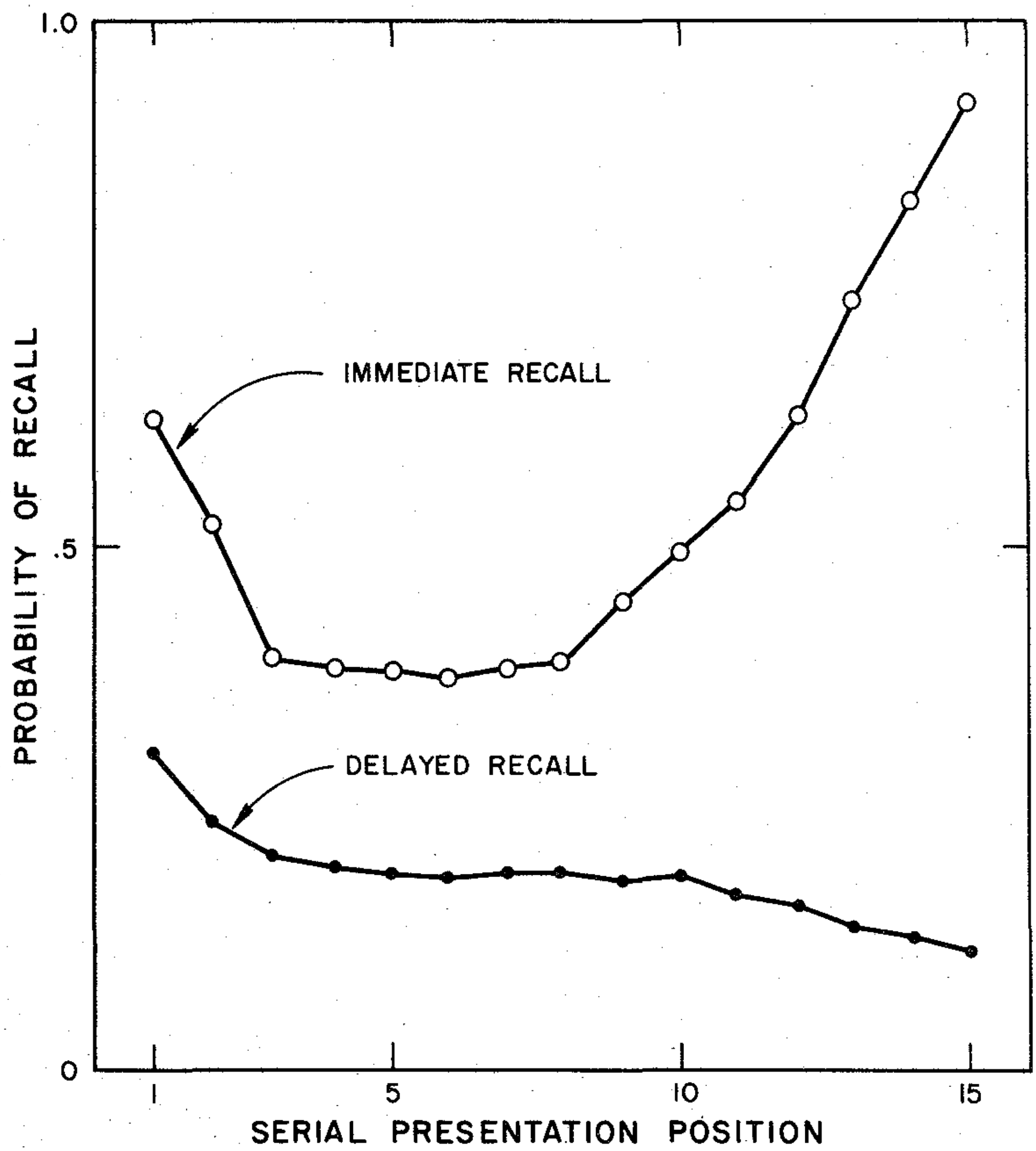
from STS, and that the earlier portions of the serial position curve reflect LTS retrieval only. In one paradigm, for example, the subject is required to carry out a difficult arithmetic task for 30 seconds immediately following list presentation and then asked to recall. One can assume that the arithmetic task causes the loss of all words in STS so that recall reflects LTS retrieval only. Indeed, the recency effect is eliminated when this experiment is performed; furthermore, the earlier portions of the serial position curve are unaffected (see Figure 3b).

Variables that influence LTS but not STS also can be manipulated. In these cases, the recency portion of the serial position curve should be relatively unaffected, while the earlier portions of the curve should show changes. One variable that affects LTS but not STS is the number of words in the presented list. As seen in Figure 3c, a word in a longer list is less likely to be recalled, but the recency effect is quite unaffected by list length. Similarly, increases in presentation rate decrease the likelihood of recalling words prior to the recency region, but leave the recency effect largely unaffected (see Figure 3d).

In free recall experiments many lists are usually presented in a session. If the subject is asked at the end of the session to recall all the words presented during the session, we would expect his recall to reflect LTS retrieval only. The probability of recalling words as a function of their serial position within each list can be plotted for end-of-session recall and compared with the serial position curve for recall immediately following presentation. The results of such an experiment are shown in Figure 4. For the delayed recall curve the primacy effect remains, but as predicted the recency effect is eliminated. In

Figure Caption

Figure 4. In addition to a recall test immediately following each list presentation, the subject may be asked at the end of an experimental session to recall all the words from that session. The delayed test should reflect LTS retrieval only. This prediction is verified by the serial position curve for the delayed test: the increasing recency effect is missing. The data are from Fergus Craik.


1.0
.5
0
PROBABILITY OF RECALL
IMMEDIATE RECALL
DELAYED RECALL
1
5
10
15
SERIAL PRESENTATION POSITION

summary, the recency region appears to reflect retrieval from both STS and LTS, whereas the serial position curve prior to the recency region reflects retrieval from LTS only.

