The Control of Short-Term Memory

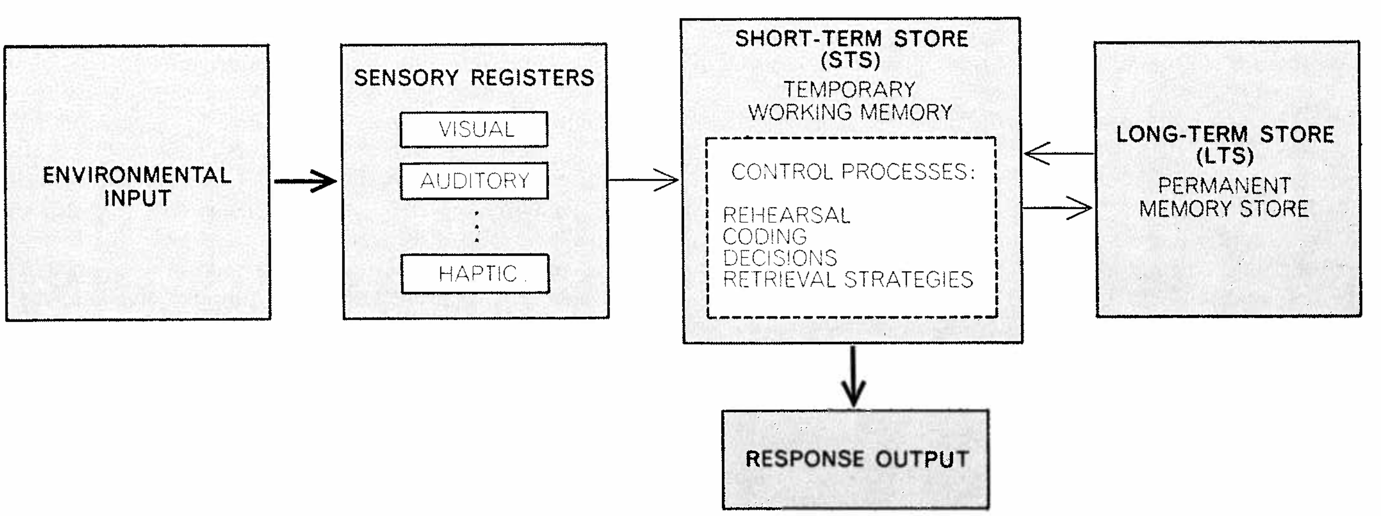
Memory has two components: short-term and long-term. Control processes such as "rehearsal" are essential to the transfer of information from the short-term store to the long-term one

by Richard C. Atkinson and Richard M. Shiffrin

The notion that the system by which information is stored in memory and retrieved from it can be divided into two components dates back to the 19th century. Theories distinguishing between two different kinds of memory were proposed by the English associationists James Mill and John Stuart Mill and by such early experimental psychologists as Wilhelm Wundt and Ernst Meumann in Germany and William James in the U.S. Reflecting on their own mental processes, they discerned a clear difference between thoughts currently in consciousness and thoughts that could be brought to consciousness only after a search of memory that was often laborious. (For example, the sentence you are reading is in your current awareness; the name of the baseball team that won the 1968 World Series may be in your memory, but to retrieve it takes some effort, and you may not be able to retrieve it at all.)

The two-component concept of memory was intuitively attractive, and yet it was largely discarded when psychology turned to behaviorism, which emphasized research on animals rather than humans. The distinction between short-term memory and long-term memory received little further consideration until the 1950's, when such psychologists as Donald E. Broadbent in England, D. O. Hebb in Canada and George A. Miller in the U.S. reintroduced it [see "Information and Memory," by George A. Miller; SCIENTIFIC AMERICAN, August, 1956]. The concurrent development of computer models of behavior and of mathematical psychology accelerated the growth of interest in the two-process viewpoint, which is now undergoing considerable theoretical development and is the subject of a large research effort. In particular, the short-term memory system, or short-term store (STS), has been given a position of pivotal importance. That is because the processes carried out in the short-term store are under the immediate control of the subject and govern the flow of information in the memory system; they can be called into play at the subject's discretion, with enormous consequences for performance.

Some control processes are used in many situations by everyone and others are used only in special circumstances. "Rehearsal" is an overt or covert repetition of information—as in remembering a telephone number until it can be writ-



INFORMATION FLOW through the memory system is conceived of as beginning with the processing of environmental inputs in sensory registers (receptors plus internal elements) and entry into the short-term store (STS). While it remains there the information may be copied into the long-term store (LTS), and associated information that is in the long-term store may be activated and entered into the short-term store. If a triangle is seen, for example, the name "triangle" may be called up. Control processes in the short-term store affect these transfers into and out of the long-term store and govern learning, retrieval of information and forgetting.

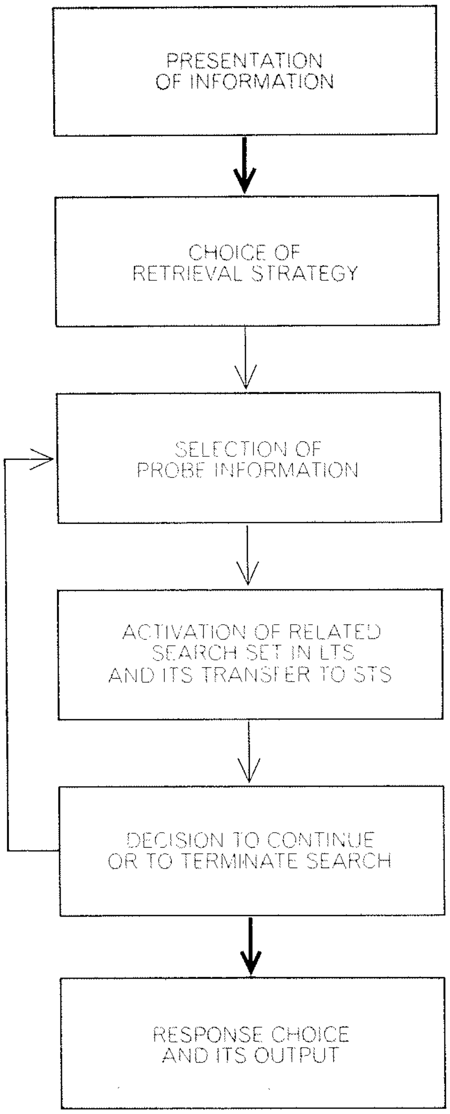
ten down, remembering the names of a group of people to whom one has just been introduced or copying a passage from a book. "Coding" refers to a class of control processes in which the information to be remembered is put in a context of additional, easily retrievable information, such as a mnemonic phrase or sentence. "Imaging" is a control process in which verbal information is remembered through visual images; for example, 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 building. There are other control processes, including decision rules, organizational schemes, retrieval strategies and problem-solving techniques; some of them 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 also from one encounter with the same task to the next.

