EXPLORATIONS WITH A SIMULATION MODEL OF SHORT-TERM MEMORY*

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Summary

A simulation model of human short-term memory has been formulated. The model postulates a number of basic information processes which are executed in a serial fashion and each has an associated time parameter. The model also postulates that information is lost from memory as a result of decay. The nature of this decay is exponential and its rate is a model parameter. Several studies were simulated in which the processing-time and decay-rate parameters were manipulated in order to determine the model's sensitivity to these parameters. Also, the model's performance was examined as a function of whether or not visual information is stored in STM and whether order information is retained perfectly or lost as a result of decay. The results of these simulated studies were compared to experimental data in order to determine at which parameter values and under which conditions of visual and order information storage the model performs most appropriately.

Introduction

The past decade has witnessed a tremendous upsurge in the amount of theoretical and experimental work on human memory that has appeared in the psychological literature. For a description of some of the most notable theoretical efforts the reader is referred to several papers.[1,2,3,4,5], A number of excellent reviews [6,7,8,9] of experimental work are also available.

This paper presents the results of some explorations of a simulation model[3] of human memory. The model is a theory of the <u>average</u> subject (s). Like several other recent theories of human memory, [1,2,4] this model postulates three separate storage systems: sensory storage - sometimes referred to as very-short-term memory (VSTM), short-term memory (STM) and long-term memory (LTM). The sensory storage is viewed as a peripheral type of memory, and there is general agreement that information stored in this type of memory is lost through decay in a matter of a few seconds or less. There are two prevailing points of view as to why information is lost from STM. One view states that information is lost as a result of decay, while the alternative is that STM has a limited capacity and items are lost by being replaced by new items entering the memory system. Since the issue has not lent itself to any clear-cut experimental resolution, the choice between these alternative postulates is almost a matter of theoretical style. Regarding LTM, it is generally agreed that while recall of information from this memory system is not perfect, the reason is a loss of <u>access</u> to the information and not a loss of the information itself. The focus of the present model is on STM.

The work reported here had two major purposes. The first purpose was to carry out sensitivity analyses of various model parameters. The specific parameters explored can be viewed in the context of two fundamental assumptions in the model: (1) the human is a serial processor; and (2) information is lost from STM as a result of autonomous decay over time. The first assumption leads to the specification of a time-charge parameter for each basic model process, while the decay assumption leads to a set of decay-rate parameters. The primary reason for exploring these parameters is to determine the model's sensitivity to them and to establish which parameter values lead to the best match with actual human memory data.

The second purpose of this effort was to explore the implications of this model for two current issues. The first issue concerns whether in attempting to model the storage and recall of a sequence of items it is necessary to postulate the loss of order information. Conrad[10] has argued that performance in such a task can be accounted for by a model that assumes order information is retained perfectly (only item information is lost). Other theorists[11*12] have proposed that order information is stored and retrieved separately from item information, and that order information may be lost independently. The second issue concerns the nature of item information that sets stored in STM. Several studies[13,14,15,16,17] indicate that STM consists primarily of auditory information. The issue is whether or not visual information is also stored and retrieved. Several studies[18,19,20] indicate that visual information seems to play a minor (if any) role in retrieval from STM. Both the order information and visual information issues were explored by appropriate manipulations of the model.

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A Description of *the* Model

Since a detailed description of the model is presented elsewhere,[3] only an overview of Its structures and processes will be presented here. Although the model is intended to represent the human memory system, in its present stage of development it is actually a simulation of performance in a particular task. The task is the standard memory-span procedure where a sequence of items Is presented, following which the subject *(s)* reproduces as many of the items as he can remember. At present the simulated task is limited to a 37 item vocabulary; the 10 digits, 0-9, the 26 letters of the alphabet, and a special symbol indicating the end of the sequence.

Before describing the structures and processes that make up the model, It is appropriate to note two basic concepts that are fundamental to understanding the model. These model concepts are a simulated clock and a window, and should be familiar to those acquainted with the EPAM model[21] of verbal learning. The clock is essentially a cumulative record of the time required by the various memory processes. Each time a process is carried out the clock is incremented by an amount of time associated with that process. The time base simulated in the model is milliseconds. The window, a series of cells, represents the visual display or the tape recorder through which items are presented to j>. The experimenter routines monitor the simulated clock and at appropriate times put information into or take information out of the window. The simulated s also monitors the window, and through it the information is "seen" or "heard".