In 1965 at a conference sponsored by the New York Academy of Sciences we put forth a mathematical model explaining these and other effects in terms of a rehearsal process. It was postulated that the subject was rehearsing a small number of words in STS at all times during presentation, including the item most recently presented. The words still being rehearsed in short-term store when the last list item has been presented were assumed to be output at once (giving rise to the recency effect). The transfer of information to LTS was assumed to be a function of the amount of rehearsal given each item during list presentation. Since the words presented first in the list do not have to share rehearsal with many other items, they were assumed to receive additional rehearsal. This extra rehearsal was supposed to cause more transfer of information to LTS for the first items (thus giving rise to the primacy effect).

This rehearsal model was given a formal mathematical statement and fit to a wide array of experiments. The model provided an excellent quantitative account of a great many results in free recall, including those discussed in this paper. A more direct confirmation of the model has recently been provided by Dewey Rundus at Stanford University. He carried out free recall experiments in which subjects rehearsed aloud during list presentation. This overt rehearsal was tape-recorded, and compared with the recall results. The discussion is simplified if the term "rehearsal set" is used to refer to those items overtly rehearsed between successive presentations of words. The number of different words contained in the rehearsal set was found to start at 1 following the first word presented and then to rise until the fourth word; from the fourth word on the number of different words in the rehearsal set remained fairly constant (at about 3.3) until the end of the list (see Figure 5a). The subjects almost always reported the members of the most recent rehearsal set when the list ended and recall began. Some particularly interesting data from these experiments are seen in Figure 5b. The figure superimposes on the serial position curve a curve giving the mean number of total rehearsals for items presented in various serial positions. A close correspondence is evident between number of rehearsals and recall probability for words prior to the recency effect; in the recency region, however, a sharp disparity occurs.

These findings provide considerable support for the assumption that LTS storage is a function of the number of rehearsals, and that the recency effect arises from STS retrieval rather than LTS. The hypothesis that storage is a function of the number of rehearsals can be checked in other ways. For example, the recall probability for a word prior to the recency region was plotted as a function of the number of rehearsals received by that word. The result was an almost linear, sharply increasing function. Furthermore, consider words presented in the middle of the list that happened to be given the same number of rehearsals as the first item presented. The recall probability for such items was identical to that for the initially presented item.

Having established the efficacy of rehearsal both in storing information in LTS and maintaining information in STS, an experiment was carried out in which the subjects' rehearsal was manipulated directly.

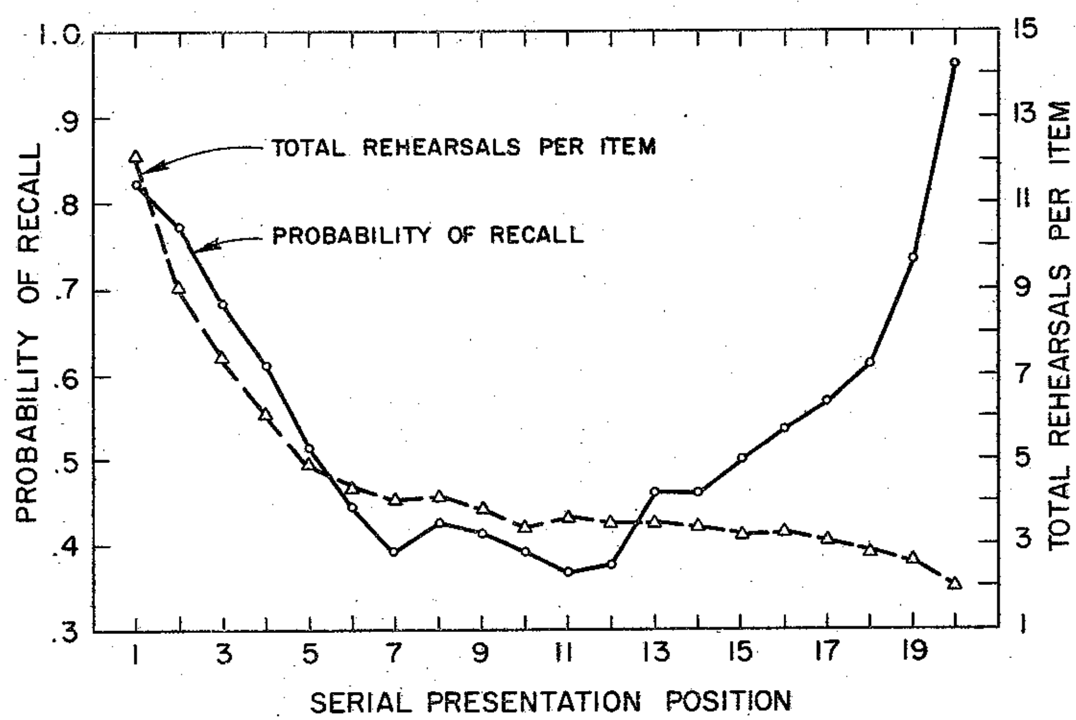
Figure Caption

Figure 5. (a) Example of a subject's rehearsal protocol. A partial listing of a subject's overt rehearsals in an experiment by Dewey Rundus. Note that the first word presented is given more total rehearsals than later words. (b) Probability of recall compared with total number of rehearsals, at each presentation position. Prior to the recency region, rehearsals and recall are closely related. Thus, LTS storage depends on the number of rehearsals given an item, and the storage differences appear in LTS retrieval.

