THE STORY OF THE TWO-STORE MODEL OF MEMORY:
Past Criticisms, Current Status, And Future Directions

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This occasion not only marks the twenty-fifth anniversary of the Attention and Performance series but also the silver jubilee of the two-store model (Atkinson & Shiffrin, 1965, 1968). The treatment of this model in textbooks on memory suggests that it has serious deficiencies. However, this assessment is quite wrong, and the two-store model is in fact capable of handling the findings that supposedly reject it.

The SAM model (Raaijmakers & Shiffrin, 1981) developed out of the two-store model and might be viewed as a contemporary version of the two-store model. A general overview is given of how this model accounts for a variety of memory phenomena. Recently, the SAM model has been modified to include a process of contextual fluctuation. This process has proven useful in applications of the SAM model to interference and forgetting phenomena. New research is discussed that extends these applications to spacing and repetition phenomena.

1 Introduction

About 25 years ago, Atkinson and Shiffrin (1965, 1968) introduced the so-called "two-store model" of memory. It proposed a distinction between a temporary Short-Term Store (STS) and a more permanent Long-Term Store (LTS). A basic assumption of the model was that storage of information in LTS is determined by the processing of information in STS. The two-store model quickly became quite popular, and for a number of years dominated the field of memory research.

In the early 1970s, however, it was claimed that a number of phenomena were difficult to explain within this model. These included a dissociation between the time that an item resides in STS and the strength of the LTS trace, and recency effects observed in situations where STS does not play any role. As a result, alternative theories were presented that could handle these findings better, the best known ones being the levels-of-processing framework proposed by Craik and Lockhart (1972) and the working-memory model proposed by Baddeley and Hitch (1974).

The preceding brief historical account, or something quite similar, appears in many current textbooks on human memory. I will argue, however, that this account is wrong, and that current versions of the two-store model are in fact quite capable of handling many problematic memory phenomena[1]. It is my hope that the present argument will lead to a reappraisal of the two-store model.

Following my reexamination of the two-store model, I will discuss a few aspects of the SAM (Search of Associative Memory) model originally proposed by Richard Shiffrin and myself (Raaijmakers & Shiffrin, 1980, 1981), which developed out of the two-store model. I will present some new applications of SAM that illustrate its usefulness as a general framework for analyzing memory processes.

2 Evaluating The Criticisms of The Two-Store Model

2.1 Basic Principles of The Two-Store Model

The Atkinson and Shiffrin (1968) version of the two-store model emphasized a distinction between permanent, structural aspects of memory and flexible control processes. They originally proposed a division of memory into three stores: the sensory registers, short-term store, and long-term store. In more recent versions (Atkinson & Shiffrin, 1971; Shiffrin, 1975, 1976), the sensory registers have been combined with STS into a single component, also termed STS. Furthermore, it is emphasized that STS should not be viewed as a physiologically separate structure. Rather, it should be thought of as the temporarily activated portion of LTS. This STS is a kind of working memory that serves the dual purpose of maintaining information in a readily accessible state and of transferring information to LTS. What gets stored in LTS is determined by the type of processing (coding, rehearsal, and attention) that is carried out in STS.

Rehearsal or coding processes in STS are control processes whose nature is determined by task constraints, prior experience, etc. Atkinson and Shiffrin (1968) presented a specific quantitative "buffer model" that incorporated one such control process, rehearsal. It was used to give a precise explanation of performance in a particular type of experimental paradigm, the continuous short-term memory task. One frequent misunderstanding seems to be the idea that this rehearsal buffer is equivalent to STS itself. However, Atkinson and Shiffrin explicitly did not view the rehearsal buffer as a structural aspect of the memory system:

> "In our view, the maintenance and use of the buffer is a process entirely under the control of the subject. Presumably a buffer is set up and used in an attempt to maximize performance in certain situations. In setting up a maximal-sized buffer, however, the subject is devoting all his effort to rehearsal and not engaging in other processes such as coding and hypothesis testing. In situations, therefore, where coding,

> long-term search, hypothesis testing, and other mechanisms appreciably improve performance, it is likely that a trade-off will occur in which the buffer size will be reduced and rehearsal may even become somewhat random while coding and other strategies increase" (Atkinson & Shiffrin, 1968, p. 113).

This shows that Atkinson and Shiffrin saw the buffer as a control process, and not as a structural aspect of the memory system. That is, STS does not consist of a fixed number of slots such that once the slots are filled STS is full. The buffer model was only a way of modelling the rehearsal process, i.e., describing which items are rehearsed at a particular time. The preceding quotation also shows that they did not regard this type of rehearsal as particularly effective with respect to storage of information in LTS.

Atkinson and Shiffrin distinguished between two aspects of STS control processes: *rehearsal*, maintaining the information in STS, and *coding*, storing information in LTS. These two aspects, rehearsal and coding, should in most practical situations be regarded as the end points of a continuum: even a "pure" rehearsal process will lead to storage of some information in LTS, and a "pure" coding process will similarly keep some of the information in a active state, and hence in STS.

What probably confused many people was that Atkinson and Shiffrin (1968) presented in their original paper a model that focused on rehearsal but that did assume some storage in LTS as a function of the length of the rehearsal period. As a result, rehearsal came to be viewed as *the* mechanism for transfer of information from STS to LTS. In later analyses (Shiffrin, 1975), this aspect was clarified by replacing the terms "rehearsal" and "coding" with "maintenance rehearsal" and "elaborative rehearsal", respectively. Maintenance rehearsal has the primary function of keeping the information in a readily accessible state while elaborative rehearsal has the primary function of storing information in LTS. Hence, according to the two-store model, it is not the amount of rehearsal per se that determines recall, but rather the amount of elaborative rehearsal. Only in those cases where the emphasis is on elaborative coding into long-term memory (e.g., in a free recall situation), would it be appropriate to assume a direct relationship between length of rehearsal and storage in long-term memory.

2.2 The Levels-of-Processing Framework

Following the introduction of the two-store model, Craik and Lockhart (1972) proposed "an alternative framework for human memory research". They assumed that memory performance is determined by the level of processing given to the to-be-remembered material. They distinguished between Type-I and Type-II processing. Type-I processing refers to continued processing at a level that serves to maintain the information in what they termed "primary memory". Type-II processing, on the other hand, involves a "deeper" analysis of the information that should lead to improved memory performance.

Their analysis received considerable support from a large number of experiments which showed that simply keeping the information in an active state (Type-I processing) has no effect on recall performance, but that Type-II processing strongly affects the probability of recalling information. Even though later experiments showed that Type-I processing has some effects on long-term storage, especially if a recognition measure is used (Dark & Loftus, 1976; Nelson, 1977), the finding that long periods of Type-I processing had little effect on recall performance was considered by Craik and Lockhart (1972) and others as crucial evidence against the two-store model. Ever since, this conclusion has been echoed over and over in many review articles (e.g., Postman, 1975; Crowder, 1982; Baddeley, 1983) and textbooks.

