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8

SHORT-TERM STORAGE: THE ORDERED OUTPUT OF A CENTRAL PROCESSOR

Robert A. Bjork
University of Michigan

The concept of short-term memory (STM), in the relatively well-specified form outlined in the influential papers by Waugh and Norman (1965) and Atkinson and Shiffrin (1968), has suffered considerable damage in the last several years. Recent empirical results and theoretical efforts have left none of the assumed characteristics of STM standing as initially formulated. It has been necessary to repair, remodel, and complicate the concept of STM in terms of encoding format, capacity, role of rehearsal, and so forth.

It is usually the case in psychology that such frequent required maintenance signals the end of the usefulness of a concept. However, to me, the notion that there exists in the human information-processor a separate short-term storage system distinct from both peripheral storage systems and longer-term storage systems seems never more viable. It is the overall pattern of empirical results that I find so convincing. Any number of results—whether differences in retrieval or recognition latency for items presumed to be in STM or LTM, differences in types of confusions and intrusions, differences between immediate and delayed recall of end items in a list relative to earlier items, or whatever—have a straightforward interpretation in terms of the distinction between STM and LTM. With some effort, any one of those results can be interpreted without making an STM–LTM distinction, but accounting for all of those results without such a distinction results at best in an extraordinarily complex and convoluted characterization of memory. Even the compelling levels-of-processing framework outlined by Craik and Lockhart (1972), which at first glance seems inconsistent with the notion of a functionally distinct short-term store, is quite compatible with the assumption that such a store exists. Taken together, this chapter and the chapters by Shiffrin and by Craik and Jacoby in this volume constitute presumptive evidence for that assertion: All three assume both a levels-of-processing framework and the existence of a short-term system that is functionally distinct from LTM.

In the section that follows, I present a characterization of the human memory system and the role of STM within that system. In the second section, I discuss the representation of rehearsal processes, and in the final section, I compare the human memory system as I have characterized it with the systems proposed by Shiffrin and by Craik and Jacoby.

THE HUMAN MEMORY SYSTEM

Figure 1 diagrams some structures and processes that I consider to be essential constituents of the human memory system.

Components of the System

Input analysis. When a verbal item is presented to the system, it is analyzed by a series of processing mechanisms. In general, as shown in Fig. 1, each successive analyzer operates on the output of the preceding

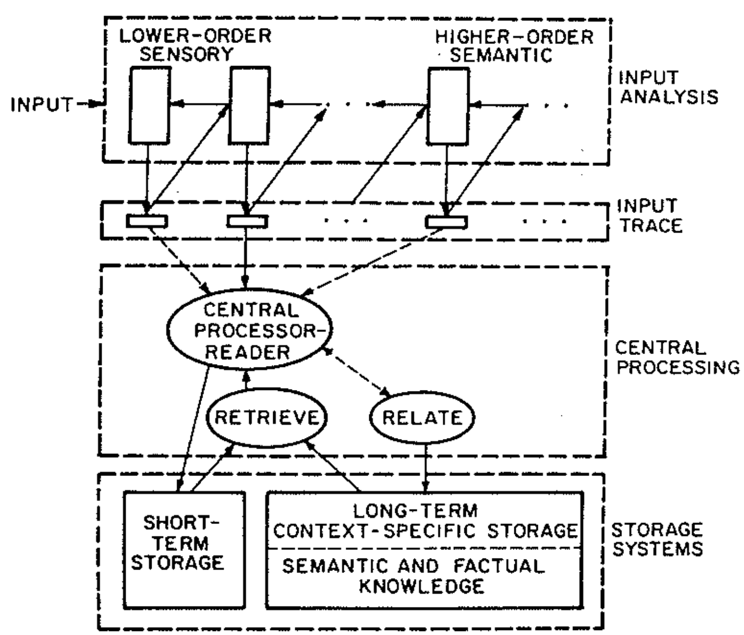

FIG. 1. The human memory system.

analyzer, but I do not assume that the analysis is serial in any strict sense. The successive analyses overlap in time—higher-level analyzers start working on the incomplete products of lower-level analyzers before the lower-level analysis is complete—and the momentary state of a higher-level analyzer may, as I have attempted to show in Fig. 1, influence the momentary state of a lower-level analyzer. Thus, for example, if a letter string presented to the system at time t constitutes a common word, the meaningfulness of that input influences the input analysis by time $t + \Delta t$, where Δt is arbitrarily small.

In general, the output of any one analysis stage is determined by (*a*) the output of the preceding stage and (*b*) the momentary state of the analyzer, which is itself influenced by (1) the nature of recent inputs to that analyzer and (2) the momentary states of higher-level analyzers. The whole analysis process is relatively fixed at the beginning and becomes more variable as it proceeds. At the higher levels, the input analysis becomes more idiosyncratic and subject to variations in local context (i.e., to the nature of just-prior inputs to the system). It is also the case that higher-level analyzers are heavily influenced by the history of the system—that is, by the relatively permanent structure of semantic and factual knowledge. Thus, there is a kind of loop in the system from the long-term storage system back to the input analyzers that is not shown in Fig. 1.

There is nothing especially novel about my assumptions with respect to the input analysis of a verbal item; it is basically a levels-of-processing system. I assume, however, that the process is essentially automatic. If a verbal item is presented, the whole analysis proceeds whether the input is being attended to or not.