We believe that the overall memory system is best described in terms of the flow of information into and out of short-term storage and the subject's control of that flow, and this conception has been central to our experimental and theoretical investigation of memory. All phases of memory are assumed to consist of small units of information that are associatively related. A set of closely interrelated information units is termed an image or a trace. Note that "image" does not necessarily imply a visual representation; if the letter-number pair *TKM–4* is presented for memory, the image that is 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.

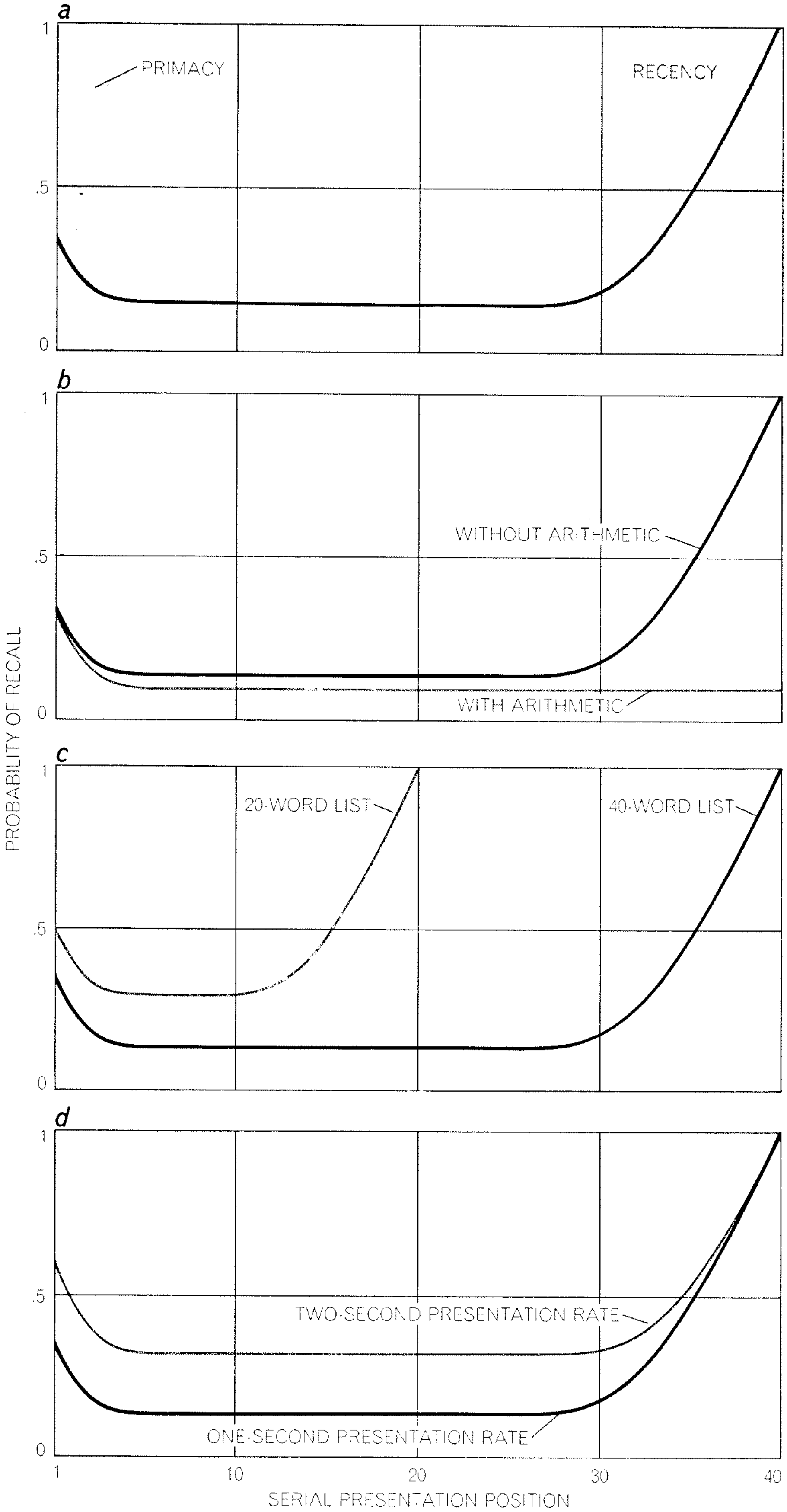
Information from the environment is accepted and processed by the various sensory systems and is entered into the short-term store, where it remains for a period of time that is usually under the control of the subject. By rehearsing one or more items the subject can keep them in the short-term store, but the number that can be maintained in this way is strictly limited; most people can maintain seven to nine digits, for example. Once an image is lost from the short-term store it cannot thereafter be recovered from it. While information resides in short-term storage it may be copied into the long-term store (LTS), which is assumed to be a relatively permanent memory from which information is not lost. While an image is in short-term storage, closely related information in the long-term store is activated and entered in the short-term store too. Information entering the short-term store from the sensory systems comes from a specific modality—visual, auditory or whatever—but associations from the long-term store in all modalities are activated to join it. For instance, an item may be presented visually, but immediately after input its verbal "name" and associated meanings will be activated from the long-term store and placed in the short-term one [*see illustration on opposite page*].