However, over the years there have also been many instances where this conclusion was rejected (Bjork, 1975; Glanzer, 1977; Shiffrin, 1977). As mentioned previously, the two-store model does not assume that every type of rehearsal is equally effective for long-term storage. In fact, the distinction between Type-I and Type-II processing is virtually the same as the earlier distinction between the control processes of rehearsal and coding, respectively, or maintenance and elaborative rehearsal. Hence, the previous results taken as evidence against the two-store model by no means invalidate it. If anything, they provide strong evidence for the role of control processes in memory.

In hindsight, it is difficult to understand why so many researchers rejected the two-store model. This rejection is even more surprising since a casual look at the Craik and Lockhart (1972) paper shows that they did in fact propose a kind of two-store model. That is, they made a distinction between primary and secondary memory, where primary memory has the function of maintaining information in an active state for further processing. It is unfortunate that proponents of the levels-of-processing framework have never put their model in a quantitative form. I believe that such an exercise would have demonstrated the close similarity between it and the two-store model of Atkinson and Shiffrin (1968).

2.3 The Working-Memory Model

The second criticism that I want to discuss briefly derives from the working-memory model proposed by Baddeley and Hitch (1974). Whereas the levels-of-processing framework focused on the nature of the relation between STS and LTS, the working-memory model entails a detailed analysis of STS itself. For the present discussion, two types of results are most relevant. The first is that concurrent memory load has a strong effect on the pre-recency part of the serial position curve but not the recency part. According to Baddeley and Hitch (1974), this result is inconsistent with the two-store model. Although their exact reasoning has never been spelled out in great detail, the basic idea seems to be that the concurrent memory load should have kept STS fully occupied, leaving little room for additional items presented on the free-recall list.

The second type of result thought to be incompatible with the two-store model is that recency effects also occur in certain types of long-term memory tasks. This long-term recency effect is interpreted by Baddeley and Hitch (1974, 1977) and others as the result of an ordinal retrieval strategy. Since the two-store model attributes recency effects in free recall to retrieval from STS, it supposedly cannot accommodate long-term recency effects other than ones based on STS.

However, the criticisms derived from the working-memory model are based on an incorrect assumption that the rehearsal buffer proposed in Atkinson and Shiffrin's model is a structural aspect of memory and that it is more or less coincident with STS. In their 1971 paper on the properties of the short-term store, Atkinson and Shiffrin already argued that STS and the rehearsal buffer should not be equated. For example, they showed that particular rehearsal strategies (i.e., rehearsing only a single item at a time) did affect the primacy part of the serial-position curve but did not affect the recency part. A similar assumption has to be made in order to explain recency effects in single-trial paired-associate recall. In such a paradigm, there is no primacy effect but there is a recency effect (see Murdock, 1974). According to the two-store model, the absence of a primacy effect indicates a one-item rehearsal strategy (in other words, a one-item buffer), i.e., at any time only a single item is actively rehearsed. If the buffer and STS were equivalent, a one-item recency effect would be predicted.

The recency effect is assumed to depend on recall from STS (i.e., those items that are still in an active state at the time of recall). Which items are still in STS at the time of recall is determined by both the rehearsal strategy and the forgetting properties of STS. Rehearsal may be thought of as re-activating an item's representation in STS (Schweickert & Boruff, 1986). If an item is not rehearsed, some time will be taken before it is really forgotten from STS. In fact, if every item was immediately forgotten once attention is taken away from it, it would be difficult to successfully implement a rehearsal strategy.

Consider now the finding that the recency effect is not attenuated by concurrent memory load, while recall from LTS is. Such a result is not incompatible with a two-store model. To explain it, one may assume that the items do enter STS, even though STS is kept busy by the concurrent memory load. Although the memory load may make it difficult to actively rehearse the items in STS (using elaborative coding strategies to store information in LTS), they need not immediately disappear once the next item on the list is presented. If the items do enter STS, the recent ones should still be retrievable from STS once recall starts.

The preceding interpretation seems reasonably plausible. Even the working-memory model has to assume that items do enter working memory in the first place; otherwise an ordinal retrieval strategy would not work, and there would not be any recall possible. Second, the serial-position curves presented by Baddeley and Hitch (1974) show some recall for earlier items, even in the memory-load condition. Hence, at least in a two-store model, this is consistent with an assumption that the task leaves spare capacity for coding processes, and that these items have indeed entered STS. Finally, it is of some interest to note that the exact pattern of results can in fact be generated by the two-store model by setting the LTS-storage parameter to a very small value while maintaining all other parameters (including buffer size) at their typical value.

What about long-term recency effects? The two-store model assumes that in a free-recall task, the subject first tries to recall those items still in STS. This, to me at least, seems a very sensible strategy. These items are easily accessible and easily lost, so why not recall them right away? This recall from STS leads to a recency effect, since the items that are still active in STS most likely come from the end of the list. However, no one would deny that other factors could also lead to a recency effect. For instance, suppose that the items at the end of the list are much easier than the other items. This too would lead to a recency effect.

The criticism of the two-store model based on long-term recency effects makes a logical error. The two-store model assumes that recall from STS leads to recency, or in symbolic form: A -> B. It does not follow that the reverse, B -> A, is also true. That is, the model does not assume that all recency effects are based on recall from STS. In fact, as I will show later, modern versions of the two-store model such as the SAM model, predict that retrieval from LTS is based on contextual retrieval cues. Such contextual retrieval will, everything else being equal, lead to an advantage for more recent items if the context stored in the memory images varies.

This analysis is supported by findings that short-term and long-term recency effects are differentially susceptible to the effects of various experimental factors. For example, long-term recency is not sensitive to output order while short-term recency is (Dalezman, 1976; Whitten, 1978). Moreover, interresponse times in regular free recall show an abrupt increase after the first three or four items (Metcalfe & Murdock, 1981). Although I am not aware of similar data in long-term recency paradigms, I expect that the results will be quite different.

3 The SAM Model

In the previous sections, I have argued that the framework of the two-store model is still viable. Nevertheless, there have been several new theoretical developments since the original papers by Atkinson and Shiffrin (1968). For example, one of these is the Search of Associative Memory (SAM) model proposed about a decade ago by Raaijmakers and Shiffrin (1980, 1981). This latter model, which is a contemporary version of the two-store model, has been extended to a large number of memory paradigms, including paired-associate recall, recognition, and interference paradigms (Gillund & Shiffrin, 1984; Mensink & Raaijmakers, 1988, 1989).

In this section, I will describe the basic elements of the SAM model, both the general framework and the way in which it has been applied to several memory paradigms. This seems appropriate, not only because SAM grew out of the two-store model, but also because it emphasizes the cumulative nature of this theoretical approach.