Input trace. As a consequence of the input analysis, an input trace is left in the nervous system. The input trace subsumes what is usually referred to as *sensory storage*. It is the product of the overlapping stages of analysis, and it is formed during a period lasting in the hundreds of milliseconds. The various components of the input trace are highly susceptible to destructive interference from subsequent inputs to memory, but even without such interference, unattended components at all levels decay rapidly. On the average, lower-level components are lost more quickly than higher-level components because the degree of destructive interference from subsequent inputs is assumed to be an increasing function of similarity, and the lower-level components of successive inputs to memory are more likely to be similar than are the higher-level components.

Central processor. The system assumes the existence of a central processor (or homunculus) that is central and critical to attention, storage, rehearsal, retrieval, and various other mnemonic activities. In general, the activities one might think of as "control processes" are under the control of the central processor. The central processor can attend to or retrieve aspects of the input trace, it can retrieve information from STM or LTM, and it can relate or associate items in constructive ways.

As a processor or handler, the central processor is a kind of bottleneck in the system; it is restricted to carrying out only one function in any given instant of time. In some nontrivial way, however, the central processor is sensitive to salience, pertinence, and so forth; as a monitor, the central processor is not serial in nature.

Storage systems. Short-term storage (STS) is defined as the output of the central processor. That is, whenever something is handled by the central processor—whether that "something" is part of the input trace, an item retrieved from STS or LTS, or a newly constructed or integrated chunk based on a combination of pieces from STS or LTS—the output of that handling exists in a state that defines STS. When items are retrieved from STS or LTS and some relation or association based on semantic or factual knowledge is formed between those items, the structure so created amounts to a modification within or entry into LTS. Items are not, however, "transferred" from STS to LTS. In any act of storing items in LTS that were in STS, something new is added. That is, the items are not entered into LTS in their STS form; rather, those items as related or elaborated on the basis of long-term knowledge are entered into LTS. Also, immediately following any such act of storage in LTS, the items as modified exist in STS as well.

Within LTS, there is a distinction between context-specific information and context-independent knowledge. Thus, the knowledge that eggs, bacon, and orange juice are frequently eaten at breakfast, that Salt Lake City is the capitol of Utah, and that DOG denotes an animal with certain properties, is, in each case, context independent. On the other hand, remembering what one had for breakfast yesterday, what one did in Salt Lake City, and that DOG was one of a list of words studied an hour ago, are all context specific. This distinction corresponds, of course, to Tulving's (1972) distinction between *episodic* and *semantic* memory. It is not, fortunately, the burden of this chapter to specify how that distinction is represented in LTS. For what it is worth, however, I assume that the store of semantic and factual knowledge is modified whenever items within the context-specific long-term store are related to or interpreted in terms of information in the current store of semantic and factual knowledge.

Characteristics of Short-Term Memory

Format. The short-term store has no particular format. The information stored in it may be acoustic, linguistic, visual, semantic, relational, or whatever depending on the activities of the central processor. In experimental settings, the format of information in STS will be determined primarily by the demands of the particular experimental task. Thus, given the nature of the responses required in typical memory experiments, those experiments will typically reveal that information in STS is stored in acoustic or linguistic form.

Forgetting. The short-term store is an "active" store; without reinstatement, items in STS are lost quickly—within a few seconds. Reinstatement consists of reprocessing by the central processor (i.e., rehearsal). Given no other demands on the central processor, such rehearsal is a compelling and habitual activity.

The mechanism by which items are lost from STS is similarity-dependent decay. The loss rate of an item in STS is independent of both the nature of that item and the number of other items in STS, but the loss rate is heavily influenced by the amount of similarity between the item in question and the other items in STS. Thus, even though loss rate is independent of number of items in STS, loss rate will tend to increase with number of items because, on the average, total amount of similarity will increase with number of items.

Capacity. The capacity of STS (the number of items that can, on the average, be maintained in or read out of STS without error) is determined by the interaction of the loss rate (independent of item type) and the rehearsal rate (a decreasing function of the complexity of the items in STS). Thus, in the present system, the fact that the number of chunks that can be maintained in or read out of STS decreases with chunk size (from letters to words to idioms, e.g., see Simon, 1974) is attributable to a decreasing rehearsal or central processing rate with increasing chunk size.

Order retention. As long as the number of items in STS does not exceed the capacity of STS, and the central processor is free to report or maintain those items, order information is retained automatically. That is, in contrast to the retrieval of episodic items from LTS, it is not necessary for the central processor, in maintaining or reporting a subcapacity set of items, to reconstruct the input order of those items. If, however, the central processor is distracted, order information is lost at least as rapidly as item information. As in the case of item information, the loss of order information is similarity sensitive.

Updating. Finally, when items are lost from STS they are completely lost in the sense that they provide no subsequent interference in the use of the STS system. Thus, the STS system is indefinitely updatable or reusable; it is, in that sense, proactive-interference-proof.

Some Comments on the System

The system as just outlined amounts to a kind of position statement. The system represents my current attempt to characterize short-term memory within the overall structure of memory in a way that makes peace with the results referred to at the start of this chapter. There remain, of course, certain results that are unfriendly if not hostile with respect to the present system.