(a)

Item Presented	Item's Rehearsed (Rehearsal Set)
1. Reaction	Reaction, Reaction, Reaction, Reaction
2. Hoof	Hoof, Reaction, Hoof, Reaction
3. Blessing	Blessing, Hoof, Reaction
4. Research	Research, Reaction, Hoof, Research
5. Candy	Candy, Hoof, Research, Reaction
6. Hardship	Hardship, Hoof, Hardship, Hoof
7. Kindness	Kindness, Candy, Hardship, Hoof
8. Nonsense	Nonsense, Kindness, Candy, Hardship
⋮	
20. Cellar	Cellar, Alcohol, Misery, Cellar

(b)



Subjects were trained to engage in one of two types of rehearsal (see Figure 6a). In the first (One-item rehearsal set) the most recently presented item was rehearsed exactly three times before presentation of the next item--no other items were rehearsed. In the second (Three-item rehearsal set) the subject rehearsed the three most recently presented items, once each before presentation of the next item; the first rehearsal set contained three rehearsals of the first word, the second rehearsal set contained two rehearsals of the second word and one rehearsal of the first word, and all subsequent rehearsal sets contained one rehearsal of each of the most recent three items. The results are shown in Figure 6b. When only one item is rehearsed at a time, each item receives an identical number of rehearsals. In this case the primacy effect disappears, as predicted. Note that the recency effect appears for items prior to the last item, even though the last item is the only one in the last rehearsal set. This fact indicates that items, even when dropped from rehearsal, require an additional period of time before they are completely lost from STS. The curve for the three item rehearsal condition shows this effect also: the last rehearsal set contains the last three presented items and these are recalled perfectly. Nevertheless, a recency effect is still seen for items prior to these three. It also should be noted that a primacy effect occurs in this condition. This was predicted because the first item in this condition received a total of 5 rather than 3 rehearsals.

In addition to these results, a delayed recall test for all words was given at the end of the experimental session (similar to the procedure the results of which are given in Figure 4). The data from this

Figure Caption

Figure 6. (a) Schematic outline of rehearsal sequences for two different rehearsal strategies given to the subject by the experimenter. In the first only the item currently being presented is rehearsed, and all items receive an equal number of rehearsals. In the second, the last three items presented are rehearsed; in this case the first two items receive more rehearsal than the remaining items. Letters in the figure represent words in the study list. (b) Results for the two rehearsal schemes. Note that for immediate recall primacy disappears when all items are given equal rehearsal. For both types of rehearsal, a noticeable recency effect exists for items prior to those in the last set being rehearsed. This indicates that items when no longer rehearsed take some additional period before they are lost from STS. The lower curves give the results from a recall test given at the end of the experimental session. These curves, which reflect LTS retrieval only, closely mirror the number of rehearsals accorded items during presentation.

(a)

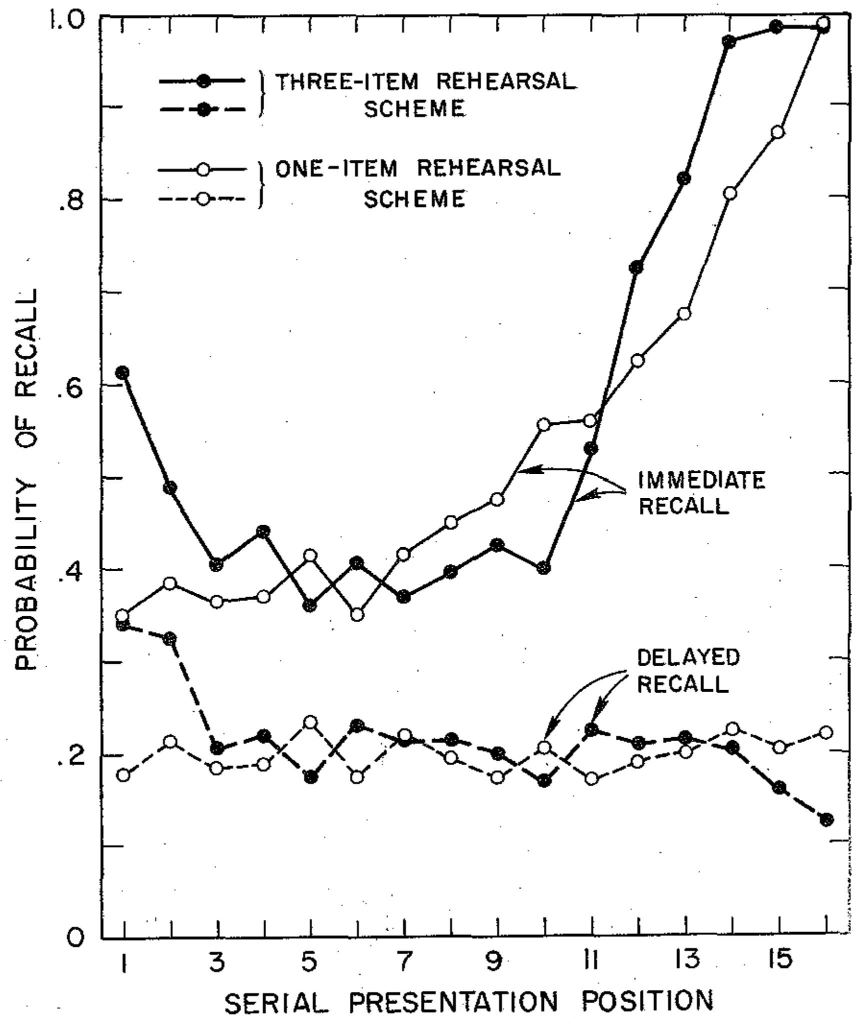
One-Item Researsal Scheme

Serial Position	Item Presented	Items Rehearsed	Total Rehearsals Per Item
1	A	AAA	3
2	B	BBB	3
3	C	CCC	3
4	D	DDD	3
5	E	EEE	3
6	F	FFF	3
⋮	⋮	⋮	⋮
14	N	NNN	3
15	O	OOO	3
16	P	PPP	3

Three-Item Rehearsal Scheme

Serial Position	Item Presented	Items Rehearsed	Total Rehearsals Per Item
1	A	AAA	5
2	B	BBA	4
3	C	CBA	3
4	D	DCB	3
5	E	EDC	3
6	F	FED	3
⋮	⋮	⋮	⋮
14	N	NML	3
15	O	ONM	2
16	P	PON	1

(b)



delayed test, which reflect retrieval from LTS only, are also given in Figure 6b (the lower two curves). Note that LTS retrieval closely parallels the number of rehearsals given an item during presentation, for both rehearsal schemes.