Our account of short-term and long-term storage does not require that the two stores necessarily be in different parts of the brain or involve different physiological structures. One might consider the short-term store simply as being a temporary activation of some portion of the long-term store. In our thinking we tend to equate the short-term store with "consciousness," that is, the thoughts and information of which we are currently aware can be considered part of the contents of the short-term store. (Such a statement lies in the realm of phenomenology and cannot be verified scientifically, but thinking of the short-term store in this way may help the reader to conceptualize the system.) Because consciousness is equated with the short-term store and because control processes are centered in and act through it, the short-term store is considered a working memory: a system in which decisions are made, problems are solved and information flow is directed. Retrieval of information from short-term storage is quite fast and accurate. Experiments by Saul Sternberg of the Bell Telephone Laboratories and by others have shown that the retrieval time for information in short-term storage such as letters and numbers ranges from 10 to 30 milliseconds per character.

The retrieval of information from long-term storage is considerably more complicated. So much information is contained in the long-term store that the major problem is finding access to some small subset of the information that contains the desired image, just as one must find a particular book in a library before it can be scanned for the desired information. We propose that the subject activates a likely subset of information, places it in the short-term store and then scans that store for the desired image. The image may not be present in the current subset, and so the retrieval process becomes a search in which various subsets are successively activated and scanned [*see illustration below*]. On the basis of the information presented to him the subject selects the appropriate "probe information" and places it in the short-term store. A "search set," or subset of information in the long-term store closely associated with the probe, is then activated and put in the short-term store. 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



RETRIEVAL from the long-term store requires a choice of strategy and selection of certain information as a "probe" that is placed in the short-term store. The probe activates a "search set" of information in the long-term store. The search set is placed in the short-term store and is examined for the desired information. If it is not found, search is halted or recycled with new probe.



PROBABILITY OF RECALL in free-recall experiments varies in a characteristic way with an item's serial position in a list: a "primacy effect" and a "recency effect" are apparent (*a*). If an arithmetic task is interpolated between presentation and recall, the recency effect disappears (*b*). Words in long lists are recalled less well than words in short lists (*c*). Slower presentation also results in better recall (*d*). The curves are idealized ones based on experiments by James W. Dees, Bennet Murdock, Leo Postman and Murray Glanzer.

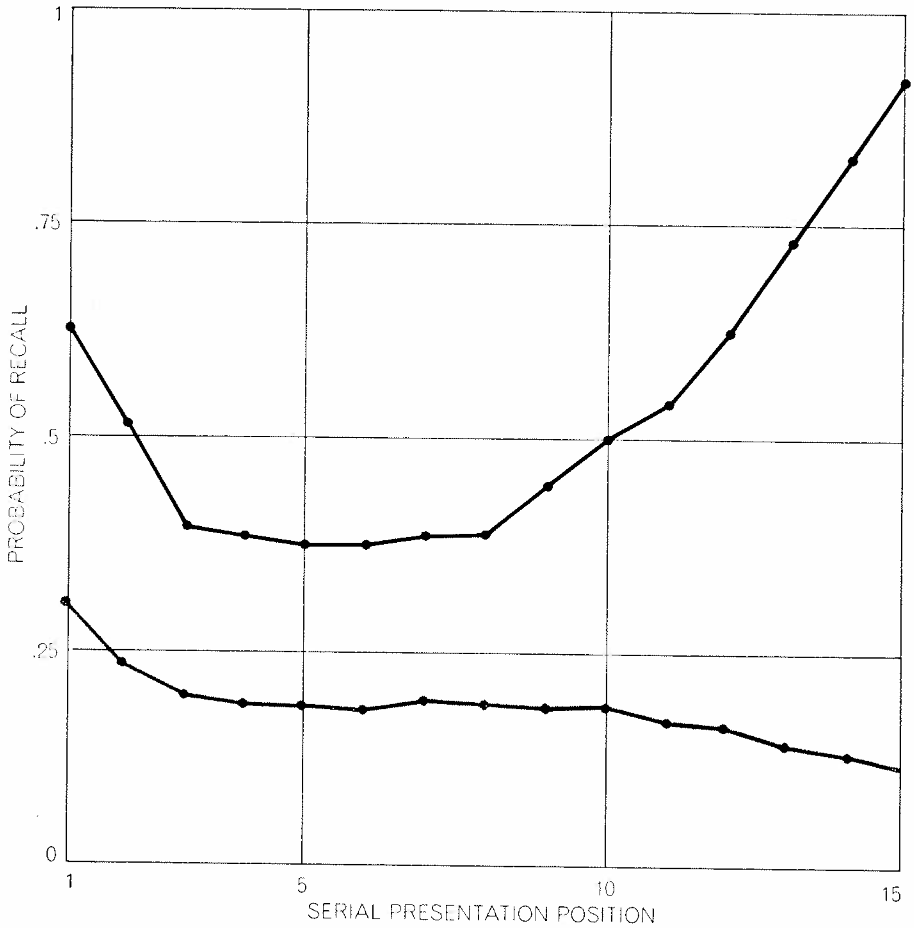
been found? If so, the search is terminated.

If the information has not been found, the subject may decide that continuation is unlikely to be productive or he may decide to continue. If he does, he begins the next cycle of the search by again selecting a probe, which may or may not be the same probe used in the preceding cycle depending on the subject's strategy. For example, a subject asked to search for states of the U.S. starting with the letter *M* may do so by generating states at random and checking their first letter (in which case the same probe information can be used in 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 result more often in successful retrieval but will take longer than alternative "random" strategies. (Note that the Freudian concept of repressed memories can be considered as being an inability of the subject to generate an appropriate probe.)