The system as proposed is relatively unique in some ways, but it clearly shares some features with other systems that have been proposed, including the systems proposed by Craik and Jacoby and by Shiffrin in this volume. The present system has much in common with the system proposed in less explicit form by Posner and Warren (1972) in their article, "Traces concepts, and conscious constructions." The assumptions about the input process are quite close in the two systems, and Posner and Warren's "conscious constructions" correspond in a general way to the output of the central processor when it is operating in a RELATE mode. The notion of "concepts," however, as defined by Posner and Warren, seems to cut across functions viewed as separable in the present system.

In order to explicate the foregoing system in reasonably concise fashion, I avoided citing the results that influenced my assumptions with respect to the various structures and processes in Fig. 1. With respect to the input process, my characterization was influenced by the work of Posner and his co-workers (e.g., Posner, 1969; Posner & Boies, 1971; Posner, Boies, Eichelman, & Taylor, 1969), by Keele's (1972) work on the Stroop effect, and by a variety of work on visual processing (e.g., Bjork & Estes, 1973; Gardner, 1973; Reicher, 1969; Shiffrin & Gardner, 1972; Shiffrin & Geisler, 1973; Wheeler, 1970). The present system was formulated without knowledge of the elegant characterization of the reading process presented by La Berge and Samuels (1974), but I see the input process in the present system as quite compatible with their model, although the present system is mute with respect to the developmental processes treated in some detail by La Berge and Samuels.

As far as the characteristics of short-term memory are concerned, my assumptions about format were influenced by the work of Shulman (1970) and Massaro (1973), and my assumptions about forgetting and the role of similarity were influenced by the work of Ligon (1968), Reitman (1971, 1974), Shiffrin (1973), and Bjork and Healy (1974). In the next section, I discuss the research work that probably had the greatest influence on my overall characterization of STM within the human memory system.

THE ROLE OF REHEARSAL

Until recently, rehearsal was generally assumed (Atkinson & Shiffrin, 1968; Waugh & Norman, 1965) to have a dual function within the human memory system. Although it was generally realized that rehearsal was not a single activity, but a collection of activities, it was assumed that all of

those activities both (*a*) maintained items in STM and (*b*) transferred those items to LTM. On the basis of a burst of recent research activity (Bjork & Jongeward, 1974; Craik & Watkins, 1973; Jacoby, 1973; Jacoby & Bartz, 1972; Mazuryk, 1974; Mazuryk & Lockhart, 1974; Meunier, Ritz, & Meunier, 1972; Woodward, Bjork, & Jongeward, 1973), however, it has become necessary to distinguish among different types of rehearsal.

Primary Rehearsal

One distinguishable type of rehearsal activity is the rote cycling or maintenance of items in STS, referred to as *maintenance rehearsal* by Craik and Watkins (1973) and as *primary rehearsal* by Woodward *et al.* (1973). Primary rehearsal appears to function primarily as a short-term holding operation; it has no consequences on long-term recall. Within the system in Fig. 1, primary rehearsal consists of a STS–retrieve–read–STS cycling of the items in STS. The process is independent of the LTS system; the items are simply maintained in their current form and are not interassociated or elaborated in any way.

The properties of primary rehearsal are illustrated quite clearly in Experiment III by Woodward *et al.* (1973). In each of four 36-word lists, subjects were cued after each word in turn whether to remember or to forget that word. The presentation of a given item (1 sec) was followed by a variable blank rehearsal period (0, 4, or 12 sec), at the end of which subjects were required, in response to a row of question marks presented for 1.5 sec, to recall the current word. Immediately subsequent to each such within-list test, there was a 1-sec cue to subjects to remember (R cue) or to forget (F cue) that word. After the R or F cue, the next word in the list was presented. In random sequence, half of the words in a list were R cued and half were F cued. At the end of each list there was an immediate recall test for the R words presented in that list, and at the end of the experiment there was a final recall test for all words presented during the experiment. After the final recall test, there was a final recognition test. The 144 words presented during the experiment were mixed together on two sheets of paper with an equal number of distractors, and subjects were asked to circle any words they remembered having seen during the experiment.

The experiment was designed to induce primary rehearsal of the current word during the rehearsal period following its presentation. Since the subject did not know, until the end of the rehearsal period, whether he was to remember the current word, it was not in his interest to do more than maintain the current word until the cue appeared. Any attempt to associate or integrate the current word with other R words in the list would be counterproductive since he might be cued to forget the current word.

In the top panel of Fig. 2, the probabilities of R-word recall and F-word intrusion during immediate recall are shown as a function of rehearsal time. Even though an increase in rehearsal time from 0 to 12 sec is enough to create order-of-magnitude improvements in recall in other situations (see, for example, the results of an experiment by Pollatsek reported in Bjork, 1970), the immediate recall of R words and intrusion of F words were independent of rehearsal time in the Woodward *et al.* experiment. The same result was obtained in the final recall of R words and F words.

