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**Mechanisms of short-term memory for serial order**

**Sliwinski, Martin John, Ph.D.**

**City University of New York, 1992**

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**MECHANISMS OF SHORT-TERM MEMORY FOR SERIAL ORDER**

by

**MARTIN J. SLIWINSKI**

**A dissertation submitted to the Graduate Faculty in Psychology in partial fulfillment of the requirements for the degree of Doctor of Philosophy, The City University of New York**

1992

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Abstract

MECHANISMS OF SHORT-TERM MEMORY FOR SERIAL ORDER

by

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Three experiments used a task that measured probed recall of digit strings to explore factors that underlie short-term memory for serial order. Associative and positional probes were used to measure recall of order information. A version of Buschke's (1963a) missing scan probe was used to measure recall of item information. Experiment 1 analyzed data from 24 young adults (mean age=22). Experiment 2 analyzed data from 4 young subjects tested over several sessions to determine whether the pattern of results observed in the aggregated data from Experiment 1 describes the performance of individual subjects as well. Experiment 3 compared recall and serial order effects of young (ages 18-26) and aged (ages 65-80) subjects. Typical serial position curves were observed for all probe types, for two levels of distractor difficulty and for two list lengths. While the comparison of serial position curves from the probed recall of order and item information did not reveal any significant differences, there was a considerable difference in recall accuracy. This difference between recall accuracy of item and order information was exaggerated in the aged, suggesting a specific impairment of memory for order in aged. Consistent with previous research, positional codes were found to be more basic than associative codes for serial order memory. However, there was some indication that additional encoding operations, such as chunking, came into play for the long stimulus lists. Application of a quantitative model (Estes' perturbation model, Lee & Estes, 1981) which relies on positional

coding of serial order met with mixed success. The model fit the serial position data from the positional probe well, especially for the short stimulus list. However, the model had difficulty predicting recall for associative probes and the long stimulus lists, providing a further indication that there are important aspects of serial order memory not captured by an exclusively positional account.

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## Introduction

Memory is certainly the most ubiquitous of all the psychological phenomena that have been subjected to rational or empirical inquiry. Although memory has long been recognized as playing a definitive role in the creation and development of an individual's personal identity, it enjoys an even more fundamental place in our lives. Memory is so basic to human experience that its presence is not often noticed, except when it fails us.

The registration and maintenance of the sequential aspect of experience are of particular importance to much of human cognition. That an event occurred may be meaningful, but often its primary importance depends upon its relations to other events. For example, an individual sentence from a conversation may have meaning in isolation, but to appreciate its impact on the conversation, what was said prior (and subsequent) to it must be known. Lashley (1951) has gone so far as to argue that an adequate understanding of serial order effects is required to understand the acquisition of complex skilled behavior as well as the principles underlying language processing. Indeed, memory for serial order information underlies many of the cognitive skills invoked in daily life.

One important serial learning phenomenon is the serial position effect. Whenever a serial list is learned, recall of items occupying positions toward either end of the list is better than recall of items occupying middle list positions. If the probability of correct recall is plotted against serial position, a U-shaped curve is observed. The superior recall of items presented early in the list has been called the **primacy** effect, while the superior recall of item near the end of the list has been called the **recency** effect. This serial position effect has been the central fact which theories of serial

learning have sought to explain. The usual serial position curve has been observed only when the retrieval of the items of a list in their original serial order is required. It is not observed when this requirement is relaxed. That is, if retrieval of an item from a list is considered correct whether or not it is recalled in its original serial position, then plotting the probability of correct recall against serial position can result in a flat function. The differential serial position curves obtained for the recall of order and content has been taken as the primary evidence for the disassociation of memory for these two types of information.