3.1 The Basic Framework

The basic framework of the SAM model assumes that during storage, information is represented in "memory images", which contain item, associative and contextual information. The amount and type of information stored is determined by coding processes in STS (elaborative rehearsal). In most intentional learning paradigms the amount of information stored is a function of the length of time that the item is studied while in STS.

According to the SAM model, retrieval from LTS is based on cues. These cues may be words from the studied list, category cues, contextual cues, or any other type of information that the subject uses in attempting to retrieve information from LTS. Whether an image is retrieved or not, depends on the associative strengths of the retrieval cues to that image. These strengths are a function of the overlap of the cue information and the information stored in the image. In most applications, the simplifying assumption is made that the strengths are a linear function of the amount of elaborative rehearsal (the amount of time that the item is actively rehearsed).

An important property of the SAM model is that it incorporates a rule to describe the overall strength of a set of probe cues to a particular image. For example, let $S(Q_j,I_i)$ be the strength of association between cue Q_j and image I_i. Then the combined strength or activation of image I_i, $A(i)$, for a probe set consisting of Q_1, Q_2, ..., Q_m is given by

$$A(i) = \prod_{j=1}^{m} S(Q_j,I_i)^{W_j} \qquad (1)$$

The W_j in this equation are weights assigned to the different cues, representing their relative salience or importance. These weights are used to model the limited capacity of STS in retrieval. The sum of the weights is assumed to be limited (Raaijmakers & Shiffrin, 1981; Gronlund & Shiffrin, 1986): adding extra cues takes attention away from the other cues. However, the key feature of Eq. (1) is that the individual cue strengths are combined multiplicatively into a single activation measure. This multiplicative feature focuses the search process on those images that are strongly associated to *all* cues.

3.2 Application to Recall Tasks

In recall tasks, the search process of the SAM model is based on a series of elementary retrieval attempts. Each attempt involves selecting or sampling one image based on the activation strengths A_i. The probability of sampling image I_i equals the relative strength of that image compared to the other images in LTS:

$$P_S(I_i) = \frac{A(i)}{\sum A(k)} \quad . \tag{2}$$

Sampling an image allows recovery of information from it. For simple recall tasks where a single word has to be recalled, the probability of successfully recovering the name of the encoded word after sampling the image I_i is assumed to be an exponential function of the sum of the weighted strengths of the probe set to the sampled image:

$$P_R(I_i) = 1 - exp\,[\, -\sum_{j=1}^{m} W_j\, S(Q_j,I_i)\,] \tag{3}$$

The probability of recall, assuming L_{max} retrieval attempts with the same set of cues, is given by the probability that the item was sampled at least once, times the probability that recovery was successful:

$$P_{recall}(I_i) = [1 - (1-P_S(I_i))^{L_{max}}]\, P_R(I_i) \tag{4}$$

Special assumptions are necessary when an image has previously been sampled using one or more of the present cues but its recovery did not lead to successful recall. In that case, recovery is based only on the "new" components of the sum in Eq. (3), corresponding to cues that were not involved in the earlier unsuccessful retrieval attempts (see Gronlund & Shiffrin, 1986).

If the retrieval attempt is successful, the associative connections between the probe cues and the sampled image are strengthened. Thus, SAM assumes that learning occurs during retrieval as well as during study. This assumption leads to a kind of retrieval inhibition, because it decreases the probability of sampling other images. If the retrieval attempt is not successful, a decision is made about whether to continue, either with the same set of cues or with some other set of cues. The decision to terminate the search process is usually based on the number of unsuccessful searches, although other types of stop rule are also possible.

3.3 Application to Recognition Tasks

Although the SAM model assumes that the process of activating information is basically the same in recall and recognition, there are some important differences between these two processes. Gillund and Shiffrin (1984) proposed that old-new recognition decisions are based on the overall activation induced by the probe cues. That is, the overall activation, *å A(k)*, defines a familiarity value that is used in the manner of signal-detection theory to determine the probability of recognition. In order to derive predictions, some assumption is also needed about the variance of the strength distributions. Typically, the standard deviation is assumed to be proportional to the mean strength value (Gillund & Shiffrin, 1984; Shiffrin, Ratcliff, & Clark, 1990).

However, within the SAM framework, other types of models are also possible. For example, I believe that it would be worthwhile to consider an alternative version that assumes instead that recognition is based on a comparison of the overall activation with both context and the item as cues versus the item cue alone. Such an alternative has not yet been worked out[1]. For most predictions, this probably would not make much difference. However, it might handle word frequency effects in recognition tasks more easily than the Gillund and Shiffrin (1984) version did.

3.4 Contextual Fluctuation

The SAM model assumes that for typical episodic-memory tasks, contextual information is always encoded in the memory image, and context is one of the retrieval cues. Context and changes in context play an important role in the prediction of forgetting phenomena. Changes in context may be discrete or occur in a more gradual way. Discrete changes are typical for studies that explicitly manipulate the test context (e.g., Godden & Baddeley, 1975; Smith, 1979). On the other hand, gradual changes may occur when the experimental paradigm is homogeneous (as in continuous paired-associate learning). In such cases, context similarity will be a decreasing function of delay.

Mensink and Raaijmakers (1988, 1989) recently proposed an extension of the SAM model to handle time-dependent changes in context. The basic idea, adapted from Stimulus Sampling Theory (Estes, 1955), is that a random fluctuation of elements occurs between two sets, a set of available context elements and a set of (temporarily) unavailable context elements. Performance is a function of the relationship between sets of available elements at different points in time (viz. study and test trials).

In this version of the SAM model, the experimental context is represented as a set of contextual elements. At any given time, only a part of this set is "perceived" by the subject, and this subset is denoted the current context. Elements in this set are said to be in the active state. All other elements are inactive. With the passage of time, the current context changes through a fluctuation process: some inactive elements become active and some active ones become inactive. At storage, only active elements are encoded in the memory image. If there are multiple study trials, each study trial gives a new opportunity for encoding a particular element in the image. The context strength at test is assumed to be proportional to the overlap between the set of context elements encoded in the image and the set of context elements that are active at the time of testing. Mensink and Raaijmakers (1989) show how some simple assumptions concerning the fluctuation process yield equations for computing the probability that any given element is active both at the time of storage and at the time of retrieval.

4 Important Applications

The SAM model was proposed to integrate phenomena from various memory paradigms within a single theoretical framework. As such, the model has been quite successful. With it, quantitative accounts have been developed for free recall, paired-associate recall, interference paradigms, and various recognition paradigms. In this chapter, I will briefly review these applications, focusing attention on those results that are most intriguing and that best illustrate the usefulness of a formal framework such as SAM. Special attention will be given to some new developments concerning spacing and repetition phenomena.