In the bottom panel of Fig. 2, final recognition probabilities are shown for R words and F words as a function of rehearsal time. The picture in the bottom panel of Fig. 2 is very different from that in the top panel: Final recognition of both R words and F words increases systematically with rehearsal time. With a somewhat different procedure, Bjork and

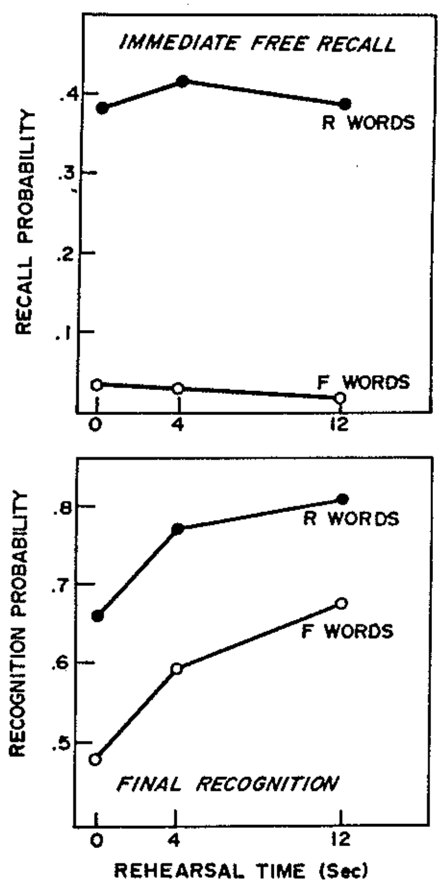

FIG. 2. Initial free recall and final recognition of to-be-remembered (R words) and to-be-forgotten (F words) as a function of rehearsal time. (After Woodward, Bjork, & Jongeward, 1973.)

Jongeward (1974) obtained a pattern of results identical to that in Fig. 2. That is, significant increases in recognition as a function of amount of primary rehearsal, but no effect of amount of primary rehearsal on recall.

Although the lack of any effects of primary rehearsal on long-term recall is consistent with the way in which I have characterized primary rehearsal in the present system, the increase in final recognition as a function of primary rehearsal obtained by Woodward *et al.* (1973) and Bjork and Jongeward (1974) poses something of a problem. Bjork and Jongeward, however, suggest an explanation of the recognition results that is at least semiplausible in terms of the present system. They propose that primary rehearsal of items in STS leads to associations between those items and the general situational context. In that sense, primary rehearsal does increase the strength of an item's representation in LTS, although no interassociation or elaboration of the items in STS are formed or stored in LTS during primary rehearsal. Since recall from LTS is mediated primarily by interassociations among items, primary rehearsal has litle or no effect on long-term recall. The recognition that a particular common word appeared during an experimental session is, on the other hand, a judgment of the word's association with the general situational context of the experiment. The question is not whether the word has been seen before—that is certainly the case—but whether the word appeared in the current context. Thus, long-term recognition should increase with amount of primary rehearsal.

Secondary Rehearsal

Another distinguishable type of rehearsal process, referred to as *elaborative rehearsal* by Craik and Watkins (1973) and as *secondary rehearsal* by Woodward *et al.* (1973), involves a variety of LTS-dependent activities by means of which items in STS are interassociated and elaborated. In terms of Fig. 1, secondary rehearsal consists of the following sequence: STS–retrieve, LTS–retrieve, relate, read–LTS (and STS). Thus, in contrast to primary rehearsal, secondary rehearsal both modifies the form of the items in STS and leads to the storage of the items as modified in LTS. From the standpoint of facilitating long-term recall, secondary rehearsal is a great deal more productive than is primary rehearsal. As a maintenance operation, however, secondary rehearsal is inefficient. It is slower than primary rehearsal, which means that items may be lost from STS while other items are being processed. Also, items in STS are not simply maintained by secondary rehearsal; they are modified and transformed in terms of item information and in terms of order information.

The differential properties of primary and secondary rehearsal are demonstrated clearly by the results of an experiment by Bjork and Jongeward (1974, Experiment II). On each of 20 trials in a modified Brown–Peterson design, subjects were asked to remember six common four-letter nouns. Each six-word string was presented for 4 sec, and the retention interval on each trial was a 20-sec unfilled interval. Prior to each trial, subjects were cued as to the way in which they were to rehearse the six words presented on that trial. On half the trials they were instructed to engage in primary rehearsal during the 20-sec retention interval, and on the remaining trials they were instructed to engage in secondary rehearsal during the retention interval. During several practice trials prior to the experiment, the difference between cycling items in rote fashion ("telephone strategy") and attempting to form associations, sentences, images, and so forth ("meaningful connections strategy") was explained in detail. At the end of each retention interval, there was a free-recall test for the six words presented on that trial. At the end of the experiment, without forewarning, one group of subjects was tested for their recall of all words presented during the experiment (final recall group), and another group of subjects was tested for their recognition of the words presented during the experiment (final recognition group). The final-recognition test was a yes–no task in which words from the experiment and a larger number of distractors were intermingled and presented one at a time.

In the left panel of Fig. 3, initial and final recall probabilities are shown as a function of processing strategy for the final recall group. In the right panel, initial recall and final recognition probabilities are shown for the final recognition group. In both panels, type of rehearsal clearly interacts with time of test. Primary rehearsal is better as a maintenance operation during the initial 20 sec following the presentation of a six-word string, but it is clearly inferior to secondary rehearsal in terms of facilitating long-term performance. A similar interaction is apparent in the results of experiments by Mazuryk and Lockhart (1974) and Mazuryk (1974).