The serial position curve has been of interest not only to investigators studying serial learning, but to those concerned with broader issues regarding memory. Its two definitive features, primacy and recency, have been used to support the 'duplex' theory of human memory (Glanzer & Cunitz, 1966). The duplex theory states that there are two distinct systems of human memory, a short-term and long-term system. Primacy effects have been interpreted as resulting from the increased opportunity for rehearsal and the subsequent entry of early list items into long-term storage, making them relatively resistant to the decay or interference affecting middle list items. In contrast, middle list items enter a short-term store already occupied by information and cannot benefit from the same amount of rehearsal as did the early list items. Consequently, retrieval for middle list items is poorer than for early list items. Recency effects have been explained by asserting that items near the end of list are still in short-term memory when recall begins. Subjects can then report end list items immediately out of the short-term store, resulting in better recall for those items. This account does not represent a theory designed to explain the serial position curve, but rather provides an example of how one serial learning effect has influenced the development of memory theory in general.

Serial learning tasks have also been widely used to study what has been called 'working memory.' Working memory refers to a system that temporarily stores and manipulates information required for complex cognitive functions such as learning, language processing and reasoning (Baddeley, 1986; 1992). A key assumption of the working memory framework is that many of the operations performed on information held in this temporary store are effortful and compete for a finite pool (or pools) of processing resources. The study of working memory usually proceeds by occupying processing resources with one task and observing the effect on performance of another concurrently performed task. In an early study, Baddeley and Hitch (1974) examined how loading working memory with strings of digits affected the serial position curve obtained for a list of words. Their surprising finding that concurrent digit load, which presumably occupied short-term storage, did not suppress recency effects was at odds with current theories of short-term and long-term storage systems, which attributed the recency effect to operation of short-term memory. This result demanded a reevaluation of theories of short-term memory as well as theories designed to explain the serial position curve.

The construct of working memory was proposed to represent both memory capacity and the more active cognitive operations inherent to short-term memory. Whether these operations compete for a single pool of resources varies from theorist to theorist, but the view that short-term memory must be understood within the context of both a finite capacity and cognitive operations that transform, manipulate and maintain information is common to all accounts. Application of the working memory framework to the study of memory and cognition has yielded important insights into the mechanisms that underlie and limit short-term memory, as well as providing a conceptual framework for explaining, as opposed to simply describing, age related

differences in memory and cognition. However, although the memory component of such paradigms usually involves serial learning, often a type of digit or word span task, what is known of serial order effects rarely influences theories of working memory. Similarly, the constructs of working memory have not been applied to further our understanding of serial order effects. Considering the importance of serial order effects to human cognition and the utility of the working memory framework, this lack of an interaction between the two is unfortunate.

Three issues are basic to the study of serial order and working memory. First is the reputed distinction between memory for order and memory for item information. The vast preponderance of evidence over the past 30 years has supported some fundamental disassociation of order and item information, the strongest evidence being differential serial position curves. This distinction is of particular importance to theories of working memory, since much of the research in this area equates, albeit implicitly, short-term memory with short-term memory for serial order. The second issue is the relative importance of associative and position information for the retrieval of order information. Theories of serial order memory usually assume that information in short-term memory is represented either by item-to-item (associative) codes or item-to-position (positional) codes. The final issue is the presence of age related differences in these above serial order phenomena. Much of what is known about working memory has been discovered through the study and comparison of different populations (e.g., young and aged adults, normal aged vs. demented patients) on various experimental tasks (Wright, 1981; Salthouse, Davenport & Prill, 1984; Baddeley, Logie, Bressi, Della Sala & Spinnler, 1986; Dannenbaum, Parkinson & Inman, 1988; Becker, 1988; Spinnler, Della Sala, Bandera & Baddeley, 1988; Gick, Craik & Morris, 1988; Morris, Gick & Craik, 1988). Yet, little work has been done in describing age related

differences in serial order effects, which is unfortunate, since many studies of age related working memory differences have used some sort of serial learning task. The study of age related differences in serial order effects (especially the distinction between order and item information) will foster a more complete understanding of these phenomena as well as provide the necessary groundwork for applying serial order tasks to the study of working memory changes associated with advanced age.