Although the digits and letters make up the simulated s's vocabulary, they are not the basic units of information with which the model deals. Instead, the information units or components are a set of visual and auditory features that define the visual and auditory dimensions of the vocabulary items. The visual components are a set of 21 basic line segments and line relationships which include elements for describing a standard printed version of the digits and letters. For example, the visual description of the letter X would consist of three components: a positive sloping line, a negative sloping line and an intersection. The auditory components are a set of 43 phonemes which are used to describe the sounds of the items[1] names. The auditory dimension of the letter B, for example, is made up of two phonemes, b and e. Each of the digits and letters can be uniquely defined by some combination of either the auditory components (which describe how the item sounds) or the visual components (which describe what the item looks like).

The basic forgetting mechanism in this model postulates that information units in STM decay in time. The model contains 30 different decay rates, where each rate is described by an exponential equation giving the probability that a unit of information, a component, can be retrived as a function of the length of time that it has been in memory. The form of these equations is

$$p - Ae^{-Bt} + C \qquad (1)$$

where p is the probability that the component is retrieved, t is the length of time the component has been in store, and A, B, C are free parameters. The C parameter, which represents the asymptote, is assumed to be 0. The A parameter, the probability of retrieval of the unit at time t = 0, is assumed to be 1. These assumptions leave the decay rate, B, as the free parameter describing the decay function.

As noted earlier, memory is represented as three separate storage systems: sensory storage, STM and LTM. The LTM is a list structure which contains information that is permanently available to s. In order to simulate the human in a memory-span task consisting of sequences of digits and letters, LTM contains information about digits and letters that is relevant to this particular task. The nature of the structure is shown in Fig. 1. It consists of a list (LO) containing the names of all items in the vocabulary (L1-L37). Each item is in turn the name of the list that contains the names of two sublists. One sublist contains the auditory components that describe the sound of the item's name, and the second sublist contains the visual components that describe what the item looks like.

The STM structure consists of an unlimited number of memory cells, M1-Mn, each of which holds all information about an individual item (a digit or letter). The cells are connected by links which represent order information. Actually, each M location is not a single cell but a large number of memory cells organized into a list structure. The memory structure for an item is shown in Fig. 2. The structure is made up of sublists each of which contains three types of information: the name of an auditory component, the clock time at which that component was stored in STM, and a decay function specifying the exponential relationship between the probability of retrieving the component and the length of time the component has been in store. An important assumption of the model should be noted; namely, the decay of the individual components of an item occurs independently. Also, Fig. 2 shows only auditory components (P's) in STM which is the procedure followed in the original version of the model. As described earlier, one purpose of the work reported in this paper was to explore the model's performance when visual as well as auditory components are stored.

The link information in the memory structure consists of the name of the memory location In which the item following the present one will be stored, a time tag representing when this information is stored, and a decay function describing the relationship between the probability of retrieving the location of the next memory cell and the time that the cell name has been in memory. It is the link information, of course, that makes it possible for the model to recall the items in the correct order. When the link decay parameter is set at a very slow rate, the model represents the situation where order information is retained perfectly.

Sensory storage is represented in a very rudimentary fashion in the present version model. It contains the names of the auditory or visual components (depending upon the mode of presentation) that are either currently in the window or have recently been removed from the window. As long as the components exist in the window, the probability of retrieving them from sensory storage is unity. If, however, an item has already been taken out of the window and the next item has not yet appeared, the probability of the item just removed from the window being retrieved from sensory storage is an exponential function of the time elapsed since the item left the window. In other words, as long as the information is in the S's auditory or visual environment, its probability of being taken in correctly is perfect; but if it has been removed from the environment its availability decays exponentially over a short period of time (the information loss will be virtually complete in two seconds). When the components of a new item appear in the window, these components are put into the sensory storage replacing those that were there previously.

There are a number of memory processes in the model which simulate S's information processing while performing this task. These processes include taking in information from the environment, storing information in memory, retrieving information from memory, and outputting information to the environment. The general flow of events in the model is as follows:

1. A set of visual or auditory components (depending upon the presentation mode) are presented to s by placing the components in the window.

2. The s notices ("sees" or "hears") the set of components.

3. The s searches LTM and finds an item whose components match the input (the item is recognized.

4. An STM structure is set up for the item with a substructure for each component. Each substructure contains the component's name, the time it was stored and an exponential function describing its decay (see Fig. 2).