4.1 Free Recall and The Part-List Cuing Effect

SAM was initially developed as a model for free recall. Although the first version of the model was conceptually simple, the predictions that follow from it have been quite complicated to analyze. This is because they involve a large number of dependencies that make it difficult to intuit what may happen as the result of a particular experimental manipulation.

Raaijmakers and Shiffrin (1980, 1981) demonstrated that SAM predicts many findings from free-recall paradigms. For example, one important prediction is the list-length effect: the longer the list, the lower the probability of recalling any particular item. This follows because the rules for terminating search imply that *relatively* fewer samples are made from a longer list than from a shorter list. In fact, it seems to be a general characteristic of retrieval processes that *the larger the number of items associated with a cue, the smaller the probability that any one of those items will be recalled*. This *cue-overload principle* has been used by Watkins to explain a number of empirical phenomena (Mueller & Watkins, 1977; Watkins, 1975; Watkins & Watkins, 1976). Thus, it is of some interest to note that the cue-overload principle can be derived from the SAM model.

Probably the most intriguing aspect of the SAM model for free recall is its prediction of the *part-list cuing effect*, a *decrease* in the probability of recall when, at test, some of the list items are given as cues. This effect has generally been considered problematic for any model that assumes the use of interitem associations in recall. It seems that giving some items as cues should aid recall of the remaining items (the target items).

However, application of the SAM model has revealed that the logic underlying this latter prediction is not correct. We showed that it is important to consider the nature of the cues used during retrieval. Experimenter-provided cues (used by the cued group in a part-list cuing experiment) are inferior to self-generated cues, because experimenter-provided cues slightly bias the sampling process in favor of cue items. For any given cue, the model predicts that there is some probability of sampling the cue item itself. By definition, the cued group starts its retrieval using the experimenter-provided cues. For the noncued or control condition, there is no such bias since this group starts retrieval with a self-generated cue. Hence, the images sampled by the cued group are less likely to come from the set of target items.

We recently completed a study in which the SAM model's explanation for the part-list cuing effect was tested against a class of theories that attribute the negative cuing effect to storage factors (e.g., Roediger & Neely, 1982). In this study, subjects were presented lists of unrelated words. They were tested either immediately or after a delay filled with learning a list of paired associates. It is assumed that the delay leads to a decrease in the strength of the contextual associations. The SAM model predicts that the usual negative effect will be obtained in the immediate-recall condition but that a positive effect will be obtained in the delayed-testing condition. The reason is that the part-list cues will help in conditions where subjects are not able to recall many items without any cues. On the other hand, most other explanations that attribute the part-list cuing effect to storage factors predict no difference in it for immediate and delayed testing. Our results (Figure 1) support the SAM model: there was a negative effect of cuing in the immediate-testing condition and a positive effect in the delay condition.

Insert Figure 1 about here

4.2 Recognition and the List-Strength Effect

The SAM model for recognition developed by Gillund and Shiffrin (1984) has been quite successful in predicting a large number of well-known findings. Recently, attention has been focussed on the so-called "*list-strength effect*" (Ratcliff, Clark, & Shiffrin, 1990; Shiffrin et al., 1990), which concerns the effects of strengthening (or weakening) some list items upon memory for other list items. Ratcliff et al. (1990) showed that strengthening some items in the list decreases recall of the remaining list items but has no or even a positive effect on recognition performance. This contrasts with the list-length effect: adding items to a list decreases both recall and recognition performance. Thus, the number of irrelevant items, but not their strength, affects recognition.

Shiffrin et al. (1990) showed that many current models (including the original SAM model) cannot predict both the presence of a list-length effect and the absence (or reversal) of a list-strength effect. However, a simple modification of SAM can handle these results. To explain them, a number of assumptions are required. First, different items are stored in separate traces but repetitions of an item within a list are stored in a single memory trace (under the conditions of these experiments). Second, the variance of activation of each separate trace, when the cue item is unrelated to the item(s) encoded in the trace, is constant regardless of the strength of the trace. Third, recall and recognition operate differently, with recognition based on the combined activation of all traces and recall based on access to a single trace.

The problematic assumption is the second one. In the SAM model for recognition (Gillund & Shiffrin, 1984), the variance of the activation for an unrelated item was assumed to increase with the strength of the context association. Since the interitem associative strength for unrelated items was always set equal to a constant residual value (d), the combined variance for such unrelated items is larger for the stronger items. In contrast, Shiffrin et al. (1990) propose that the residual strength is not a constant but decreases as a function of the strength of the image. Yet while this assumption seems ad hoc, it can be defended using a *differentiation* argument: the better the image is encoded, the clearer are the differences between it and the test item, and hence the lower the activation. In this way, a constant or even decreasing variance may be predicted, depending on the weighting of context and item cues.

A crucial aspect of this explanation is that repetitions of an item are assumed to be stored in a single memory image. To evaluate it further, Murnane and Shiffrin (1989) tested whether a reversal of the list-strength effect in recognition occurs if repetitions are presented in such a way that they are likely to be encoded in separate images. They found that repetitions of words in different sentences produced a list-strength effect whereas repetitions of entire sentences did not. This demonstrates that the nature of the encoding of a repeated item is a crucial factor.

Clearly, we now need a more detailed model of how the relation between the information in a cue item and a stored image determines associative strength, not only for items studied separately but also for items studied together. In addition, some older theoretical analyses should be repeated to see whether the extended SAM model's predictions are still the same.

4.3 Interference and Forgetting

Mensink and Raaijmakers (1988) applied the SAM model with the contextual-fluctuation assumption to several classic findings on interference and forgetting. The model can handle most of the findings on retroactive and proactive interference and transfer relations between lists in a straightforward way, including results that were problematic for classical interference theories.

A crucial requirement for many of these predictions is that recall performance depends on both the relative and absolute strengths of the memory images. In the SAM model, the sampling process is a function of the relative strength of the target image compared to the other images, whereas the recovery process is a function of the absolute strength. For example, if one equates recall in the interference and control conditions by giving the interference condition more study trials, this does not imply that the respective associative strengths are also equal. Instead, the model predicts that if the probability of recall is equalized, the absolute strength will be higher and hence the relative strength lower for the interference condition (otherwise recall would not be equal). This enables us to account for a number of results, including the differential effects of interference on accuracy and latency measures (Anderson, 1981).

4.4 Spacing of Repetitions in Continuous Paired-Associate Recall

Recently, we have also used the SAM model to explain results concerning the spacing of repetitions. Suppose an item is presented twice for study (at times P_1 and P_2) and tested at a later time T. If the retention interval (i.e., the interval P_2-T) is relatively long, the probability of recall increases as a function of the spacing between the two presentations (the interval P_1-P_2). With short retention intervals, however, the probability of recall decreases as a function of the spacing between the presentations. With intermediate retention intervals, the results are more complicated, often showing a nonmonotonic effect of spacing (Glenberg, 1976, 1979).