A review of the relevant research in the areas of serial order effects and working memory is required. Any such review must begin with the work of Hermann Ebbinghaus. Ebbinghaus (1885/1964) provided the first experimentally rigorous inquiry into serial order learning. Specifically, in several experiments, he subjected certain long-standing principles of associationism (e.g., the laws of frequency and of contiguity) to empirical scrutiny. By hypothesizing that the strength of associations between elements of a list is a decreasing function of the time or number of intervening members (p. 92), he proposed that remote associations link non-contiguous items in a series. From his results, Ebbinghaus theorized that decreased savings were a function of the time or number of intervening items and reflected a decrease in the “strength” of the associations between items. Though often viewed as proposing that serial order information is stored via pairwise associative chains (Lewandowsky & Murdock, 1989), he was the first to provide an empirical basis for the existence of remote (and reverse) associations, concepts which still play important roles in contemporary models of serial learning (e.g., Johnson, 1991).

Murdock (1987) has argued that Ebbinghaus’ construct of pairwise (and remote) associations was the first interference theory of serial order effects. Specifically, interference theories explain forgetting by asserting that both proactive

interference and retroactive interference function to disrupt or weaken the associative bonds that link together items in memory. An alternative set of theories explain forgetting with a decay mechanism. Conrad (1965) proposed a fixed address model in which information is stored in separate slots or bins. Conrad's theory states that items are stored in distinct bins and encoded with respect only to their individual properties (and not their associations to other items or positions). The order of items is fixed at presentation and would be retrieved in their original order at recall if all information were still available. To account for retrieval errors, Conrad proposed a decay process during which the contents of the individual bins blur, resulting in a partial loss of acoustic information. According to his theory, the decay of attributes did not result in the exchange of positions. Therefore, Conrad reasoned that subjects guess from a set of items (i.e. the response availability store) that share acoustic characteristics similar to the original item. Consequent retrieval errors would then be due to acoustic confusions and account for **both** transpositional (order) errors and content (item) errors.

Conrad framed the general issue of whether memory for order is distinct from memory for content within the context of information loss. Specifically, the question of interest was whether the forgetting of order information and the forgetting of content information were linked. He concluded that the same mechanism, acoustic confusions, produced both types of errors. Murdock and von Saal (1967) also affirmed the interdependence of item and order information in short-term memory. They discovered that while sets of three words belonging to the same category were more likely to be recalled than sets composed of words from different categories, same category words were also more likely to be recalled in the wrong order. This category effect suggested a dissociation between item and order information. However, Murdock and Von Saal concluded that loss of order information was both primary to and increased the

likelihood of the loss of item information because order and item errors both increased as a function of retention interval.