Another analysis by Bjork and Jongeward (1974) illustrates that order information in STS tends to be maintained by primary rehearsal and lost as a natural consequence of secondary rehearsal. Bjork and Jongeward computed the proportion of trials on which the relative output order of the words that were recalled matched the input order of those words. Even though subjects were free to recall in any order, the overall proportion of primary-rehearsal trials on which the words were recalled in the correct relative order was .81. Given that all six words were recalled, the proportion was .93. On secondary-rehearsal trials, however, the corresponding proportions were .34 and .29. Thus, primary rehearsal is a fundamental maintenance operation not only in the sense that items are kept available in STS, but also in the sense that the ordering of those items is also

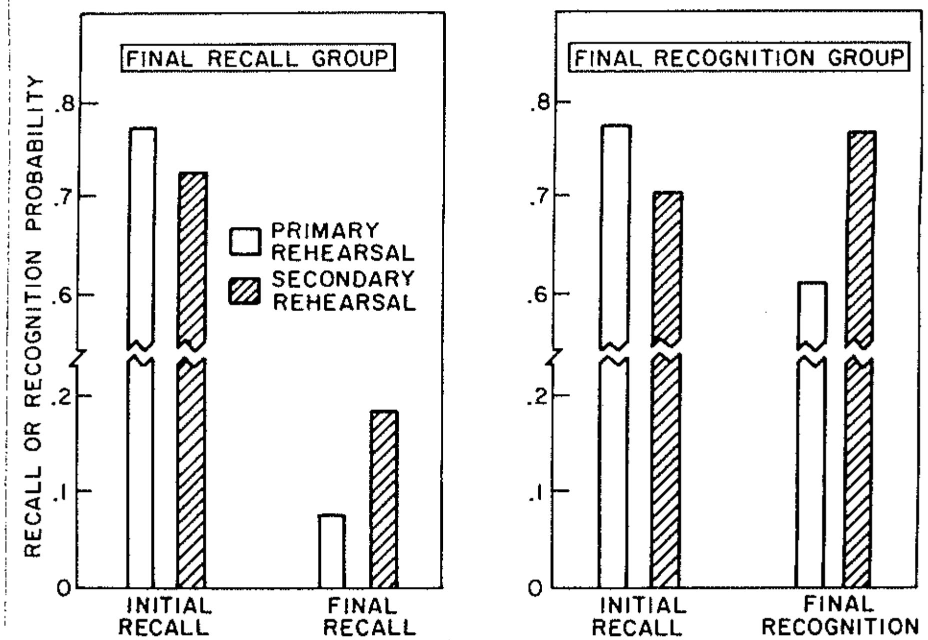

FIG. 3. Left Panel: Initial and final recall as a function of rehearsal strategy; Right Panel: Initial recall and final recognition as a function of rehearsal strategy. The false-alarm probability for new words on the final recognition task was .193. (After Bjork & Jongeward, 1974.)

preserved. On the other hand, secondary rehearsal elaborates, integrates, and rearranges the items in STS on the basis of idiosyncratic or not-so-idiosyncratic knowledge.

The differences between primary and secondary rehearsal are further illuminated by some research by Elmes and Bjork (1975). In several experiments, Elmes and Bjork employed a procedure similar to that employed by Bjork and Jongeward, except that five rather than six words were presented either once or twice on a given trial, and the retention intervals were both varied and filled with a distractor activity. As in the Bjork and Jongeward experiment, subjects were instructed to engage in either primary or secondary rehearsal at the time of each presentation. The recall proportions for once-presented words in Elmes and Bjork's Experiments I and II are shown in Fig. 4 as a function of rehearsal instruction and retention interval. The retention curves in Fig. 4 demonstrate again the increasing advantage of secondary rehearsal as recall is tested at increasing delays. Recall performance by the uncued control subjects in Experiment II fell, as one might expect, between the performance levels on primary and secondary trials for the cued subjects. For what it is worth, however, the details of the recall performance by control subjects indicate that they engaged almost exclusively in primary processing on first presentations, and

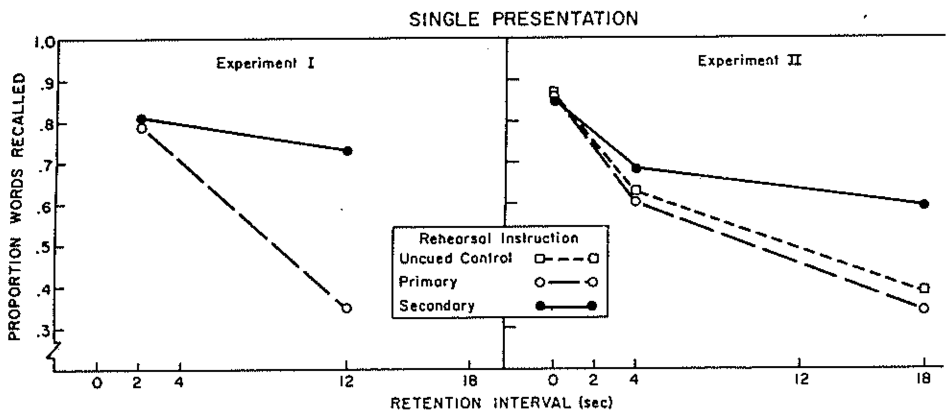

FIG. 4. Initial recall of once-presented items as a function of rehearsal strategy and retention interval. (After Elmes & Bjork, 1975.)

they engaged in a mixture of primary and secondary processing on second presentations.