5. If the next item has not yet been presented (which is determined by examining the window to see if something new has appeared), the items already in STM are rehearsed during the interitem interval. Rehearsal consists of retrieving components of an item from an STM cell, recognizing the item by finding a match in LTM, and then updating the component substructures in STM. Updating involves resetting the time tag to the current value of the clock and changing the decay function so that the component decays at a slower rate. Rehearsal during the interitem interval always starts with the first item in the sequence.

6. At specific points during the above activities s checks the window to find out if a new item has been presented, and if it has the process branches back to step two. The window checkpoints occur every time s finishes processing a complete item. In other words, the window will be checked after a new item is taken in and recognized and after each item is rehearsed.

7. When the special "output" signal appears and is recognized, control is transferred to a respond process that attempts to recall the items. The respond routine works much like the rehearsal routine in that components are retrieved from STM and recognized as an item in LTM. An additional process in responding involves outputting the item to the environment--simulating S's writing or verbalizing the item.

8. When recall of a sequence is complete, the STM structures representing that sequence are erased. A new sequence is then begun with nothing in STM. Thus, at present the model does not deal with proactive or retroactive interference between sequences.

One additional procedure should be spelled out that is not included in the above description; namely, the manner in which the model orders the items during rehearsal and responding. As mentioned earlier, the STM structures contain link information (see Fig. 2) which specifies the name of the cell in which the components (with their associated time tags and decay functions) of the *next* item are stored. This link information is added to the STM structure *after* the next item is taken in. In other words, the link information in the first memory structure will not be put there until the second item has been taken in and set up in the second memory structure. During rehearsal and responding the model attempts to go from one item to the next by retrieving the location of the next item. This retrieval effort is simply a matter of using the decay function specified in the link and computing a probability of retrieval. A random number is then generated and the link is or is not retrieved. When a link is not retrieved, the model will randomly select one of the STM structures that has not yet been addressed in the current rehearsal or respond sequence. Of course, when the decay parameter is set at a very slow rate, link information is not lost - a condition to be explored.

It is worthwhile to note the kinds of mistakes that the model makes and what the outcomes of these mistakes are. A first type of error occurs when the presentation rate being simulated is very fast and an item enters and leaves the window before *S* sees or hears it. When such an event occurs the model simply continues its normal pattern of behavior as though nothing had happened; i.e., s simply missed the item. A second type of error results, from the failure to retrieve components from STM. When only a subset of an item's components are retrieved from the STM which do not define a unique item in LTM, the model must choose among those items in LTM that are consistent with the retrieved components. Suppose, for example, the auditory components of the letter F (e and f) had been stored in an STM structure. If during rehearsal or responding the retrieval process had retrieved only the e phoneme, there would be nine letters in LTM consistent with this retrieved component—F, L, M, N, S and X. The model would choose among these alternatives on a random basis. From this description of the procedure and the fact that <u>components</u> make up the contents of STM, It should be obvious that the intrusion errors made by model tend to have <u>components</u> in common with the correct item. This commonality of components, incidentally. has been demonstrated in several experiments.13,16 A third type of mistake that the model makes has to do with the ordering of Item (except where order information is retained perfectly). If in attempting to find the location of the next item in STM the model fails to retrieve the appropriate link, it may go to an inappropriate STM location. Since this link or order information is independent of the item information (components), the model is capable of retrieving the correct items but getting them in an incorrect order—a result that is clearly consistent with actual performance data.

As mentioned earlier, each time a basic process is carried out the clock is Incremented by an amount of time associated with that process. The model contains 7 such time-charge parameters. The basic processes for which time is charged and the names of the time-charge parameters--in parentheses—are:

1. Check window (TCHKW)—this process determines if a new item has appeared in the window;

2. Basic store and update (TSTUP)—this process stores or updates a component in STM;

3. Basic component retrieval (TRTCOM)~ this process retrieves a component from STM;

4. Basic link retrieval (TRTLNK)—this process retrieves a link from STM;

5. Discrimination/recognition (TDSCRM)— this process retrieves an Item from LTM that is consistent with a set of components;

6. Discrimination/recognition decision (TDMDEC)--when more than one item in LTM is consistent with a set of components, this process chooses one of the alternatives;

7. Respond (TRSPND)--this process simply outputs an item to the environment.

Parameter Sensitivity Studies

A series of simulation runs was carried out to explore the model's performance: (1) with different values of the time charge parameters; (2) with different component-decay rates; (3) when the decay rate for links is virtually perfect (order information is not lost); and (4) when visual as well as auditory components are stored in STM. The model is programmed in SLIP and has been run on a CDC 6400 computer. In its present stage of development the model requires approximately 40,000 memory locations and simulates performance on slightly more than two sequences per second.