This portrayal of the memory system almost entirely in terms of the operations of the short-term store is quite intentional. In our view information storage and retrieval are best described in terms of the flow of information through the short-term store and in terms of the subject's control of the flow. One of the most important of these control processes is rehearsal. Through overt or covert repetition of information, rehearsal either increases the momentary strength of information in the short-term store or otherwise delays its loss. Rehearsal can be shown not only to maintain information in short-term storage but also to control transfer from the short-term store to the long-term one. We shall present several experiments concerned with an analysis of the rehearsal process.

The research in question involves a memory paradigm known as "free recall," which is similar to the task you face when you are asked to name the people present at the last large party you went to. In the typical experimental procedure a list of random items, usually common English words, is presented to the subject one at a time. Later the subject attempts to recall as many words as possible in any order. Many psychologists have worked on free recall, with major research efforts carried out by

Bennet Murdock of the University of Toronto, Endel Tulving of Yale University and Murray Glanzer of New York University. The result of principal interest is the probability of recalling each item in a list as a function of its place in the list, or "serial-presentation position." Plotting this function yields a U-shaped curve [*see "a" in illustration on opposite page*]. The increased probability of recall for the first few words in the list is called the primacy effect; the large increase for the last eight to 12 words is called the recency effect. There is considerable evidence that the recency effect is due to retrieval from short-term storage and that the earlier portions of the serial-position curve reflect retrieval from long-term storage only. In one experimental procedure the subject is required to carry out a difficult arithmetic task for 30 seconds immediately following presentation of the list and then is asked to recall. One can assume that the arithmetic task causes the loss of all the words in short-term storage, so that recall reflects retrieval from long-term storage only. The recency effect is eliminated when this experiment is performed; the earlier portions of the serial-position curve are unaffected [*b*]. If variables that influence the long-term store but not the short term one are manipulated, the recency portion of the serial-position curve should be relatively unaffected, whereas the earlier portions of the curve should show changes. One such variable is the number of words in the presented list. A word in a longer list is less likely to be recalled, but the recency effect is quite unaffected by list length [*c*]. Similarly, increases in the rate of presentation decrease the likelihood of recalling words preceding the recency region but leave the recency effect largely unchanged [*d*].



EFFECT OF DELAY is tested by asking subjects to recall at the end of a session all words from the entire session, and then plotting probability of recall against serial position within each list. An experiment by Fergus Craik compares immediate recall (*black*) with delayed recall (*color*). The delayed-recall curve emphasizes transitory nature of recency effect.

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 retrieval from long-term storage 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 [*see illustration on this page*]. For the delayed-recall curve the primacy effect remains, but the recency effect is eliminated, as predicted. In summary, the recency region appears to reflect retrieval from both short-term and long-term storage whereas the serial-position curve preceding the recency region reflects retrieval from long-term storage only.

In 1965, at a conference sponsored by the New York Academy of Sciences, we put forward a mathematical model explaining these and other effects in terms of a rehearsal process. The model assumed that in a free-recall task the subject sets up a rehearsal buffer in the short-term store that can hold only a fixed number of items. At the start of the presentation of a list the buffer is empty; successive items are entered until the buffer is filled. Thereafter, as each new item enters the rehearsal buffer it replaces one of the items already there. (Which item is replaced depends on a number of psychological factors, but in the model the decision is approximated by a random process.) The items that are still being rehearsed in the short-term store when the last item is presented are the ones that are immediately recalled by the subject, giving rise to the recency effect. The transfer of information from the short-term to the long-term store is postulated to be a function of the length of time an item resides in the rehearsal buffer; the longer the time period, the more rehearsal the item receives and therefore the greater the transfer of information to long-term storage. Since items presented first in a list enter an empty or partly empty rehearsal buffer, they remain longer than later items and consequently receive additional rehearsal. This extra rehearsal causes more transfer of information to long-term storage for the first items, giving rise to the primacy effect.

This rehearsal model was given a formal mathematical statement and was fitted to a wide array of experiments, and it provided an excellent quantitative account of a great many results in free recall, including those discussed in this article. A more direct confirmation of the model has recently been provided by Dewey Rundus of Stanford University. He carried out free-recall experiments in which subjects rehearsed aloud during list presentation. This overt rehearsal was tape-recorded and was compared with the recall results. The number of different words contained in the "rehearsal set" (the items overtly rehearsed between successive presentations) was one after the first word was presented and then rose until the fourth word; from the fourth word on the number of different words in the rehearsal set remained fairly constant (averaging about 3.3) until the end of the list. The subjects almost always reported the members of the most recent rehearsal set when the list ended and recall began. A close correspondence is evident between the number of rehearsals and the recall probability for words preceding the recency effect; in the recency region, however, a sharp disparity occurs [*see illustrations below*]. The hypothesis that long-term storage is a function of the number of rehearsals can be checked in other ways. The recall probability for a word preceding 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. And words presented in the middle of the list given the same number of rehearsals as the first item presented had the same recall probability as that first item.

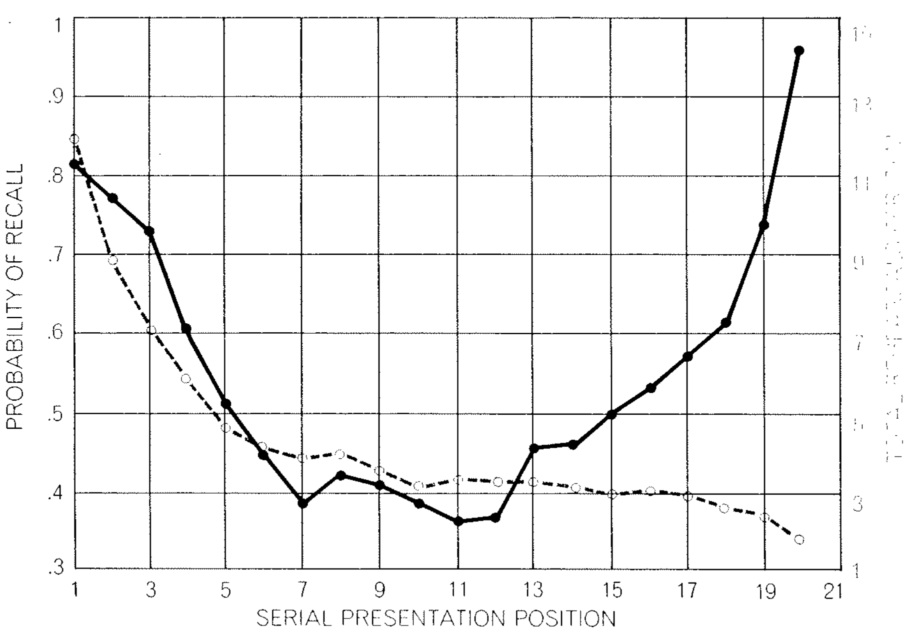
With efficacy of rehearsal established both for storing information in the long-term store and for maintaining information in the short-term store, we did an experiment in which the subjects' rehearsal was manipulated directly. Our subjects were trained to engage in one of two types of rehearsal. In the first (a 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 (a three-item rehearsal set) the subject rehearsed the three most recently presented items once each before presentation of the next item, so that 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 sets contained one rehearsal of each of the three most recent items [*see illustrations on opposite page*].