Two additional analyses carried out by Elmes and Bjork, one of intrusions during initial recall and the other of clustering during final recall, provide support for the differential functions attributed in the above-cited experiments to primary and secondary rehearsal. During initial recall, the proportions of errors on primary-rehearsal trials that were acoustic or semantic intrusions were .34 and .03, respectively. The corresponding proportions on secondary-rehearsal trials were .19 and .16. Thus, in terms of those proportions, primary rehearsal resulted in about twice as many acoustic intrusions, but only about one-fifth as many semantic intrusions, as did secondary rehearsal. That pattern is consistent with the notion that primary rehearsal consists of a cycling of items in STS in a form suitable to the task, in this case acoustic, whereas secondary rehearsal consists of a semantic elaboration or interassociation of the items in STS. During final recall, the extent of clustering by input string was five times higher for strings given secondary rehearsal than it was for strings given primary rehearsal during input. Once again, that result is consistent with the idea that secondary rehearsal, in contrast to primary rehearsal, leads to storage in LTS of the items as elaborated and interrelated.

The Interaction of Primary and Secondary Rehearsal

To some extent, primary and secondary rehearsal can be viewed as having a symbiotic relationship. On the one hand, even if one's goal is long-term storage of the items being rehearsed, primary rehearsal provides

the basis for subsequent secondary rehearsal. Since secondary rehearsal is relatively inefficient as a maintenance operation, interspersed periods of primary rehearsal are necessary to keep the current contents of STS available for additional secondary processing. Primary rehearsal is "primary" in the sense that it is a kind of re-presentation scheme by means of which a faithful copy of items is kept available in STS over the short term, either to be reported in that form or to be transferred in modified form to LTS. Secondary rehearsal, on the other hand, can both facilitate primary rehearsal by chunking separate items in STS and can, to some extent, remove the need for additional primary rehearsal by storing an adequate representation of the items in LTS.

DISCUSSION

Summary of the Present System

The present system is meant to characterize the principal components of the memory system of the adult human being. The system consists of (*a*) a set of highly sophisticated input mechanisms, the output of which is an input trace; (*b*) a single central processor that attends, reads, rehearses, relates, and so forth; and (*c*) two storage systems, a short-term store consisting of the output of the central processor, and a long-term store consisting of context-dependent episodic knowledge and context-independent semantic and factual knowledge.

The input process translates the nominal form of a verbal item as presented into a functional internal representation—the input trace. When a verbal item is seized by the input analyzers that underlie the input process, it is subjected to a series of overlapping levels of analysis that proceed from relatively fixed and primitive sensory analyses to more variable and idiosyncratic semantic analyses. With adult humans and common verbal materials the input process is automatic—that is, does not require attention. As a consequence of the input process, a multicomponent input trace is left in the nervous system, the components of which correspond to the different levels of analysis that are carried out. The notion of an input trace can be viewed as extending the notion of a sensory store to include higher-level as well as lower-level components. Although the input process is automatic, it is not deterministic; that is, the output of a given analyzer is a stochastic process determined by the momentary state of the analyzer, which is influenced by prior inputs to the system. Thus, the same nominal item presented to the same individual at different times may result in different input traces, especially in terms of the higher-level components.

Probably the most innovative feature of the present system is the overall dependence of the system on the activities of a single central processor. As a processor or handler of information, the central processor is limited to one function at a time; as a sensor or monitor, the central processor has no such limitation and is sensitive to salience, pertinence, and so forth. There is a sense in which the central processor drives the system. The output of the central processor defines STS, and although the input process is independent of the central processor, components of the input trace do not survive past the brief life of that trace unless read (entered into STS) by the central processor. The central processor is also responsible for the retrieval of information from STS and LTS, for the maintenance of information in STS, and for the storage of information in LTS. Items are maintained in STS via rehearsal, which consists of either a rote cycling of items in STS through the central processor (primary rehearsal) or a constructive, LTS-dependent activity by means of which items in STS are interassociated or chunked (secondary rehearsal). Storage in LTS is achieved when items retrieved from STS or LTS by the central processor are related or interassociated on the basis of semantic or factual knowledge. During secondary rehearsal, therefore, the items as chunked or interrelated are stored in LTS as well as maintained in STS. During primary rehearsal there is no such LTS storage, but the items being maintained in STS may become associated with the general situational context.

In the present system, STS is an active store; unless maintained via rehearsal, items in STS are lost quickly, within a relatively few seconds. Items in STS are lost via a decay process that is independent of item type, but is heavily influenced by amount of similarity among the items in STS. The capacity of STS is determined by the interaction of the loss rate of items in STS (independent of item type) and the rate at which those items can be rehearsed (a decreasing function of item size or complexity). As long as the number of items in STS do not exceed its maintenance capacity, order information as well as item information is preserved in STS.