The Structure and Function of the Short-term Store

These results strongly implicate rehearsal in the maintenance of information in STS and the transfer of that information to LTS. The question then arises: what are the forgetting and transfer characteristics of STS in the absence of rehearsal? Attempts to control rehearsal have usually involved a difficult verbal task such as arithmetic. For example, Lloyd and Margaret Peterson at Indiana University (see Short-term memory, Scientific American, July, 1966, 215 (1), 90-95) presented a three letter trigram to be remembered; the subject next engaged in a period of arithmetic and then was tested for his trigram memory. Figure 7 illustrates the probability of recall as a function of the duration of arithmetic. The loss observed over time is similar to that seen in the recency effect in free recall. The reasons are apparent: STS loss caused by an arithmetic task is similar to STS loss caused by a series of intervening words to be remembered. The asymptote of the curve in Figure 7 reflects the retrieval of the trigram from LTS alone, and the earlier portions of the curve represent retrieval from both STS and LTS. The loss of the trigram from STS is thus represented by a decreasing function prior to the asymptote.

It has often been assumed that the forgetting observed during arithmetic reflects an automatic STS decay which inevitably occurs in the absence of rehearsal. These views have ignored the effect of the

Figure Caption

Figure 7. Probability that a three letter trigram will be recalled following a period of arithmetic. The arithmetic is presumed to prevent rehearsal. Earlier theories proposed that STS decay in the absence of rehearsal was represented by the curve in this illustration, but they failed to take into account the effect of the arithmetic task itself. The data is based on experiments by Lloyd and Margaret Peterson.

arithmetic itself. Other theories have tried to implicate the intervening activity as the cause of the loss. Indeed, evidence is available showing that the amount of new material between presentation and test on a given item of information is a much more important determinant of STS loss than the amount of time between presentation and test. However, there are at least two explanations of this finding. The first holds that the activity between presentation and test is the direct cause of an item's loss from STS. The second explanation proposes that STS information decays at a fixed rate in time in the absence of rehearsals, but that rehearsals will delay the loss. The latter explanation supposes that the rate of intervening activity will affect the number of rehearsals that can be given to the to-be-remembered item, and thus indirectly determine the rate of loss.

It has recently become possible to choose between these two explanations of STS loss. The impetus arose in a thesis by Judith Reitman at the University of Michigan. She substituted a signal detection task for the arithmetic task in the Peterson and Peterson paradigm. The signal detection task consisted of responding whenever a weak tone was heard in a continuous background of white noise. Surprisingly, no STS loss was observed after 15 seconds of this task, even though subjects reported no rehearsal during the signal detection. If we accept the view that rehearsal is not occurring, then we could conclude that STS loss is due to the type of interference during the intervening interval. Another important issue which could potentially be resolved using the Reitman paradigm concerns the transfer of information from STS to LTS: does transfer occur only at initial presentation and at subsequent rehearsals, or instead throughout the period that the information resides in STS, regardless of rehearsals?

To answer these questions, the following experiment was carried out. The design is given in Figure 8. A consonant pentagram (such as QJXFK) was presented for 2.5 seconds for the subject to memorize. This was followed by a signal detection task in which pure tones were presented at random intervals in a continuous background of white noise. The subjects pressed a key whenever they thought they detected a tone (this task was difficult--only about three-fourths of the tones presented were correctly detected). The signal detection period lasted for either 1, 8, or 40 seconds, with tones occurring on the average every 2.5 seconds. In conditions 1, 2, and 3 the subjects were tested on the consonant pentagram immediately following the signal detection. In conditions 4, 5, and 6 the subjects were required to carry out 30 seconds of difficult arithmetic following the signal detection before they were tested. To insure that rehearsal would not occur, subjects were paid for performing well on signal detection, and for accurately performing their arithmetic, but were not paid for letter memory. In addition, they were instructed not to rehearse letters during signal detection or arithmetic. When queried, subjects reported they were not consciously aware of rehearsing. However, because the question of rehearsal is quite important, an additional experiment was carried out. Upon completion of the first experiment, subjects were run in the same conditions, but with new instructions to rehearse the pentagram aloud following each tone detection.

The pattern of results is depicted in Figure 9. The two lower curves represent retrieval from LTS only, since these curves give

Figure Caption

Figure 8. The design of a short-term letter memory experiment in which arithmetic and signal detection are both used to prevent rehearsal. A random array of five consonants, such as XKVJZ, is presented for 2.5 seconds. The subject then carries out 1, 8, or 40 seconds of signal detection (detecting brief tones in a continuous background of white noise), followed by 0 or 30 seconds of arithmetic, followed by a test for letter memory. In one variation of the experiment subjects rehearsed during the signal detection task, and in the other they did not.