When only one item is rehearsed at a time, each item receives an identical number of rehearsals and the primacy effect disappears, as predicted. Note that the recency effect appears for items preceding the last item even though the last item is the only one in the last rehearsal set. This indicates that even when items are dropped from rehearsal, it takes an additional period of time for them to be completely lost from short-term storage. The curve for the three-item rehearsal condition shows the effect also. The last rehearsal set contains the last three items presented and these are recalled perfectly, but a recency effect is still seen for items preceding these three. It should also be noted that a primacy effect occurs in the three-rehearsal condition. This was predicted because the first item received a total of five rehearsals rather than three. A delayed-recall test for all words was given at the end of the experimental session. The data confirmed that long-term-store retrieval closely parallels the number of rehearsals given an item during presentation, for both rehearsal schemes.

These results strongly implicate rehearsal in the maintenance of information in the short-term store and the transfer of that information to the long-term system. The question then arises: What are the forgetting and transfer characteristics of the short-term store in the absence of rehearsal? One can control rehearsal experimentally by blocking it with a difficult verbal task such as arithmetic. For example, Lloyd R. Peterson and Margaret Peterson of Indiana University [see "Short-Term Memory," by Lloyd R. Peterson; SCIENTIFIC AMERICAN, July, 1966] presented a set of three letters (a trigram) to be remembered; the subject next engaged in a period of arithmetic and then was asked to recall as many letters of the trigram

ITEM PRESENTED	ITEMS 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

OVERT-REHEARSAL experiment by Dewey Rundus shows the effect of rehearsal on transfer into long-term storage. The subject rehearses aloud. A partial listing of items rehearsed in one instance shows typical result: early items receive more rehearsals than later items.



EFFECT OF REHEARSAL is demonstrated by comparison of an item's probability of recall (*black*) with the total number of rehearsals item receives (*color*). The two are related in regions reflecting retrieval from long-term storage (preceding recency region). That is, long-term storage efficacy depends on number of rehearsals and is reflected in retrieval.

as possible. When the probability of recall is plotted as a function of the duration of the arithmetic task, the loss observed over time is similar to that of the recency effect in free recall [*see top illustration on next page*]. Short-term-store loss caused by an arithmetic task, then, is similar to loss from short-term storage caused by a series of intervening words to be remembered. The flat portion of the curve reflects the retrieval of the trigram from long-term storage alone and the earlier portions of the curve represent retrieval from both short-term and long-term storage; the loss of the trigram from short-term storage is represented by the decreasing probability of recall prior to the asymptote.

Does the forgetting observed during arithmetic reflect an automatic decay of short-term storage that occurs inevitably in the absence of rehearsal or is the intervening activity the cause of the loss? There is evidence that the amount of new material introduced between presentation and test is a much more important determinant of loss from short-term storage than simply the elapsed time between presentation and test. This finding is subject to at least two explanations. The first holds that the activity intervening between presentation and test is the *direct* cause of an item's loss from short-term storage. The second explanation proposes that the rate of intervening activity merely affects the number of rehearsals that can be given the item to be remembered and thus *indirectly* determines the rate of loss.

It has recently become possible to choose between these two explanations of loss from the short-term store. Judith Reitman of the University of Michigan substituted a signal-detection task for the arithmetic task in the Petersons' procedure. The task consisted in responding whenever a weak tone was heard against a continuous background of "white" noise. Surprisingly, no loss from short-term storage was observed after 15 seconds of the task, even though subjects reported no rehearsal during the signal detection. This suggests that loss from the short-term store is due to the type of interference during the intervening interval: signal detection does not cause loss but verbal arithmetic does. Another important issue that could potentially be resolved with the Reitman procedure concerns the transfer of information from the short-term to the long-term store: Does transfer occur only at initial presentation and at subsequent rehearsals, or does it occur throughout the pe-