Time Charge Parameters

In the initial version of the model the following "base" values (in milliseconds) were assigned to the seven time-charge parameters: TCHKW = 25, TSTUP - 25, TRTCOM = 25, TRTLNK - 25, TDSCRM - 100 TDMDEC = 300 and TRSPND = 250. These particular values were selected to allow the model match the results of experiments23,24 which indicate that ss are capable of rehearsing 3 to 4 items per second. The differences in magnitude among these values reflect the fact that the TRTLNK, TDSCRM, TDMDEC and TRSPND parameters are associated with processing an entire item, while TSTUP and TRTCOM are associated with processing component information and are, therefore, added to the clock many times within the processing of a single item.

Five of the time-charge parameters were varied in eight computer runs according to the values in Table 1. TSTUP and TRTCOM were assigned identical values and each manipulation of a particular parameter was combined with the base values of the other parameters. In other words, the results of these runs do not provide data regarding the interactions between the parameters. Each of the eight conditions of the time-charge parameters was simulated within nine conditions of two task variables. These task variables and the values at which they were represented were presentation rate (1, 2 or 3 consonants per sec.) and sequence length (6, 8 or 10 consonants). The reason for using only consonants in these sequences will be discussed later. Twenty-five sequences were simulated under each of the 72 conditions. The simulated *S* was required to recall as many consonants as presented (he has to guess when the correct Item is not remembered).

In analyzing the model's performance, an item-scoring technique was used. In order to be considered correct an item had to be in the

Table 1.

Values Assigned to Time-Charge Parameters

Time-Charge Parameter	Time (msec.)	
	Base Values	Other Simulated Values
TSTUP & TRTCOM	25	10, 50, 100
TDSCRM	100	250
TRTLNK	25	50, 100
TRSPND	250	500

proper position in the output sequence. Table 2 presents a summary of the results. Increases in the value of TSTUP and TRTCOM from 10 to 100 msec, produced consistent decrements in the model's performance. A serial position analysis showed that for the 25 and 50 msec, values most of this decrement was localized in the middle and end of the sequence. At 100 msec, however, the decrement occurred at all serial positions. The increase in TDSCRM also produced a marked performance decrement, especially at the fastest presentation rate. This decrement resulted primarily from poor performance on items from the third serial position to the end of the list. Virtually no effect was obtained for increases in TRTLNK to 50 msec, and only a slight decrease in performance at 100 msec. Similarly, increasing TRSPND to 500 msec, produced little overall decrement except for the latter serial positions in the longer sequences.

Decay Rates for Components

In the simulation runs discussed above the exponential decay functions associated with auditory components in STM were assigned an initial slope parameter value of .200. In two additional series of 25 runs (for each of the 9 conditions of the task variables) these decay parameters were assigned values of .080 and .040 which represent slower rates of decay. The time-charge parameters were assigned their base values in these runs. The resulting simulated data (see Table 3) revealed a consistent improvement in performance with slower decay rates. This improvement is most notable, however, when the model's responses are scored on the basis of whether or not a consonant was correctly recalled from the memory cell in which it was originally stored. This scoring technique is somewhat analogous to a "free recall" situation where the order of responses is not relevant.

Decay Rates for Links

The decay rate for link information, which was assigned a "base" value of .084 was also run at .002. This latter value represents a very shallow decay curve (virtually perfect retention of order information). The simulated results are presented in Table 4. For all levels of presentation rate and sequence length performance increased. In contrast to the improvement found by decreasing the decay rates of component information, the improvement associated with a high probability link retrieval is reflected primarily when the output order of the sequence is considered in scoring (not surprisingly). The serial position analysis indicated a general flattening of the recall curves resulting from improvement in the middle and end of the sequences.