Recent work by Raaijmakers and van Winsum-Westra shows that this complicated state of affairs is predicted by the SAM model through its assumptions concerning contextual fluctuation. As the spacing interval increases, the context at P_2 will include more new, not yet encoded, elements that may be added to the memory image. Encoding more elements in the image increases the expected overlap between the test context and the contextual elements in the image.

Although the basic principle is quite straightforward, the full SAM model requires supplementary assumptions that complicate matters. Crucial here is what happens on the second presentation, P_2. It is assumed that on P_2, an implicit automatic retrieval attempt is made for the image stored on P_1 (a study-phase retrieval assumption). New context elements that are present on P_2 are only added to the image formed on P_1 if that image is retrieved on P_2. If it is not retrieved, a new storage attempt is made, based only on the information present on P_2. Also, to accommodate effects of differential storage strengths, it is assumed that each storage attempt either succeeds or fails. If it is not successful, the probability of sampling that image on a future retrieval attempt is zero. It is further assumed that no new storage takes place for any item still in STS on P_2.

According to this model, spacing of repetitions has a number of effects. As mentioned, due to context fluctuation, more new context elements are stored when an item is "recognized" on P_2. As the spacing interval increases, the probability that the item is still in STS on P_2 decreases. Both of these effects lead to an increase in the probability of recall at test (i.e., they increase the likelihood that new information is added to the trace on P_2). However, spacing also has a negative effect. The longer the spacing interval, the lower the probability that the image is successfully retrieved on P_2. This is a simple forgetting effect: as the interval increases, the expected overlap between the contexts at P_1 and P_2 decreases, and this decreases the strength of the context cue at P_2. Together, these factors produce a nonmonotonic effect of spacing. The spacing effect has an initial increase followed by a decrease, the maximum point depending on the length of the retention interval (P_2 to T).

Insert Figure 2 about here

The present extension of the SAM model has been used successfully to fit the results of a number of well-known experiments (e.g. Glenberg, 1976, Rumelhart, 1967; Young, 1971). The most clear demonstration of the nonmonotonic effect of spacing is provided by Young (1971). Figure 2 shows the observed data and the SAM model's predictions. We have also fit this model to the results of a multitrial learning experiment reported by Rumelhart (1967) in which the spacing between repetitions was varied (Figure 3). This demonstrates that SAM can handle the basic learning data that were the main focus of the Markov models in the 1960's.

Insert Figure 3 about here

Another particularly interesting aspect of the present model is that it provides an explanation for the intriguing results of Ross and Landauer (1978). According to their analysis, most theories of spacing effects based on encoding or contextual-variability assumptions, predict beneficial effects of spacing for both two presentations of the same item and for two presentations of two different items. That is, the probability of recalling either of the two items should increase. However, Ross and Landauer (1978) showed that such a result is not obtained: a typical spacing effect only occurs for one item presented twice, not for two items presented once each.

The SAM model can handle this result because it treats these two situations quite differently. For the one-item case, it predicts that new information is often added to the same memory trace (if the item is recognized). In the two-item case, it predicts that two different images are formed. Since recall depends on the overlap in elements with each image separately, the spacing of the presentations by and large only matters for the single-item case. This is illustrated in Figure 4, which shows predicted patterns of results for these two types of items.

Insert Figure 4 about here

To explain these results, the SAM model must assume that repetitions of an item are often encoded in the same memory image. This assumption, which we have also used in the analysis of interference data, agrees with one that Shiffrin et al. (1990) have found necessary to account for the list-strength effects in recognition. That the same assumption is needed in quite different applications provides additional evidence for it.

The preceding account of spacing effects is in many respects quite similar to the Components-Levels theory proposed by Glenberg (1979), although he did not present a quantitative analysis. Interestingly, Glenberg and Smith (1981) mention the Ross-Landauer result as the one result that the Component-Levels theory cannot explain. Our analysis of the SAM model shows that their conclusion may not have been correct and that their theory can probably handle more data than they are aware of. This illustrates, once again, the usefulness of quantitative modelling of memory phenomena.

5 Some Important Theoretical Issues

The preceding applications show that the SAM model is a quite powerful framework for analyzing memory experiments. Perhaps the most significant aspect of a model such as SAM is that it provides a tool for the analysis of various complex and/or problematic memory phenomena. Quantitative predictions for specific designs can be obtained quite easily, and such analyses may lead to novel insights into the conditions under which particular phenomena are obtained. This has been true, for example, concerning the part-list cuing effect, the list-strength effect, various interference effects, and the Ross-Landauer results for spacing of repetitions.

Even though the SAM model has been applied to many results in the memory literature, there are still a number of issues that need to be dealt with. In this final section, I will discuss a few of these for which there are some preliminary ideas.

5.1 The Nature of The Units of Memory

The first issue concerns the nature of the units in memory. In the original SAM model for free recall, it was assumed that the units in memory, the memory images, corresponded to single words presented on the list. However, the SAM model does not restrict images to single words. Indeed, in our recent accounts of paired-associate recall, we have assumed that images correspond to the word pairs presented on the list. The nature of the units in memory is of course not an issue unique to the SAM model. Other theories will also, at some time, have to consider it.

In principle then, the SAM model has great flexibility for representing memory images. Does this mean that there is complete freedom to choose whatever units one likes? The answer is, not surprisingly, no. Several constraints follow from the functional rules in the SAM model (Raaijmakers & Shiffrin, 1981; Shiffrin, Murnane, Gronlund & Roth, 1989). These constraints are:

1. An image is unitized in the sense that the encoded information can be recovered from that image without further sampling.
2. Information encoded in other, nonsampled images does not contribute to the recovery process.
3. To recover the core information in an image other than the sampled one requires that image to be sampled on a subsequent retrieval attempt.

The general framework of the SAM model assumes that what gets stored in LTS is what gets attended to in STS. A corollary of this assumption is that the nature of the stored units depends on coding processes in STS. For example, if a subject focuses on sentences, the memory images might be sentences, whereas if the focus is on single words, the memory images would correspond to words. This does not deny that the images themselves might be structured in some way. For example, if they correspond to sentences, a complete theory might specify how specific words are retrieved from them. However, such retrieval is assumed to be qualitatively different from retrieval of the image itself. In SAM, retrieval of information from within an image is part of the recovery process and is independent of the information in the other, nonsampled memory images.

Shiffrin et al. (1989) describe some experiments to investigate the nature of the units in memory when subjects are presented at study with sentences and are cued at test with some words from those sentences to recall the remaining words. In their analysis, they not only investigated the nature of the units in memory but also the nature of the units in retrieval. The data clearly favoured a model that posits the use of sentence-level units in storage and retrieval.