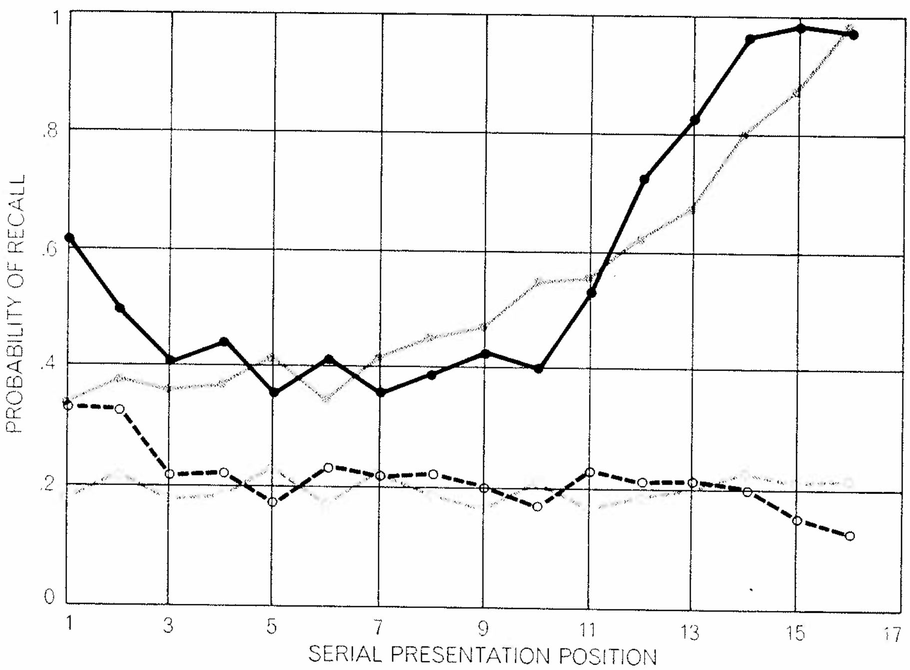
ONE-ITEM REHEARSAL SCHEME

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

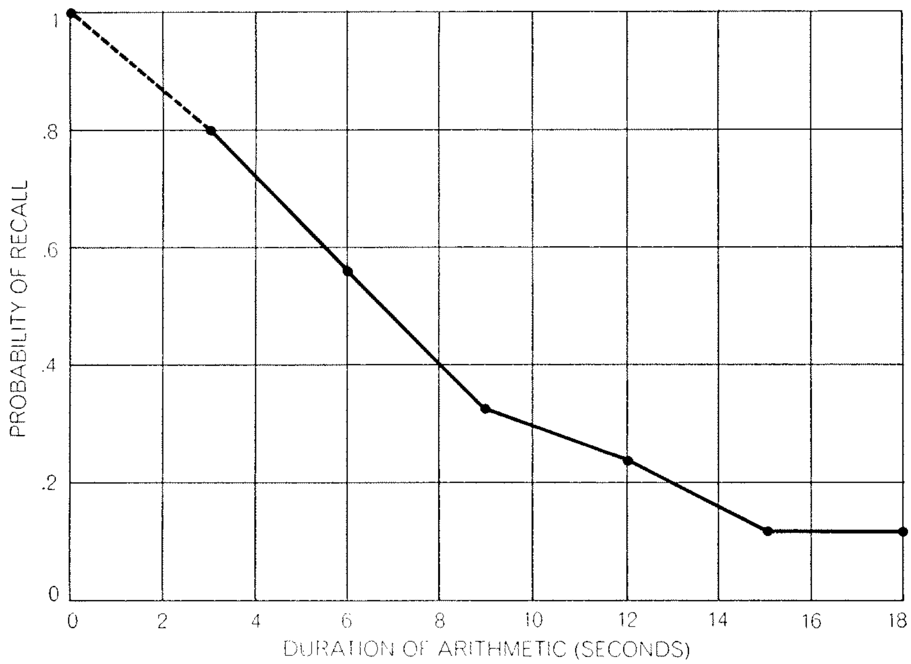
THREE-ITEM REHEARSAL SCHEME

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

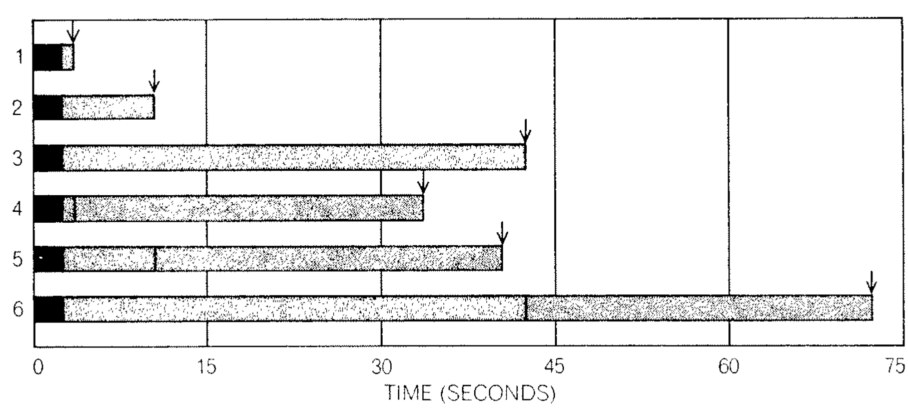
NUMBER OF REHEARSALS is controlled with two schemes. In one (*top*) only the current item is rehearsed and all items have three rehearsals. In the other (*bottom*) the latest three items are rehearsed; early ones have extra rehearsals. (Letters represent words.)



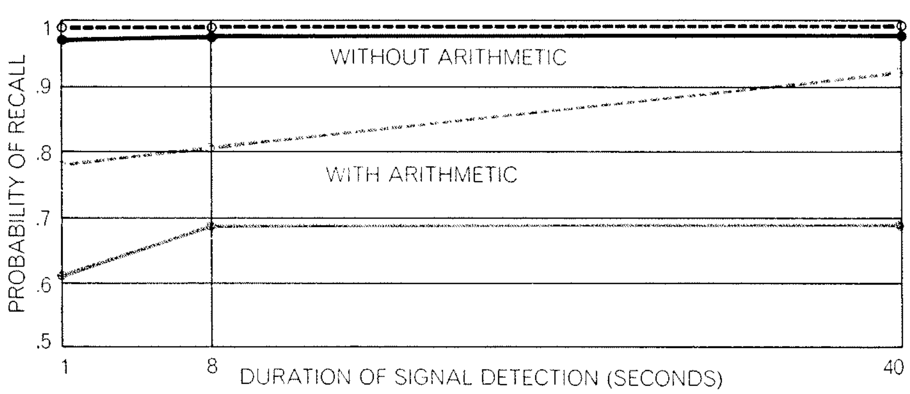
PRIMACY EFFECT disappears with one-item rehearsal (*color*), in which all items have equal rehearsal, but remains with three-item rehearsal (*black*). Recency effect is pronounced for both schemes in immediate recall (*solid lines*). Curves for delayed recall (*broken lines*), which reflect only retrieval from long-term storage, parallel the number of rehearsals.