Type of Information Stored in STM

In the above runs only auditory components (phonemes) were stored in STM, irrespective of the presentation mode. Although a wealth of evidence suggests that STM is basically auditory, when items are visually presented their visual components may be initially stored in STM. The implicit review of items during rehearsal, however, may be completely along an auditory dimension; and the visual components stored in STM would not get "updated." Thus, the visual components would be of increasingly less value in correctly discriminating a letter as time went on. In order to explore these ideas the model was run with visual components getting stored in STM but not updated during rehearsal. Again, this condition was run for all 9 task-variable conditions, and base values were assigned to the time-charge and decay parameters. The results shown in Table 5 suggest that visual information aids performance only for the fastest rate and only when a free recall scoring criterion is used. As might be expected, this improvement tends to be localized toward the end of the sequences.

Comparisons With Experimental Data

The results of simulation runs were compared with unpublished data collected in our laboratory. Data from all presentation rate conditions of eight and ten consonant sequences were available for comparison. The model's results and the experimental data are presented in Table 6. Scoring for both the model and experimental results took into account the proper order of responding. Comparing the experimental results to the basic model, the effect of sequence length is similar in the model and the experimental results. However, the model's performance is not affected by the rate variable as is the experimental results. The model performs too well at the fastest rate and not well enough at the slowest rate. The fit to these data does improve, however, with certain parameter manipulations. When the initial rate of decay for auditory components is reduced to .080 the model fits very well except at fastest rate where its performance still tends to be high. Changing the time-charge parameters TSTUP and TRTCOM to 10 msec, also produces a fairly close fit to these data. In addition, the 10 msec, time-charge value predicts the inverse relationship between presentation rate and performance. The model's

Table 2. Percent Items Correct in Time-Charge Parameters Sensitivity Study (Free Recall Scoring - Order Not Important)

Time Charge Parameter Values

(Each combined with "base" values of others)

Task Parameter

Presentation Rate	.3			.5			1.0		
Sequence Length	6	8	10	6	8	10	6	8	10
Base Values	62	50	35	64	38	30	59	47	36
TSTUP, TRTCOM = 10	59	42	36	67	47	36	67	64	45
TSTUP, TRTCOM = 50	52	42	30	46	38	20	54	38	31
TSTUP, TRTCOM = 100	45	38	22	52	31	28	39	24	12
TDSCRM = 250	46	39	23	46	41	27	46	35	20
TRTLNK = 50	62	50	28	58	44	30	63	48	39
TRTLNK = 100	61	48	28	58	36	25	55	43	27
TRSPND = 500	53	43	37	63	37	28	51	43	34

Table 3. Percent Items Correct in Component Decay Rate Sensitivity Study ("Free Recall" Scoring - Order Not Relevant)

Decay Rate Parameter Values

Task Parameters

Presentation Rate	.3			.5			1.0		
Sequence Length	6	8	10	6	8	10	6	8	10
.200	72	63	57	67	60	56	63	56	53
.080	79	77	69	76	78	72	83	68	69
.040	91	83	83	89	83	77	83	83	78

Table 4. Percent Items Correct in Link Decay Rate Sensitivity Study (Output order relevant in scoring criterion)

Decay Rate Parameter Values

Task Parameters

Presentation Rate	.3			.5			1.0		
Sequence Length	6	8	10	6	8	10	6	8	10
.084	62	50	35	64	38	30	59	47	36
.002	73	68	62	69	69	55	67	64	52

Table 5. Percent Items Correct in Parameter Study Exploring Effect of Storing Visual Components in STM

	Task Parameters									
	Presentation Rate		.3			.5			1.0	
	Sequence Length	6	8	10	6	8	10	6	8	10
Ordered Scoring Criterion	Only Auditory Components Stored	62	50	35	64	38	30	59	47	36
	Auditory Plus Visual Components Stored	74	44	34	56	43	31	61	61	40
Free Recall Scoring Criterion	Only Auditory Components Stored	72	63	57	67	60	56	63	56	53
	Auditory Plus Visual Components Stored	78	72	59	74	66	58	77	66	58

Table 6. Percent Items Correct for Model Results and Laboratory Experiment (Ordered scoring criterion)*

		PRESENTATION RATE		
Sequence Length	Data Source	0.3	0.5	1.0
8	Experiment	43	56	64
	Basic Model*	50	38	47
	Basic Model With Perfect Order Information	68	69	64
	Basic Model With Visual Cues Stored	44	43	61
10	Experiment	29	38	51
	Basic Model*	35	30	36
	Basic Model With Perfect Order Information	62	55	52
	Basic Model With Visual Cues Stored	34	31	40

Basic Model refers to the situation where the model was run with the basic values for the time-charge and component-decay rate parameters, link information decaying and only auditory cues in STM.

performance on the fastest rate is more in line with observed data when the TDSCRM parameter value is 250 msec.