5.2 Semantic Memory

As described in this chapter, the SAM model has been applied to the major episodic memory paradigms. What has not been done yet is to a specify how the model would handle retrieval from semantic memory (e.g. in word-association tasks). Although a complete model has not yet been developed for this latter process, I would like to propose some ideas that may serve as a useful starting point.

The basic idea here is that semantic memory represents an accumulation of many specific episodic memories. That is, an episodic-memory image is characterized by the inclusion of contextual information. Recalling a particular episodic image requires an appropriate context cue. However, if a particular association is stored in a large number of different contexts, its retrieval will become more or less independent of any specific contextual retrieval information. Hence, it will acquire "semantic" properties. Thus, a semantic association is not stored as one very strong image, but is represented by a large number of images. This implies that the semantic-episodic distinction should be viewed as a continuum, with some associations completely context-bound, some completely context-free, and others in between. The extent to which an association is context-free would then depend not just on the total number of times it has been stored but also on the total number of different contexts in which it has been stored.

Retrieval of semantic associates would be context-free in more than one sense. First, they would tend to become activated regardless of the particular context at the time of retrieval. Second, even when context is not used as a cue, they would still be activated because retrieval probability depends simply on the relative number of images (more accurately, the strengths of the images) that incorporate them as opposed to other associations.

Such an account of semantic memory may be used to answer a criticism raised by Humphreys, Bain and Pike (1989) against several memory models including the SAM model. This involves the so-called "*crossed associates*" problem, which stems from the fact that subjects do not suffer overwhelming interference when presented with a paired-associates list containing semantic associates in different pairs such as *bread-queen* and *king-butter*. Humphreys et al. (1989) claimed that SAM could not handle this result. According to them, the model would predict the retrieval of *butter* in response to the cue *bread*, since *butter* is strongly associated to both the context and the item cue.

This claim is not correct, however. In SAM, cues are associated to images, not to more or less abstract (semantic) representations of individual words. As a result, one possibility is that each memory image may correspond to a single word. We assume that semantic memory consists of a large number of episodic images. So the cue *bread* will be associated to a number of images containing the word *butter*, whether or not *butter* was on the list. If the pair *king-butter* was on the list, a new image containing *butter* will be formed. The cue *bread* will not be strongly associated to this image, since the image contains no interitem information with both *bread* and *butter*. The SAM model does not assume a single memory representation for *butter*. The strong pre-experimental association between *bread* and *butter* is not due to one strong link between *bread* and *butter* but to the fact that both items have co-occurred many times and this information is reflected in a large number of images.

Another possibility is that each image corresponds to a pair of words. This is the usual assumption in SAM for lists of paired associates. In this case, the cue *bread* is associated to a number of pre-existing images containing both *bread* and *butter* but not to the experimental image representing the pair *king-butter*. The result is that

SAM does not predict strong interference. The explanation by SAM is in this case basically the same as that of Humphreys et al. (1989).

5.3 Implicit Memory

Another topic that we have not yet dealt with is "implicit memory". One fruitful idea to explore with the SAM model, is that tasks may differ in how much retrieval relies on the use of context cues. This idea, which is similar to one adopted by Humphreys et al. (1989), assumes that in implicit or indirect memory tasks, subjects do not rely much on specific contextual cues.

Even though context is not explicitly used as a cue, recent exposure to an item may still affect the probability of retrieval on a subsequent implicit memory test. For example, certain types of amnesic patients who show little or no memory on an explicit memory task perform quite well on implicit memory tasks (Graf & Schacter, 1985; Moscovitch, 1984). Such results might be explained by assuming that amnesics are impaired in the use of context information for retrieval. This implies that they will show impairments on explicit memory tests but much less on implicit tests, since on such tests, both amnesic and normal subjects do not explicitly use contextual retrieval cues.

This account of the amnesic deficit is still sketchy but has obvious similarities to many other explanations (see Squire & Butters, 1984). In my view, a more adequate theoretical analysis, using formal modelling techniques) could prove very helpful in deciding between these various explanations.

6 Conclusion

The results reviewed in this chapter show that the SAM model provides a useful framework for the analysis of memory phenomena. Since SAM is based on the general two-store model described by Atkinson and Shiffrin (1968), one may conclude as well that the two-store model is far from obsolete, contrary to suggestions by some critics (e.g., Crowder, 1982). The distinction between a temporary limited-capacity memory (active memory, working memory, or STS) and a more permanent memory (LTS) is an almost universal aspect of contemporary models of memory, even in ones that claim to be alternatives to a two-store model. Perhaps this stems from a requirement that any reasonable model of memory must have a way of retaining information for brief periods of time.

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Notes

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[1] The observation that a levels-of-processing account is quite compatible with the STS/LTS framework has been made several times in the past (e.g., see Bjork, 1975; Shiffrin, 1977), although this does not seem to have had any influence on the typical textbook presentation.

[2] A similar assumption is made by Humphreys, Bain and Pike (1989).