ARITHMETIC TASK before recall reduces the probability of recall. Lloyd R. Peterson and Margaret Peterson charted recall probability against duration of arithmetic. The probability falls off with duration until it levels off when recall reflects retrieval from long-term storage alone. Does curve reflect only lack of rehearsal or also nature of intervening task?



TWO TASKS were combined in an experiment with these six conditions. Five consonants were presented for 2.5 seconds (*dark gray*), followed by a signal-detection task for one second, eight seconds or 40 seconds (*color*), followed in three cases by arithmetic (*light gray*). Then came the test (*arrows*). Rehearsal during detection was included in a control version.



NATURE OF TASKS is seen to have an effect. In the absence of arithmetic, signal detection leaves the short-term store virtually unaffected, with rehearsal (*broken black curve*) or without (*solid black*). Arithmetic, however, causes loss from the short-term store (*color*); decreased recall shown reflects retrieval from long-term store only. Retrieval improves with duration of signal detection if there is rehearsal, which increases transfer to the long-term store (*broken colored curve*) but not in the absence of rehearsal (*solid color*).

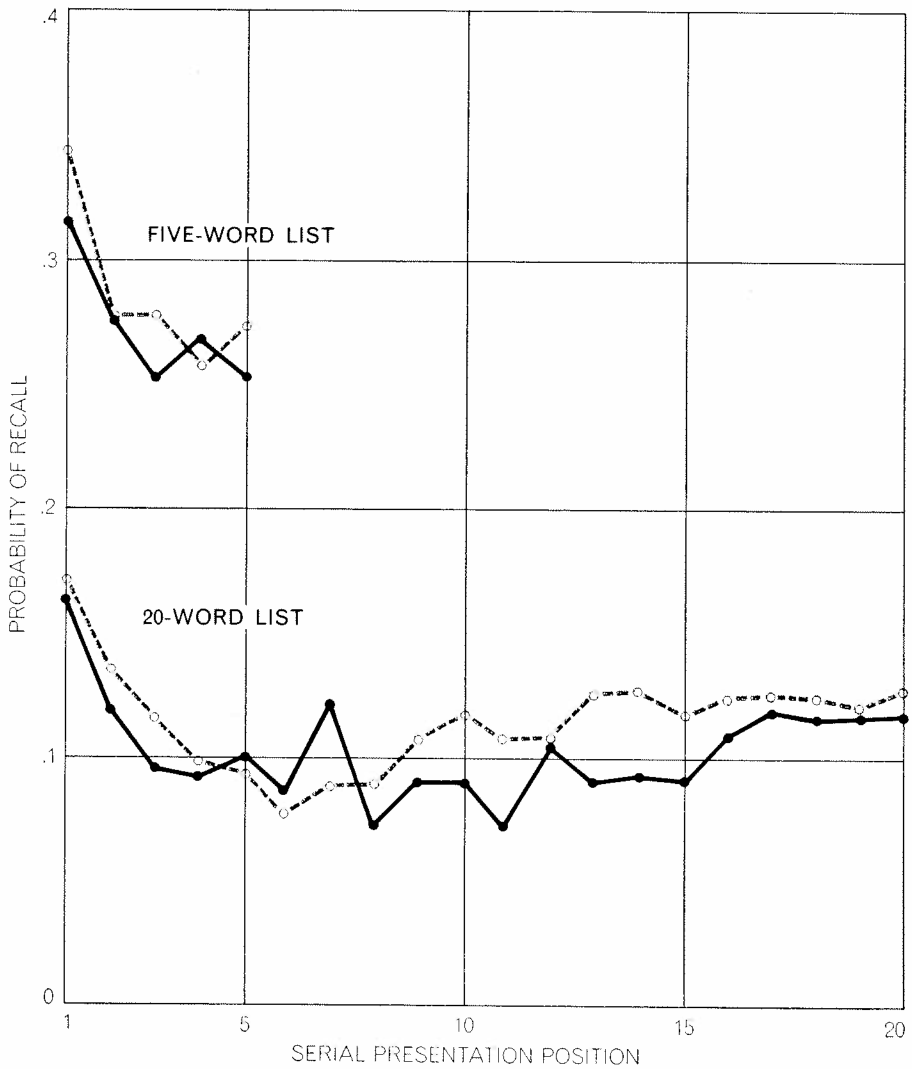
riod during which the information resides in the short-term store, regardless of rehearsals?

To answer these questions, the following experiment was carried out. A consonant pentagram (a set of five consonants, 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 against a continuous background of white noise. The subjects pressed a key whenever they thought they detected a tone. (The task proved to be difficult; only about three-fourths of the tones presented were correctly detected.) The signal-detection period lasted for either one second, eight seconds or 40 seconds, with tones sounded on the average every 2.5 seconds. In conditions 1, 2 and 3 the subjects were tested on the consonant pentagram immediately after the signal detection; in conditions 4, 5 and 6, however, they were required to carry out 30 seconds of difficult arithmetic following the signal detection before being tested [*see middle illustration at left*]. In order to increase the likelihood that rehearsal would not occur, we paid the subjects for performing well on signal detection and for doing their arithmetic accurately but not for their success in remembering letters. In addition they were instructed not to rehearse letters during signal detection or arithmetic. They reported afterward that they were not consciously aware of rehearsing. Because the question of rehearsal is quite important, we nevertheless went on to do an additional control experiment in which all the same conditions applied but the subjects were told to rehearse the pentagram aloud following each detection of a tone.

The results indicate that arithmetic causes the pentagram information to be lost from the short-term store but that in the absence of the arithmetic the signal-detection task alone causes no loss [*see bottom illustration at left*]. What then does produce forgetting from the short-term store? It is not just the analysis of any information input, since signal detection is a difficult information-processing task but causes no forgetting. And time alone causes no noticeable forgetting. Yet verbal information (arithmetic) does cause a large loss. Mrs. Reitman's conclusion appears to be correct: forgetting is caused by the entry into the short-term store of other, similar information.