Comparison with the Craik and Jacoby and Shiffrin Systems

Although there are important differences among the systems proposed in this symposium, their overall convergence is more striking than are their points of divergence. That convergence is especially remarkable since the three systems *do* diverge in substantial ways from systems proposed in the past—with the possible exception of the proposal by Posner and Warren (1972)—and since we each felt that we were staking out important new ground in our proposals. After the fact, there is one sense in which the convergence of the three systems is not so surprising: To some extent, we have all been influenced by the same empirical results, and we have interpreted those results in somewhat similar ways. Whether we have been led or misled remains to be seen.

In the remainder of this section, I comment on the similarities and differences among the three systems, and criticize certain aspects of each of the systems.

Input processes. The input process is characterized in much the same way in each of the three systems. The process is assumed in each case to proceed from relatively fixed lower-level analyses to more variable higher-level analyses. All three systems assume that the process is essentially automatic, although Craik and Jacoby assert that attention is required for unfamiliar analyses.

The formal similarities in the three characterizations of the input process are not as apparent as they might be because there are substantial differences among the systems in terminology and emphasis. In my own system, the stress is on the input process as an active analysis, the product of which is an input trace: Input analyzers stand poised and ready to dissect verbal inputs. Shiffrin assumes something more like a multilevel template-matching process. Every possible coding or feature of an input exists in the long-term store, and upon presentation, a subset of those codes or features lights up automatically, without any active analysis being assumed. Craik and Jacoby assume a process that seems in emphasis to fall midway between my characterization and Shiffrin's characterization. To some extent, I find the template-matching aspect of Shiffrin's system implausible. Whereas it is not difficult for me to imagine that the visual receptors could, for example, achieve an encoding of any possible visual input, however novel, in terms of low-level features, it seems unlikely to me that every possible low-level feature of an item—every line, angle, curve, shading, figure–ground contrast, and so forth—exists in LTS waiting to be activated.

Central processing. The notion of a central processor is fundamental to each of the three systems, but the systems differ in the degree to which any such processor or homunculus is brought out into the open. In my own system an explicit central processor is proposed as a kind of executive consciousness that controls and governs the system; without the involvement of the central processor, nothing happens in the system beyond the formation of input traces. In making the overall operation of human memory dependent on a limited-capacity consciousness or processor, I see myself as supporting the efforts of Mandler (1974, 1975), and of Posner and his co-workers (e.g., Posner & Klein, 1973), to rescue the concept of consciousness from the "oubliettes of behaviorism" (Mandler, 1975).

Although some kind of central processor is implicit in the systems of Craik and Jacoby and Shiffrin, they are much less explicit about its existence or properties. In Craik and Jacoby's system, the central processor has much the same functions as it does in my system, but there seems always to be an implicit executive or operator. Thus, for example, in statements such as "The processor is deployed within the existing cognitive structures" and "Once conscious attention has been removed from an item . . ." there is an implicit agent that does the deploying or removing. In Shiffrin's system, the central processor lurks in the background. He says, for example, "The most important function of STS . . . is that of active control of thinking, problem solving, and general memorial processes." Since STS in Shiffrin's system is a storage system—that is, a set of activated features in LTS—it cannot, by itself, control anything. Thus, the statement is clearly not meant to be taken at face value; rather, an implicit conscious agent is being assumed. Although I think it would be at least partly unfair, I think Mandler (1975) might view the Craik and Jacoby and Shiffrin papers (and possibly my own as well) as evidence for his assertion that "to speak freely of the need for a concept of consciousness still ties the tongues of not a few cognitive psychologists."

There are, I think, some advantages in assuming an explicit central executive. Not only does one avoid excessive use of the passive voice, one also avoids attributing control processes to repositories or buffers and, more important, one tends to think of processes such as attention, rehearsal, and retrieval as having certain common properties because they are governed by the same central processor. Thus, as Mandler (1974) points out, the similar restrictions on immediate memory span and absolute judgment that puzzled George Miller (1956) might both reflect the limitations of a single central processor. What I find unsatisfying at this point about my own characterization of the central processor is that I am so vague about the mechanisms involved. It is one matter to attribute explicit properties to the central processor—that it operates in serial as a processor and in parallel as a monitor, for example—but it is quite another to come up with a detailed mechanism that has those properties.

The nature of STS. On the surface, it might appear that Craik and Jacoby, Shiffrin, and myself have very different ideas about the nature of STS. Certainly, Shiffrin and myself use the term "STS" in very different ways and Craik and Jacoby avoid the term altogether. In terms of formal properties, however, I see the systems as quite similar. There is a reasonably close correspondence between STS, "working memory," and "items selected for rehearsal" in my system, Craik and Jacoby's system, and Shiffrin's system, respectively. What Shiffrin refers to as STS corresponds more closely in its properties to the input trace in my system than it does to STS in my system.

Despite these definitional differences, each system assumes an STS with much the same properties. In each case, STS is an active store from which items are lost rapidly unless maintained by rehearsal, and the contents of

STS are unlimited in format. Our notions about the capacity of STS are also roughly similar in that the number of items that can be maintained or reported is assumed to be a function of the limitations of a central processor, although I assume that the capacity of STS is determined by the interaction of loss rate and rehearsal rate for the items in STS. It is also the case in all three systems, almost by definition, that items in STS can be retrieved rapidly and reliably.