When the model is executed with perfect order Information, its performance is clearly too high. On the other hand, the best fit to the experimental data is obtained when visual components are stored in STM along with the auditory components.

Another experiment[25] was recently completed in our laboratory that provides additional data to which the model may be compared. The instructions in one condition of this study required s to output the items in the same sequence as they were input; i.e., the first item first, the second item next, the third next, etc. This procedure matches the way the model attempts to respond and is clearly different from the procedure frequently employed by experimental Ss where the task allows the items to be output in any order. Bergman's experiment also contained the latter condition.

Figure 3 presents the serial position curves from the Bergman study and the model's output, where the sequences consisted of 8 consonants and the presentation rate was 1.0 sec. An appropriate comparison to make is the model's output where order is taken into account in scoring and the Bergman results where Ss had to output the items in the same order that they were presented. in both of these situations order information was crucial to correctly recalling the sequence. A second comparison involves the two situations where order information is not crucial; namely, the model's output scored without regard to order of output and Bergman's condition in which ss could give the items in any order. While no statistical tests were carried out, the model's fit to the data is regarded as good.

Discussion

In general, the effects of the various parameter manipulations explored in these studies were as expected. The time-charge parameters associated with processing component Information, TSTUP and TRTCOM, have a greater influence on the model's performance than those parameters associated with processing an entire item, TCHKW, TRTLNK, TDSCRM, TDMDBC and TRSPND. Also, decreasing the decay rate of components and links Improves performance, as does storing visual components in STM. The explanations for these effects is quite straightforward. With smaller time-charges for the parameters more processing gets done in a given simulated time period (e.g., more rehearsal) which leads to better performance. The slower decay rates and storage of visual components simply results in more information being retrieved from STM.

Comparisons between the model's output and the experimental data indicate that the combination of "base" time-charge values and base decay rates does not result in the best fit. A shorter time-charge for the TSTUP and TRTCOM parameters and a longer value for TDSCRM provides a much better fit. Also, a slower initial decay rate for the components leads to better results.

Of possibly greater significance are the findings related to the issues of perfect order information and the storage of visual components in STM. Clearly, the model's performance is too high with perfect order information. This result supports those theories$_{11,12}$ which propose the independent loss of order information and refutes Conrad's[10] suggestion that the loss of order information is not a necessary ingredient of such theories. The improved match between the experimental data and the model when visual components are stored argues that visual information, while not so crucial as auditory information, is an important part of STM.

The value of the present model as a first approximation to a theory of human memory will, of course, depend to a large extent upon its validity when applied to a variety of other tasks. It is one thing to develop a model that represents behavior in a memory-span task; it is quite another matter to demonstrate that the basic ingredients of that model apply to other tasks. Plans are to extend the model to deal with other standard memory procedures such as split-span studies, relative recency judgments, delayed recall and free recall.

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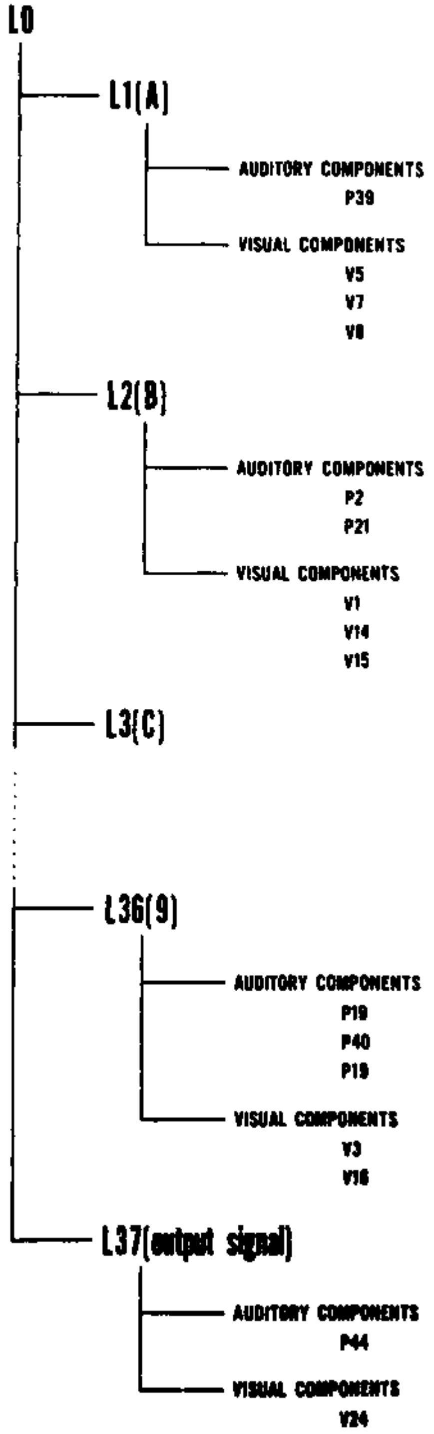