What about the effect of rehearsal? In the arithmetic situation performance improves if subjects rehearse overtly during the signal-detection period. Presumably the rehearsal transfers information about the pentagram to the long-term store; the additional transfer during the long signal-detection period is reflected in the retrieval scores, and the rehearsal curve rises. The no-rehearsal curve is horizontal over the last 32 seconds of signal detection, however, confirming that no rehearsal was occurring during that period. The fact that the lowest curve is flat over the last 32 seconds has important implications for transfer from the short-term store to the long-term. It indicates that essentially no transfer occurred during this period even though, as the results in the absence of arithmetic show, the trace remained in the short-term store. Hence the presence of a trace in the short-term store is alone not enough to result in transfer to the long-term store. Apparently transfer to the long-term system occurs primarily during or shortly after rehearsals. (The rise in the lowest curve over the first eight seconds may indicate that the transfer effects of a presentation or rehearsal take at least a few seconds to reach completion.)

The emphasis we have given to rote rehearsal should not imply that other control processes are of lesser importance. Although much evidence indicates that transfer from short-term storage to long-term is strongly dependent on rehearsals, effective later retrieval from long-term storage can be shown to be highly dependent on the type of information rehearsed. Coding is really the choosing of particular information to be rehearsed in the short-term store. In general, coding strategies consist in adding appropriately chosen information from long-term storage to a trace to be remembered and then rehearsing the entire complex in the short-term store. 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, *HRM* reminds you of "homeroom" and you think of various aspects of your fourth-grade classroom. Your retrieval performance will be greatly enhanced. Why? First of all, the amount and range of information stored appears to be greater with coding than with rote rehearsal. Moreover, the coding operation provides a straightforward means by which you can gain access to an appropriate and small region of memory



LENGTH OF LIST rather than amount of "interference" governs recall probability. Subjects were asked to recall the list before the one just studied. Five-word lists (*top*) were recalled better than 20-word lists (*bottom*) whether they were followed by intervening lists of five words (*black*) or of 20 words (*color*). The data are averages from three experiments.

during retrieval. In the above example, when *HRM* is presented at the moment of test, you are likely to notice, just as during the initial presentation, that *HRM* is similar to "homeroom." You can then use "homeroom" (and the current temporal context) as a further probe and would almost certainly access "fourth grade" and so generate the correct response.

As the discussion of coding suggests, the key to retrieval is the selection of probe information that will activate an appropriate search set from the long-term store. Since in our view the long-term store is a relatively permanent repository, forgetting is assumed to result from an inadequate selection of probe information and a consequent failure of the retrieval process. There are two basic ways in which the probe selection may prove inadequate. First, the wrong probe may be selected. For instance, you might be asked to name the star of a particular motion picture. The name actually begins with *T* but you decide that it begins with *A* and include *A* in the probe information used to access the long-term store. As a result the correct name may not be included in the search set that is drawn into the short-term store and retrieval will not succeed.

Second, 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. For example, if you are asked to name a fruit that sounds like a word meaning "to look at," you might say "pear." If you are asked to name a living thing that sounds like a word meaning "to look at," the probability of your coming up with "pear" will be greatly reduced. Again, you are more likely to remember a "John Smith" if you met him at a party with five other people than if there had been 20 people at the party. This effect can be explained on grounds other than a failure of memory search, however. It could be argued that more attention was given to "John Smith" at the smaller party. Or if the permanence of long-term storage is not accepted, it could be argued that the names of the many other people met at the larger party erode or destroy the memory trace for "John Smith." Are these objections reasonable? The John Smith example is analogous to the situation in free recall where words in long lists are less well recalled from long-term storage than words in short lists.

The problem, then, is to show that the list-length effect in free recall is dependent on the choice of probe information rather than on either the number of words intervening between presentation and recall or the differential storage given words in lists of different size. The second issue is disposed of rather easily: in many free-recall experiments that vary list length, the subjects do not know at the beginning of the list what the length of the list will be. It is therefore unlikely that they store different amounts of information for the first several words in lists of differing length. Nevertheless, as we pointed out, the first several words are recalled at different levels.

To dispose of the "interference" explanation, which implicates the number of words between presentation and recall, is more difficult. Until fairly recently, as a matter of fact, interference theories of forgetting have been predominant [see "Forgetting," by Benton J. Underwood, SCIENTIFIC AMERICAN, March, 1964, and "The Interference Theory of Forgetting," by John Ceraso, October, 1967]. In these theories forgetting has often been seen as a matter of erosion of the memory trace, usually by items presented following the item to be remembered but also by items preceding 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 article assumes long-term storage to be permanent; it maintains that the strength of long-term traces is independent of list length and that 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 the interference explanations, we presented lists of varying lengths and had the subject attempt to recall not the list just studied (as in the typical free-recall procedure) but the list before the last. This procedure makes it possible to separate the effect of the size of the list being recalled from the effect of the number of words intervening between presentation and recall. A large or a small list to be recalled can be followed by either a large or a small intervening list. The retrieval model predicts that recall probability will be dependent on the size of the list being recalled. The interference model predicts that performance will be largely determined by the number of words in the intervening list.

We used lists of five and of 20 words and presented them in four combinations: 5–5, 5–20, 20–5, 20–20; the first number gives the size of the list being recalled and the second number the size of the intervening list. One result is that there is no recency effect [*see illustration on preceding page*]. 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 short-term storage and so the curves represent retrieval from long-term storage only. The significant finding is that words in lists five words long are recalled much better than words in lists 20 words long, and 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 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 preceding list, then selection of an adequate probe would no longer be possible. The results demonstrate the importance of probe selection, a control process of the short-term store.

The model of memory we have described, which integrates the system around the operations of the short-term store, is not in any sense a final theory. As experimental techniques and mathematical models have become increasingly sophisticated, memory theory has undergone progressive changes, and there is no doubt that this trend will continue. We nevertheless think it is likely that the short-term store and its control processes will be found to be central.