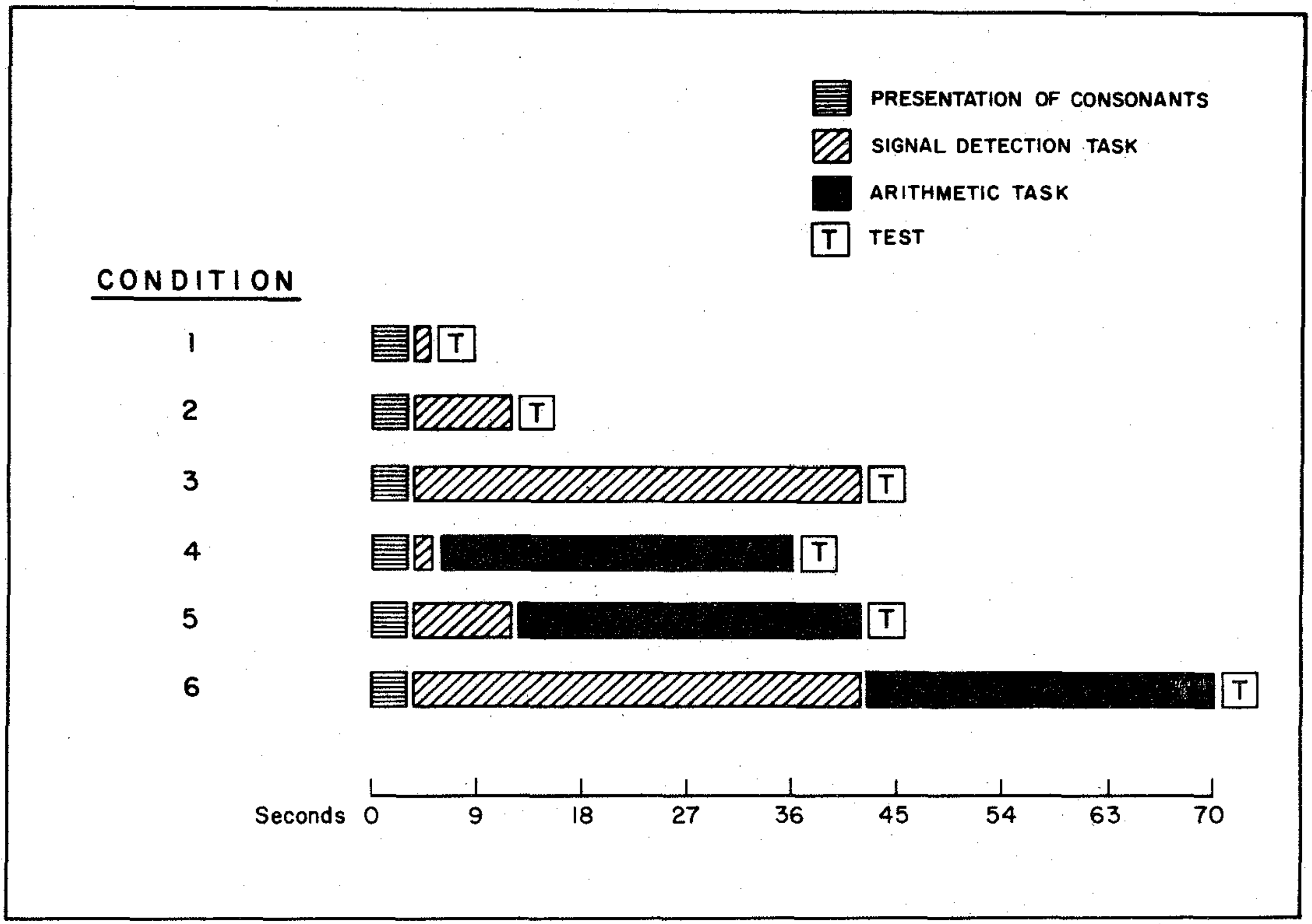
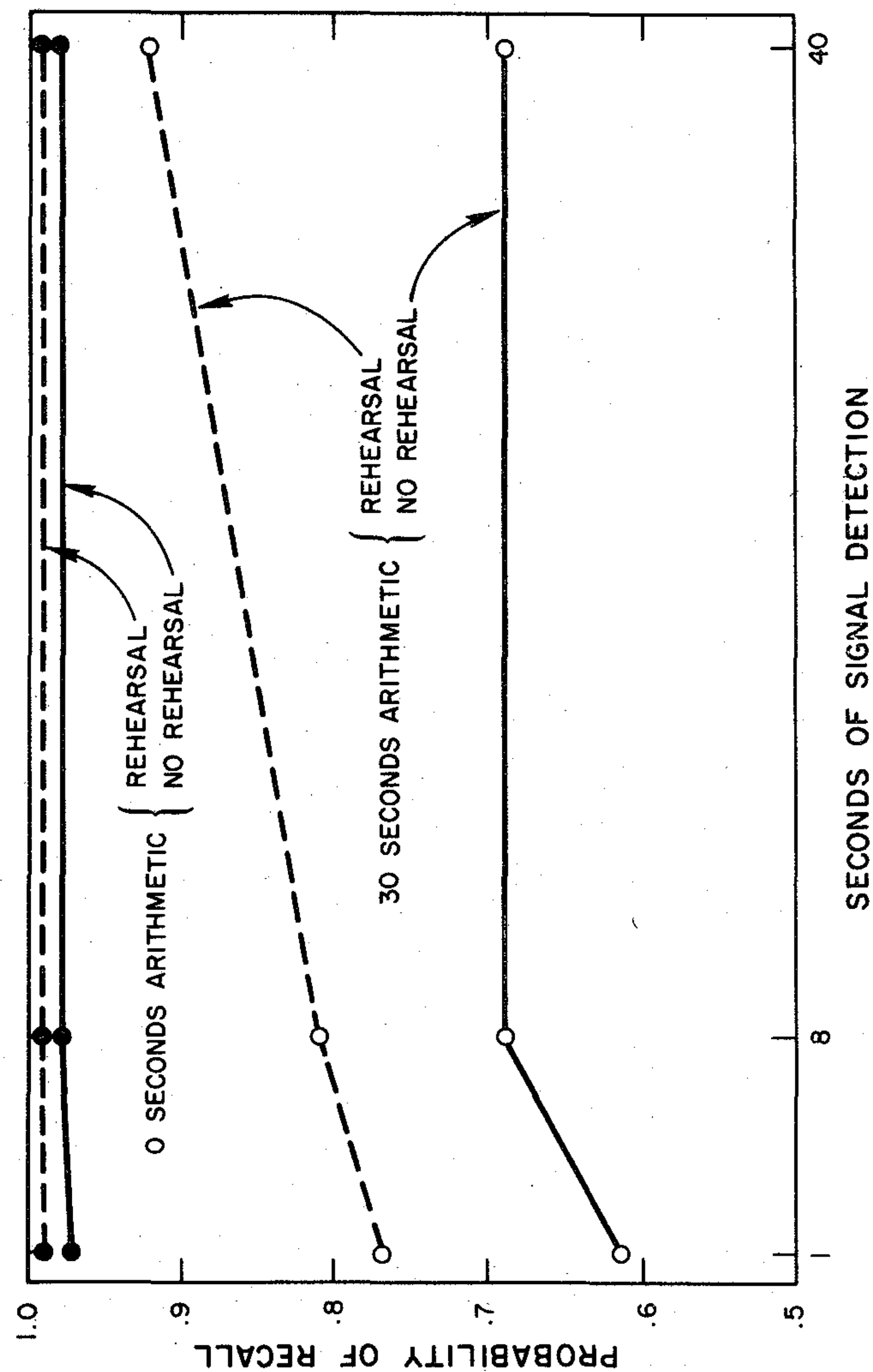