Figure 1. Long-term Memory Structure

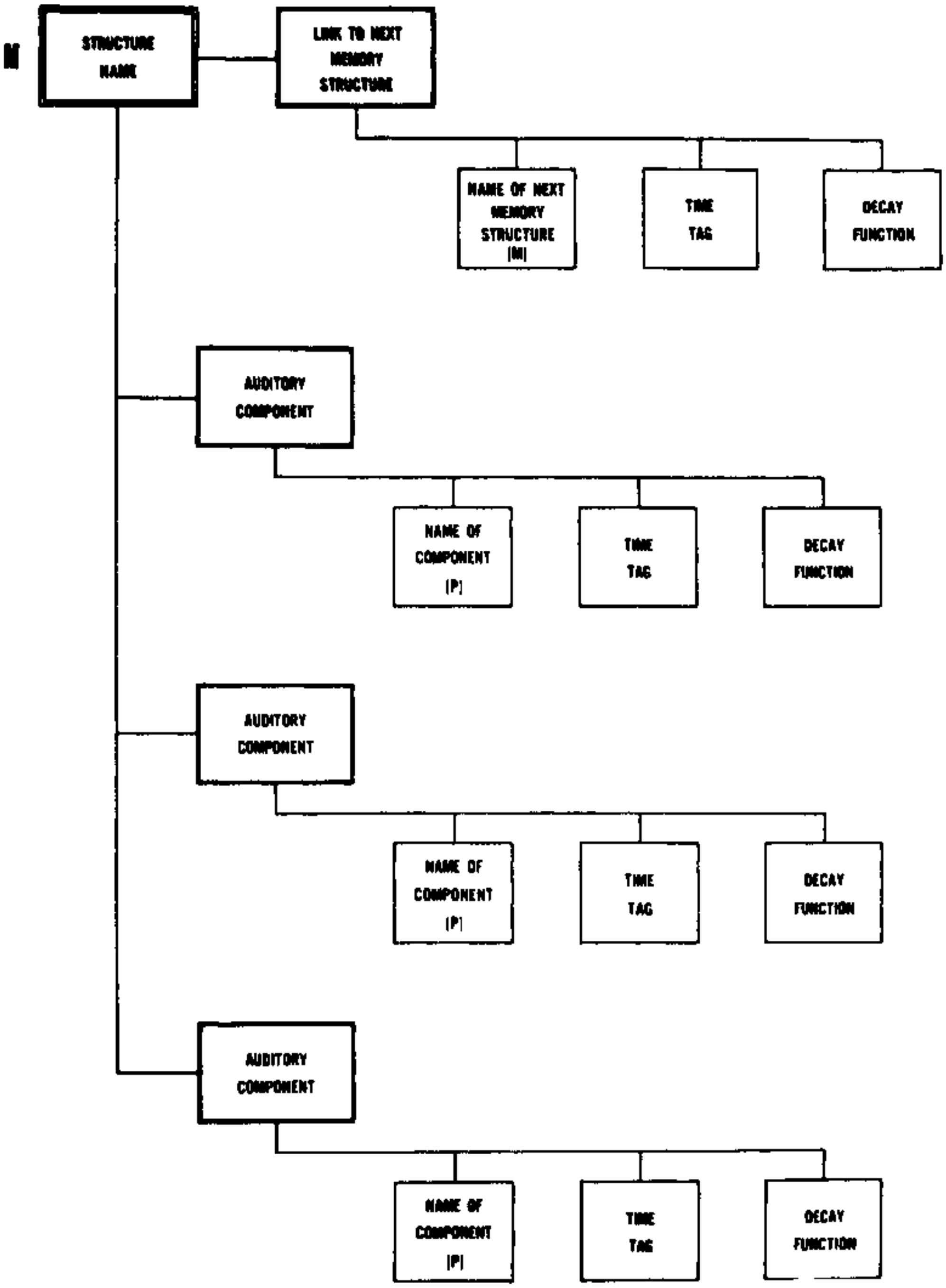

Figure 2. Short-term Memory Structure for a Single Item