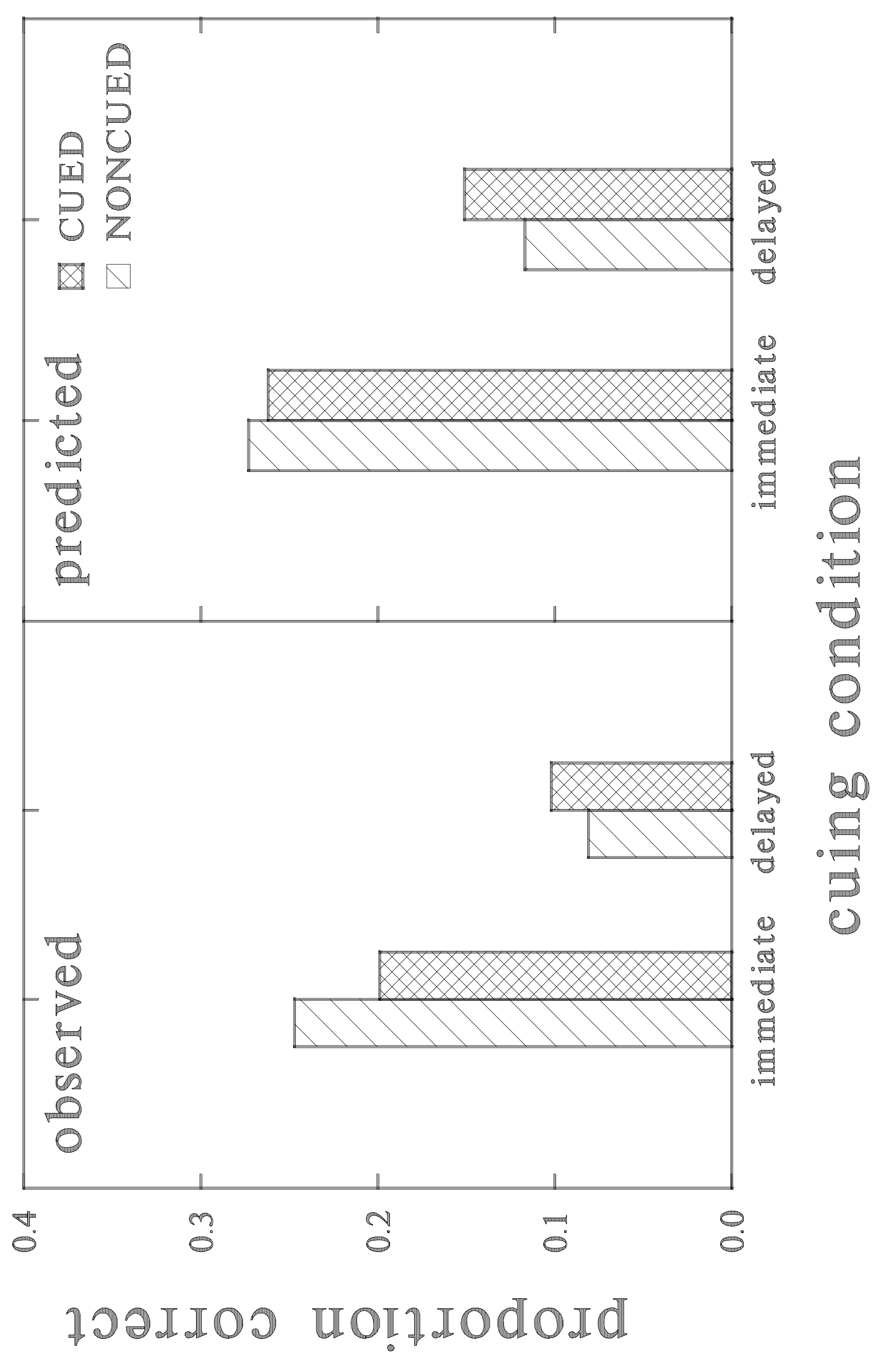
Figure legends

Figure 1: Proportion correct in free recall with and without part-list cues for immediate and delayed testing. The left panel gives observed data from an unpublished experiment; the right panel gives simulated results from the SAM model for free recall.

Figure 2: Observed and predicted probabilities of recall as a function of spacing interval (number of intervening items). Data from Young (1971).

Figure 3: Observed (dots) and predicted (lines) probabilities of recall for Experiment I of Rumelhart (1967). Each graph gives the spacing (number of intervening items) between successive presentations.

Figure 4: Predictions of the SAM model for the probability of recalling one or both of two items each presented once, and for the probability of recall of a single item presented twice, as a function of the spacing interval (number of intervening items) between the two presentations. Parameter estimates and experimental design are based on the SAM model applied to the experiment of Young (1971).


observed
predicted
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NONCUED
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immediate
delayed
cuing condition
proportion correct
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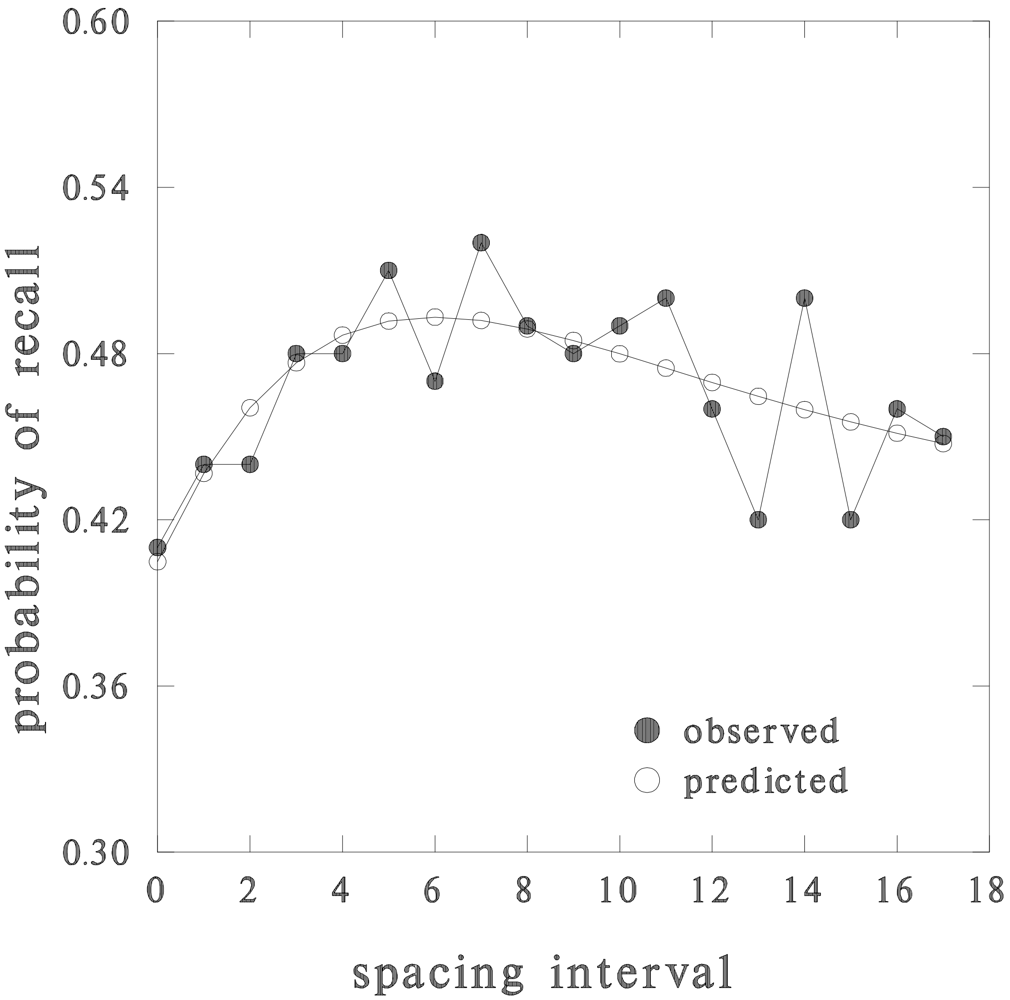
Figure 1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18
spacing interval
observed
predicted