PRESENTATION OF CONSONANTS
SIGNAL DETECTION TASK
ARITHMETIC TASK
T TEST
CONDITION
1
2
3
4
5
6
Seconds 0 9 18 27 36 45 54 63 70

Figure Caption

Figure 9. The results of the experimental design presented in Figure 8. The probability that a letter will be recalled in its correct position. The upper curves show that signal detection, with or without rehearsal, leaves STS relatively unaffected. The lower curves give LTS retrieval, since the long period of arithmetic causes the contents of LTS to be lost. The lower dashed curve rises throughout the period of signal detection because the rehearsal results in additional transfer from STS to LTS. However, the lower solid curve is horizontal over the last 32 seconds of signal detection. Thus a trace can remain in STS for considerable periods without significant transfer from STS to LTS, as long as rehearsal is not used.


PROBABILITY OF RECALL
1.0
.9
.8
.7
.6
.5
1
8
40
SECONDS OF SIGNAL DETECTION
0 SECONDS ARITHMETIC
REHEARSAL
NO REHEARSAL
30 SECONDS ARITHMETIC
REHEARSAL
NO REHEARSAL

performance following 30 seconds of arithmetic; we assume that arithmetic causes the pentagram information to be lost from STS. The top curves give performance when arithmetic is not used; they show that the signal detection task alone causes no loss whatever. Since performance is essentially perfect immediately following signal detection, regardless of the duration of signal detection, it may be presumed that this task does not produce forgetting from STS for verbal material.

What then does produce forgetting from STS? Information input and its analysis is not by itself enough: the subject is performing a difficult information processing task during the signal detection period, but no pentagram forgetting occurs. The same data show that time alone causes no noticeable forgetting. Yet verbal information (arithmetic) does cause a large loss. Thus Reitman's conclusion appears to be correct: forgetting is caused by the entry into STS of other similar information.

Note that the above arguments depend upon the assumption that rehearsal is not occurring during the signal detection period. Evidence that this is the case is seen if one compares the two lower curves in Figure 9. The dotted curve shows that performance improves if subjects rehearse overtly during the signal detection period. Presumably the rehearsal transfers information about the pentagram to LTS. This additional transfer to LTS is reflected in the retrieval scores, and the dotted curve rises. But the lowest curve is horizontal over the last 32 seconds of signal detection, indicating that no rehearsal was occurring during this period.

The fact that the lowest curve is flat over the last 32 seconds has important implications for STS to LTS transfer. This curve indicates that essentially no STS to LTS transfer occurred during this period. Yet the top curve shows that the trace remains in STS throughout this period. Hence the presence of a trace in STS is not alone enough to result in transfer to LTS. Apparently transfer to LTS occurs primarily during or shortly after rehearsals. The rise in the lowest curve over the first 8 seconds may indicate that the transfer effects of a presentation or rehearsal take at least a few seconds to reach completion. Work along these lines is being pursued, and many questions remain. Still this discussion should indicate how an understanding of control processes, and experimental manipulation of them, can provide answers to basic questions about the structure and function of the memory system.

The emphasis we have given in the above discussion to rote rehearsal does not imply that other control processes are of lesser importance. Although much evidence indicates STS to LTS transfer is strongly dependent upon rehearsals, effective LTS retrieval can be shown to be strongly dependent upon the type of information that is rehearsed. The choice of particular information to be rehearsed in STS is a control process called coding. There are many coding strategies that have dramatic effects on long-term retrieval. In general, these strategies consist of adding appropriately chosen information from LTS to a trace to be remembered, and then rehearsing the entire complex in STS. Consider, for example, the following verbal mnemonic. Suppose you are given (as is typical in memory experiments) the stimulus-response pair "HRM - 4"; later "HRM" will be presented alone and you will be expected to respond "4." If you simply rehearse HRM - 4 several times, your ability to respond correctly later will probably not be high. Suppose, however, you notice that HRM reminds you of "homeroom" and you think of various aspects of your fourth grade classroom. In this case your ability to recall the correct response will increase markedly.