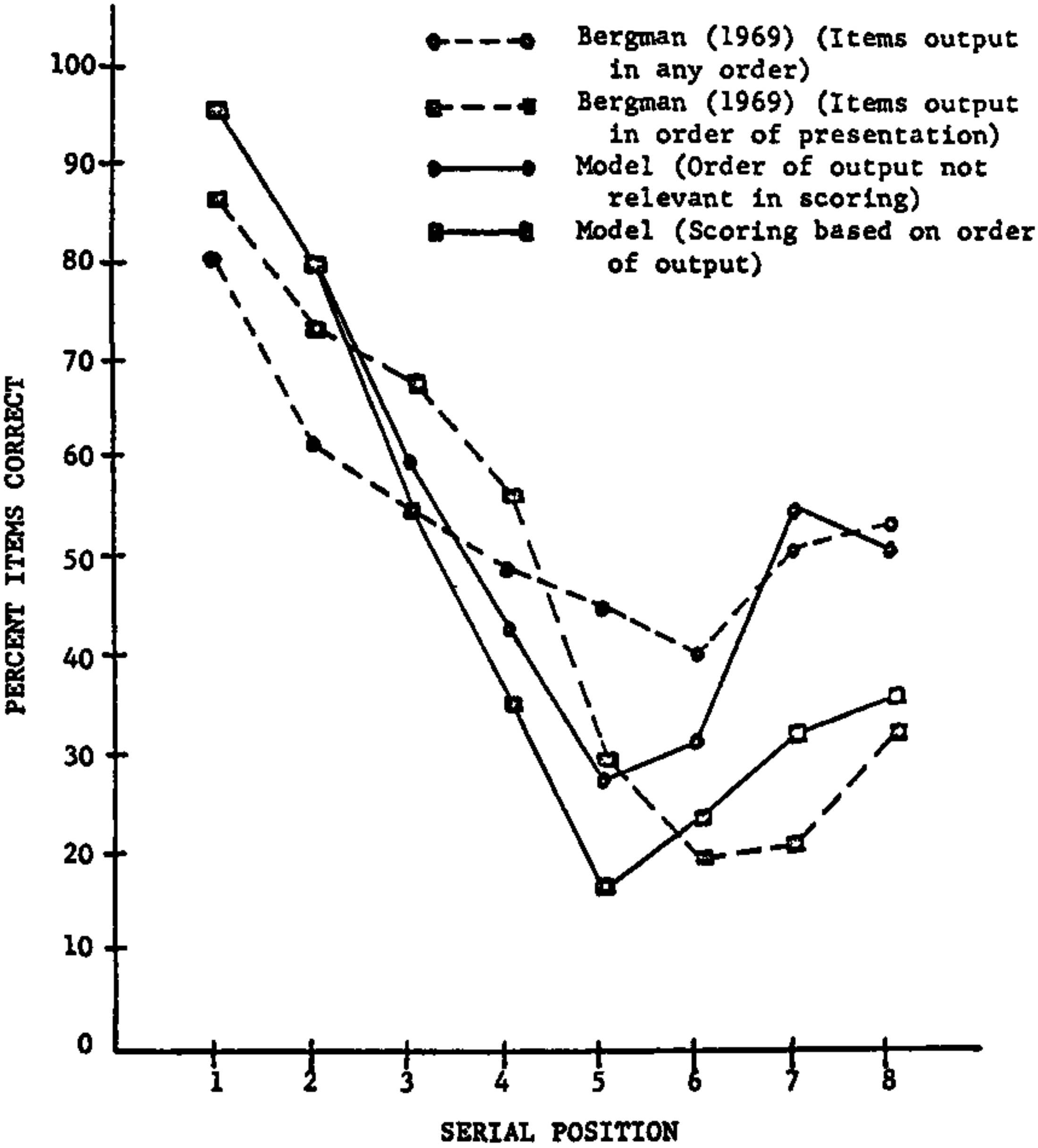

Figure 3. Serial Position Curves for Model and Experiment on Sequences of 8 Consonants Presented at a 1 Sec. Rate