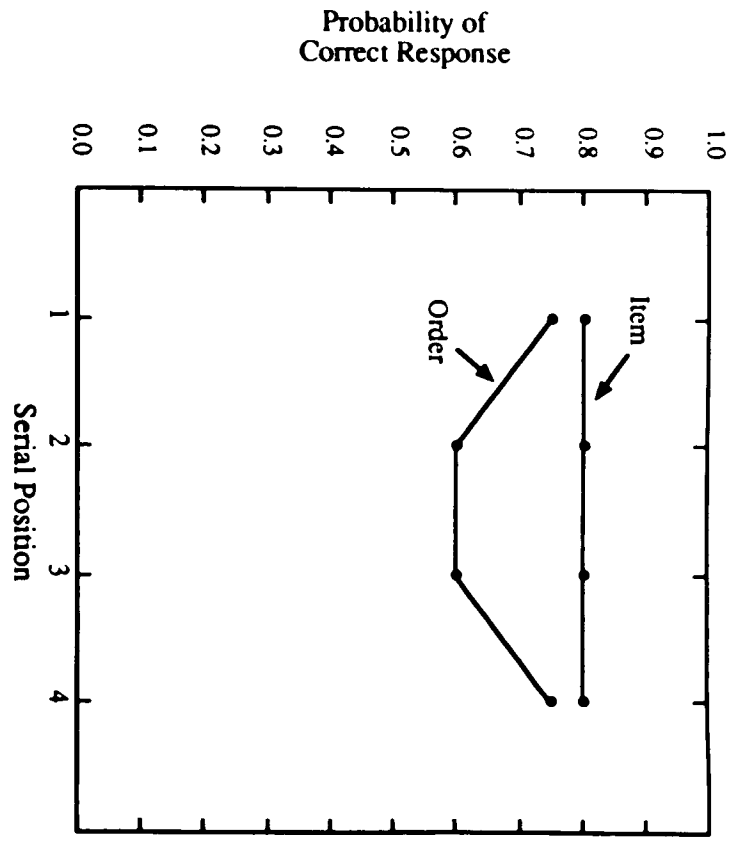
In contrast, another line of research involving the comparison of serial position curves for item and order information suggested not only a distinction between the two, but that content and order errors result from fundamentally different processes. A series of experiments reported bowed serial position curves for order errors and flat curves for item errors (Aaronson, 1968; Fuchs, 1969). The most influential of early studies demonstrating the distinction between item and order information are those of Healy and colleagues (Bjork & Healy, 1974; Healy, 1974). Bjork and Healy used a distractor task in which the subject was presented with a sample of four consonants (drawn from a set of 12), after which a sequence of digits was read aloud. Recall depended upon both memory for item and order information. Retention for these two types of information was measured by using two different scoring procedures, namely an order-based and an order-free method. Order-based scoring required the subject to report an item in its correct position for a correct response, while order-free scoring only required the subject to report the items from the test list without regard to their original order of presentation. Bjork and Healy reported that when using order-based scoring, serial position errors showed a bow shaped function which was absent when order-free scoring was used.

Healy (1974) extended these findings by experimentally separating item and order information. Healy used the same paradigm as Bjork and Healy (1974) with one exception. In her first experiment, subjects had only to remember order information, while in the second experiment only item information had to be remembered. This was implemented by presenting subjects in the first experiment (order-only) with the same

four letters on every trial, varying only their presentation order, and in the second experiment (item-only) by limiting the letters that could appear in any given serial position to a set of three. The results supported those previously reported (Aaronson, 1968; Fuchs, 1969; Bjork & Healy, 1974), demonstrating a bow shape serial position function in the order-only experiment and distinctly non-bowed functions in the item-only experiment.

Consistent with previous work, Hitch (1974) reported differential serial position curves for item and order information using partial report procedures. Subjects were presented with a list of eight (sampled from a set of 12) letters and were probed to report an item from a given serial position in one of three ways. The first probe condition indicated the spatial position of the target item, the second indicated the sequential position of the target item, and the third combined both spatial and sequential cues. Hitch found bowed but asymmetrical serial positions functions for order errors and flat functions for item errors. Differential serial position curves for item and order information have consistently been reported under a variety of similar experimental conditions. The curve for order information is clearly bowed in shape, indicating relatively better retention for the two end items. Figure 1 displays hypothetical curves characteristic of those commonly obtained by Healy (Bjork & Healy, 1974; Healy, 1974; Cunningham et al., 1984; Healy, 1987). Furthermore, the middle items show approximately equal retention, giving the curve its symmetrical shape. Note, however, that this symmetry is not observed in all paradigms designed to assess memory for

Figure 1. Hypothetical serial position curves for the recall of item and order information, typical of those reported by Healy (1974; Bjork & Healy, 1974).



order information (see Hitch, 1974 and Lewandowsky & Murdock, 1989). Also note that the serial position curve for item information is flat. The shape of this curve has been replicated by a variety of paradigms, with one significant exception.