Figure 2

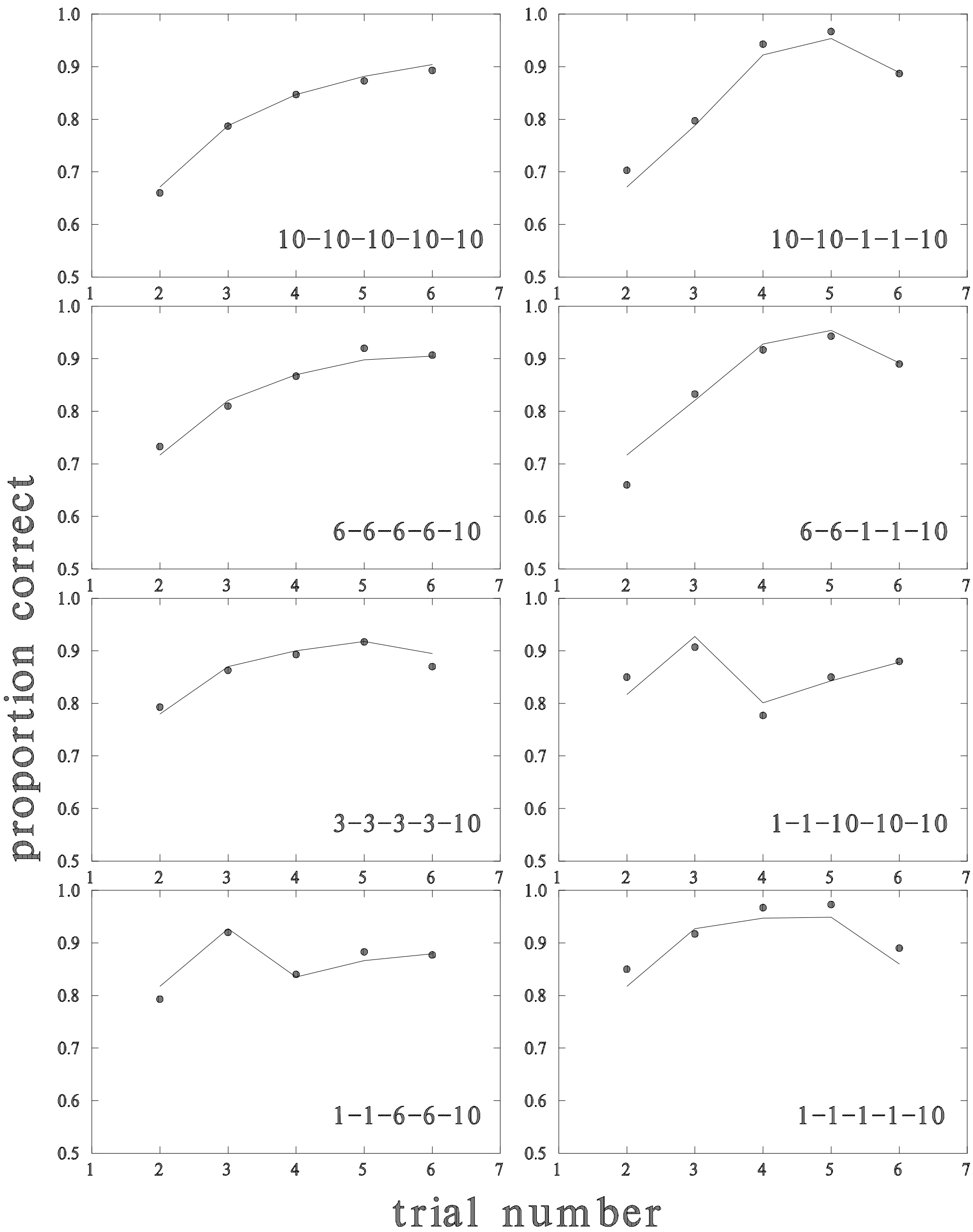
proportion correct
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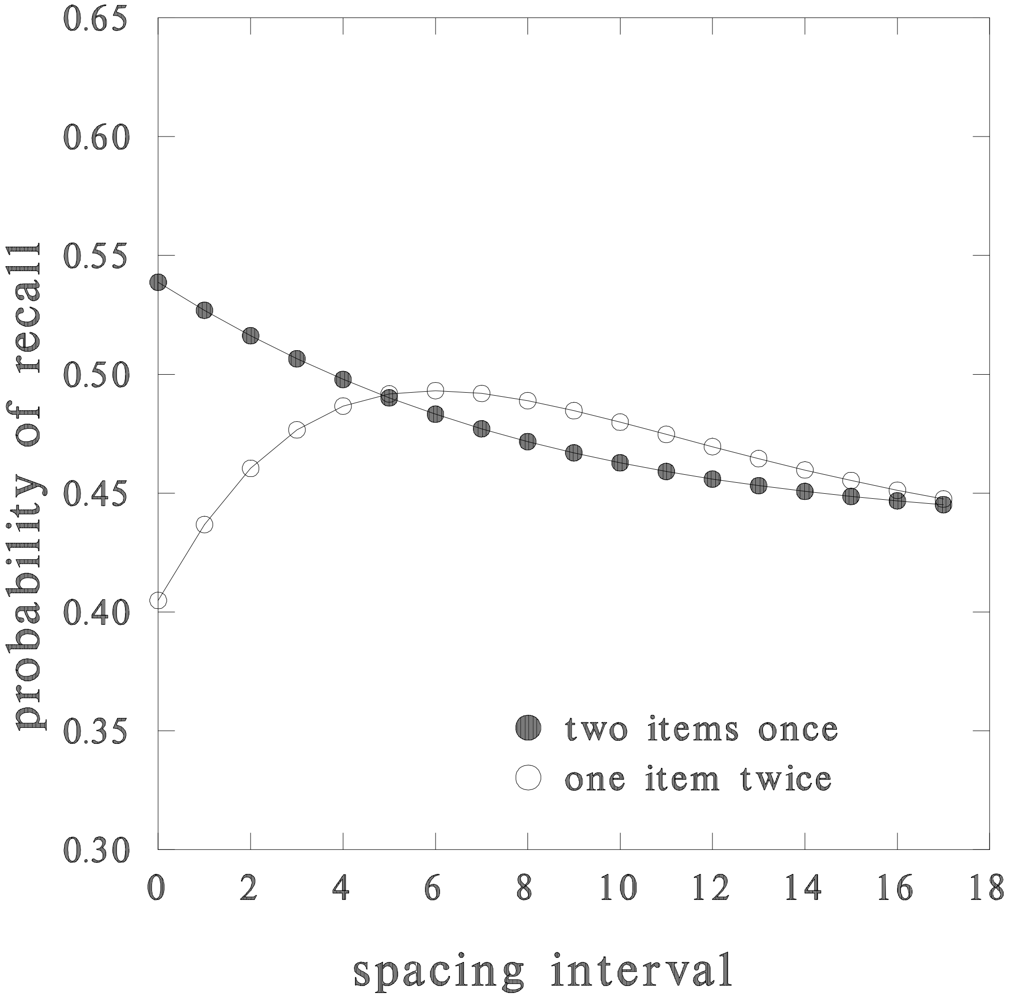
Figure 3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14
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18
spacing interval
two items once
one item twice

Figure 4