There are, however, several differences between our characterizations of STS.

1. I make certain strong assumptions about the retention of order information in STS, whereas Craik and Jacoby and Shiffrin do not comment on that problem.

2. Shiffrin assumes that what he calls STS "has at least the structure of LTS, in which it is embedded." I presume that should also be the case for what I call STS, that is, for any subset of his STS that is selected for maintenance or rehearsal. A possible problem with that view is that STS capacity for words seems little affected by variables such as word frequency, concreteness–abstractness, semantic similarity, or even, in the case of bilingual or trilingual individuals, whether the words are presented in one, two, or three languages (for a review of those findings, see Craik, 1971).

3. Craik and Jacoby propose a "resolving power" interpretation of the limits on STS capacity. The idea is that conscious attention can be characterized as a kind of field analogous to a visual field: items in the center of the field are well attended or discriminated, whereas items nearer the pheriphery of the attentional field are not well discriminated. The resolving-power notion seems to me to have considerable potential, but it seems somewhat inconsistent with Craik and Jacoby's later assertion that an item is lost from STS in all-or-none fashion when attention is diverted from that item. They do say, however, that it may be necessary to "soften" that all-or-none assumption.

Forgetting from STS. In all three systems, items in STS or working memory are lost quickly unless maintained in STS via conscious attention or rehearsal. I assume that the mechanism of loss is similarity-dependent decay. Shiffrin assumes that the loss mechanism is similarity-dependent interference. Those two mechanisms may not be differentiable. Craik and Jacoby attribute forgetting from working memory solely to diversion of attention, without assuming that similarity plays a role. In their system, however, items lost from working memory may be retrievable via backward scanning or reconstruction of recent episodic memory. Short-term forgetting phenomena are assumed, in Craik and Jacoby's system, to reflect several different mechanisms.

The nature of LTS. Although there are some substantial differences in terminology, I do not think there are important differences among the three systems in the characterization of LTS. In all three systems there is a distinction between context-dependent or episodic memory and context-independent or semantic memory. Storage in or modification of LTS also seems to be viewed in much the same way. There are some differences in the extent to which retrieval mechanisms are specified; I comment on those differences in what follows.

The role of rehearsal. In all three systems there is a distinction between rehearsal as a rote maintenance process (primary rehearsal) and rehearsal as a constructive coding process (secondary rehearasl). Only the latter is assumed to interassociate items in STS and to transfer or store the items thereby in LTS. The fact that long-term recall is independent of amount of primary rehearsal is consistent with the notion that primary rehearsal maintains items in STS without transferring those items to LTS, but the Woodward *et al.* (1973) and Bjork and Jongeward (1974) finding that long-term recognition does increase as a function of primary rehearsal poses a problem for that notion. As possible explanations of the recognition results, Shiffrin proposes that primary rehearsal does transfer low-level codes to LTS (codes that would not support recall but would support recognition), and I propose that items given primary rehearsal are associated in long-term episodic memory with the general situational context (which facilitates long-term recognition, but has no appreciable effect on long-term recall). Craik and Jacoby do not attempt to explain the recognition findings.

Retrieval. It is a weakness of my own system that I have so little to say about retrieval from STS and LTS. Both Craik and Jacoby and Shiffrin have much more to offer in the way of explicit proposals about retrieval processes. Craik and Jacoby's dual-process representation of retrieval from episodic memory is particularly innovative and promising. I do agree with Shiffrin, however, that the overlap between the context in which an item was stored and the context in which retrieval of that item is attempted should be a critical factor in the reconstructive process proposed by Craik and Jacoby. I also think that the extent to which the backward-scan mechanism will produce systematic recency effects should be a function of the extent to which items or events as stored constitute a well-ordered temporal series. If items are presented too close together in time, or if the functional input position of an item is smeared over time via interassociation of successive items, the effects of recency should be attentuated (for more on that argument, see Bjork & Whitten, 1974).

Some Residual Common Problems

At this point, I am probably more impressed than I should be with the progress represented by the present papers. To end on a realistic note, I want to list a few important problems that remain relatively untouched in the proposals by Craik and Jacoby, Shiffrin, and myself.

1. The retention of order information. None of us has much to say in the way of providing specific mechanisms by means of which order information is retained or lost. Estes's (1972) model stands more or less by itself in the literature as an attempt to face up to that problem.

2. The representation of context. Each of the chapters in this book cites the importance of context in the overall operation of human memory, but mechanisms are lacking. To say that we know an item was presented in a certain context because it is associated with that context, or is stored together with information about that context, or is tagged in memory with a context label, amounts, without further specification, to stating a tautology.

3. The mechanisms by which items and sets of items are differentiated in memory. The difference in the recall of to-be-remembered and to-be-forgotten items in the Woodward *et al.* results in Fig. 2 is only one of many possible illustrations of the remarkable ability of subjects to differentiate sets of items in memory. Such set differentiation is fundamental to the executive control of rehearsal, to search processes such as those embodied in the Sternberg task and related tasks, and to the interaction and interference among items in memory. Beyond saying that subjects are remarkable, however, we have little to say about the possible mechanisms involved.

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