Numerous experiments have demonstrated the efficacy of such coding techniques. Why does such a control process enhance retrieval? First of all, the amount and range of information stored during coding appears to be greater than that stored when rote rehearsal is used. Secondly, the coding operation provides a straightforward means by which the subject can gain access to an appropriate and small region of memory during retrieval. In the above example, when HRM is presented at the moment of test, the subject who has been coding would be likely to notice, just as he did during the initial presentation, that HRM was similiar to "homeroom." He could then use "homeroom" (and the current temporal context) as a further probe and would almost certainly access "fourth grade" and thence generate the correct response.

There are numerous coding techniques, and many popular books have been written by professional mnemonists who put forth techniques of this sort as "tricks" to aid one's memory. Some of the most effective techniques use imaging, a type of coding in which the subject forms visual images as an aid to retrieval. Many specialized coding techniques have been shown to be especially helpful for particular tasks. Techniques have been developed to help learn paired-associates, dates of special events, commonly used numbers, long lists, speeches, and outlines for lectures. The interested reader can turn to specialty books for examples (an historical treatment can be found in The Art of Memory by F. A. Yates, Chicago: University of Chicago Press, 1966).

In addition to coding, imaging and rehearsal, "decision making" characterizes a class of control processes of great importance. Decision making usually involves a rule or strategy that enables the subject to choose between several possible courses of action, or several possible responses. For example, suppose subjects are asked to recall as many state names as possible. One subject might decide to adopt the strategy of naming states alphabetically, another might name them in geographic order, and a third might decide to name them in the order that they first come to mind. Considerable differences in performance can result from such decisions.

Long-term Retrieval and Forgetting

The discussion of coding has indicated how retrieval may be enhanced by storing information in such a way that cues will later be available to probe LTS accurately. That is, the key to retrieval is the selection of probe information that will activate an appropriate search-set from LTS. Since in our view LTS is a relatively permanent store, forgetting is assumed to result from an inadequate selection of probe information, and a resulting failure of the retrieval process. There are two basic ways in which the probe selection may prove inadequate. The first refers to cases where the wrong probe is selected. For example, you might be asked to name the star of a particular movie. The name actually begins with T but you decide that it begins with A and include "A" in the probe information used to access LTS. As a result the correct name may not be included in the search-set which is drawn into STS, and retrieval will not succeed. The second way probe selection can prove inadequate depends on the size of the search-set accessed by the probe. If the probe is such that an extremely large region of memory is accessed, then retrieval may fail even though the desired trace is included in the search-set.

Currently research is being carried out to identify the precise mechanisms that are responsible, but the effect itself is quite clear. For example, if asked to name a fruit which sounds like a word meaning "to look at" you might say "pear." But if asked to name a living thing which sounds like a word meaning "to look at," the probability of responding "pear" will be greatly reduced. As another example, suppose you attend a party with five other people, one named "John Smith." If asked later to name the people at the party, you might be likely to remember "John Smith." If there had been 20 people at the party, recall of this name would have been less likely. However, besides a failure of the memory search, other explanations of this effect can be proposed. It could be argued that more attention was given to "John Smith" at the smaller party. Or if the permanence of LTS is not accepted, it could be argued that the names of the many other people met at the larger party could erode or destroy the memory trace for "John Smith." Are these objections reasonable? To answer this question we note that this example is analogous to that seen in free recall when lists containing five or 20 words are presented for recall. As shown in Figure 3c, words in longer lists are less well recalled from LTS than words in short lists.

We would like to show that the list length effect in free recall is dependent upon the choice of probe information used to access the to-be-recalled list, rather than upon the number of words intervening between presentation and recall, or upon differential storage given words in lists of different size. The second issue is disposed of rather easily:

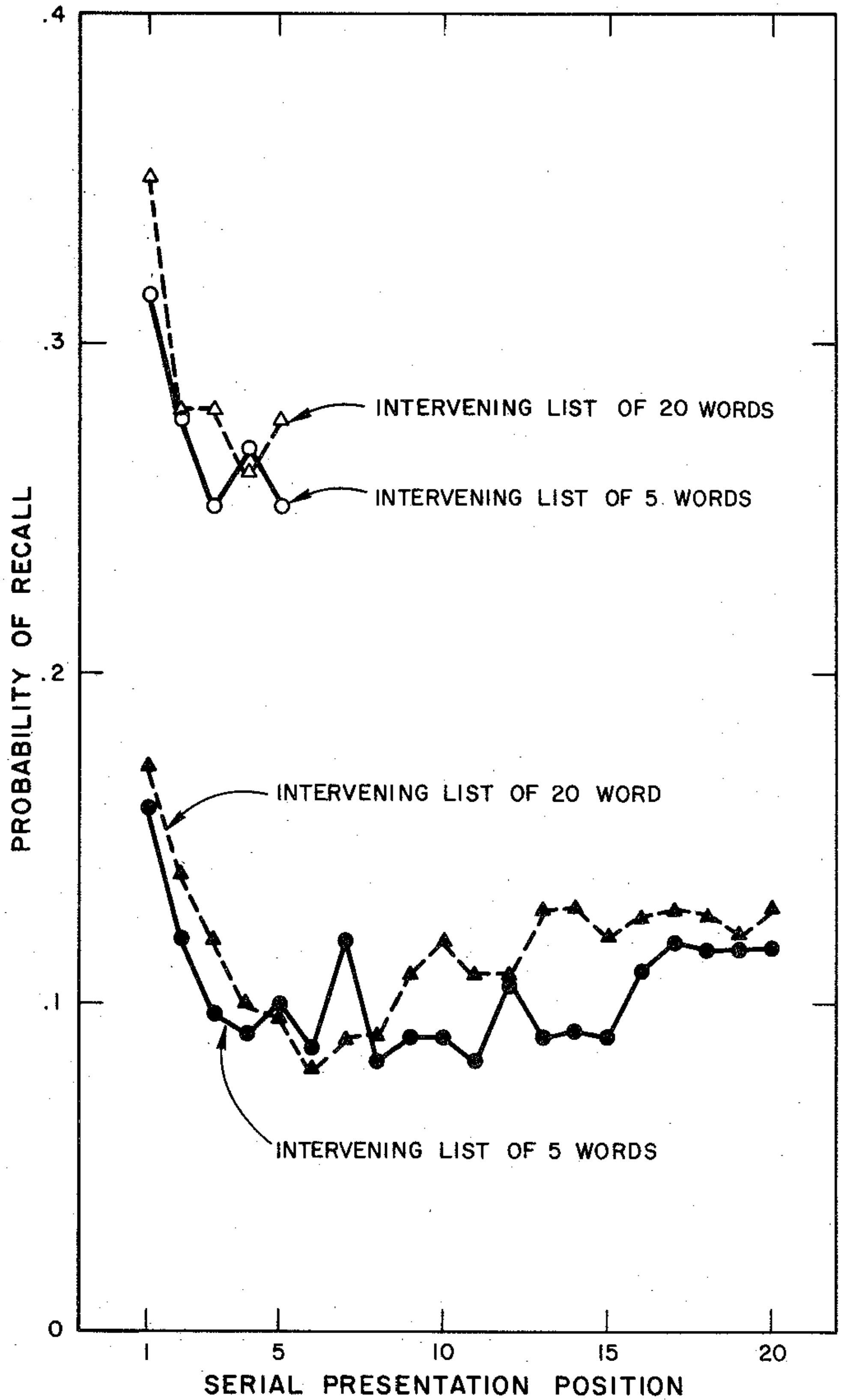
in many free recall experiments which vary list length the subjects do not know at the beginning of the list what the length of the list will be. Thus they cannot reasonably store different amounts of information for the first several words in the lists of differing length. Nevertheless the first several words are recalled at different levels (see Figure 3c). To dispose of the interference explanation (which implicates the number of words between presentation and recall) is more difficult. Until fairly recently interference theories of forgetting have been predominant (see Benton J. Underwood, Forgetting, Scientific American, 1964, 210 (3), 91-99, and John Ceraso, The Interference Theory of Forgetting, Scientific American, 1967, 217 (4), 117-124). In these theories, forgetting has often been seen as a matter of erosion of the memory trace--usually caused by items presented following the item to be remembered, but also caused by items prior to the item to be remembered. The list length effect might be explained in these terms since the average item in a long list is preceded and followed by more items than the average item in a short list. On the other hand, the retrieval model presented in this paper assumes LTS to be permanent and maintains that the strength of long-term traces is independent of list length. Forgetting results from the fact that the temporal-contextual probe cues used to access any given list tend to elicit a larger search-set for longer lists, thereby producing less efficient retrieval.

In order to distinguish between the retrieval and interference explanations, the following experiment was carried out. A series of lists of varying lengths were presented. Following each list the subject attempted to free recall not the list just studied (as in the typical free recall procedure) but instead the list preceding the last list studied. This procedure eliminates the confounding between the size of the list being recalled and the number of words intervening between presentation and recall. A large or small list to be recalled can be followed by either a large or small intervening list. The retrieval model predicts that recall probability will be dependent upon the size of the list being recalled, assuming that the subject has probe information to access this list. The interference model predicts the major component of performance to be determined by the number of words in the intervening list. In the experiments, list lengths of five and 20 were alternated randomly in a session.

The results are depicted in Figure 10. Four conditions are distinguished: 5-5, 5-20, 20-5, 20-20 where the first number gives the size of the list being recalled and the second number gives the size of the intervening list. The results are plotted as serial position curves similar to those in Figure 3b. Note that there is no recency effect in any of the curves; this would be expected since there is another list and another recall intervening between presentation and recall. The intervening activity causes the words in the tested list to be lost from STS; consequently, the curves represent retrieval from LTS only. The results presented in Figure 10 seem quite clear: words in lists of length 5 are recalled much better than words in lists of length 20, but the length of the intervening list has little, if any effect. The retrieval model can predict these results only if a probe is available to access the requested list. It seems likely in this experiment that the subject has available at test appropriate cues (probably temporal in nature) to

Figure Caption

Figure 10. Serial position curves for a free recall task in which the subject recalls the list *prior* to the one just studied. The top two curves give the recall probabilities for words in lists of length 5 with either a 5 or 20 word list intervening between presentation and recall. The lower two curves give the recall probabilities for words in lists of length 20, with either a 5 or 20 word list intervening between presentation and recall. The curves give results averaged from those obtained in a series of three experiments. The results show that a word's probability of recall is dependent upon the length of list in which it is imbedded, and independent of the number of words intervening between presentation and recall. The results are predicted by a theory which postulates LTS forgetting to be a failure of retrieval.



.4
.3
.2
.1
0
PROBABILITY OF RECALL
INTERVENING LIST OF 20 WORDS
INTERVENING LIST OF 5. WORDS
INTERVENING LIST OF 20 WORD
INTERVENING LIST OF 5 WORDS
1
5
10
15
20
SERIAL PRESENTATION POSITION

enable him to select probe information pertaining to the desired list. If the experimental procedure were changed so that the subject was asked to recall the 10th previous list, then selection of an adequate probe would no longer be possible. The results in Figure 10 demonstrate the importance of probe selection, a control process of STS. There are other control processes which can be used during retrieval. These include the strategy by which the search is terminated, the decision to accept a given image as the one sought, and the method by which new probes are generated when old ones prove unproductive.

Only a brief overview of the memory system has been presented, but hopefully it has clarified our approach, which integrates the system around the operations of short-term store. There is no intent to imply that the system as described is in any sense a final theory. As experimental techniques and mathematical models in the memory area have become increasingly sophisticated, theory has undergone progressive changes. There is no doubt that this trend will continue, but we think it quite likely that the short-term store and its control processes will be central to any future system.

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