An important series of papers by Buschke (1963a, 1963b, 1967) introduced an innovative technique for assessing memory called the “missing scan” procedure. This procedure relies on the subject’s knowledge of class membership of a set of items to assess memory for content. The missing scan procedure involves presenting all but one item of a defined set to the subject and requires the subject to name the item not presented. To perform this task, the subject need only remember the content of what was presented and not the order of presentation. For example, assume the class of items being used is the set of numbers ranging from 1 to 10. On a given trial the subject is presented with the numbers 1-4-8-10-3-6-7-5-9 and is asked to report which number was **not** presented (i.e. 2). An error occurs when the subject reports one of the items presented on the current trial. Therefore, an item is forgotten when it is incorrectly reported as the item that was not presented. In the above example, if the subject were to report ‘8’ as the missing number, the item occupying the third position in the list is considered to have been forgotten.

Buschke examined the relative probability of forgetting an item as function of serial position. He found distinct primacy and recency effects. Buschke’s missing scan experiments have been the only experiments to produce a serial position curve for item information that is not flat. It is unclear why these findings and the missing scan method have not made any impact on the study of serial position curves of item and order information.

The empirical phenomenon of differential serial position curves for item and order information has been taken as strong evidence supporting the proposition that the retention processes for these two types of information are fundamentally different. The models of particular relevance to this interpretation offer theoretical explanations of serial order effects in general, and the serial position curve in particular. There are two major theoretical frameworks regarding the mechanisms underlying serial order effects. The **serial chaining** hypothesis claims that each item in a list is associated to the next, so recall of one item serves as a cue for recall of the next. The competing **serial position** hypothesis proposes that each item is linked to a position in the list, rather than to another item. There has been a long standing controversy whether information entering sequentially into short-term memory is encoded by item-to-item or item-to-position associations. It is possible, and perhaps advantageous for order information to be represented by both associative and positional codes.

One of the more influential theories of serial order memory has come from the work of Estes, called the “perturbation model,” and is based on the encoding and perturbation of position information (Estes, 1972; Lee & Estes, 1977; Lee & Estes, 1981, Cunningham, Healy & Williams, 1984; Healy, Fendrich, Cunningham & Till, 1987). According to this theory, information about the order of items is conveyed not by the order in which they were presented, but by the “current state of encoded information concerning the attributes having to do with relative position among the events of a trial” (Lee & Estes, 1981, p. 164). Upon presentation of an item, information about its context that is specific to the trial in which it occurred as well as its relative position within that trial, are encoded. During the interval between encoding and retrieval, the representations of this context information are reactivated in an automatic rehearsal-like process, where this information is recoded. Each reactivation

updates the contextual information, introducing random error into the recoding of the memory representations. These errors can occur either with respect to the relative position of items on a given trial (i.e. order errors), or with respect to the trial on which an item occurred (i.e. item errors). Thus, this model handles the retention of item and order information jointly, without requiring distinct mechanisms to represent these types of information.

Although the critical type of information in the perturbation model is clearly positional, later formulations of the model assumed that memory representations are organized in a hierarchical manner (Lee & Estes, 1981). This hierarchy represents ascending levels of abstraction, ranging from the internal structure of the stimulus (i.e. order information) to the context in which the stimulus and its components are set (i.e. item or content information). While the number of operative levels of this hierarchy depends on the experimental details, an example will help to make the nature of this hierarchy more concrete. The paradigm most often used to study this model involves the presentation of eight letters, divided into two four-letter segments, over multiple trials. Three levels are required to explain performance on this task. At the lowest level of processing, information regarding the position of individual items within a segment of the list is represented. At the next higher level, codes are stored that signify in which segment a particular item occurred. The highest level of encoding contains information that indicates the trial of a particular item. How this theory accounts for the serial position curve is described in detail below in the section on modelling. Briefly, the model assumes that information linking an item to a serial position can perturb with equal probability in either direction. End items, however, can be recoded to occupy erroneous positions in only one direction and therefore have a lower probability of being recalled in an incorrect serial position. The model's formal implementation of this

feature yields bowed serial position curves that approximate those observed in empirical data.

Shiffrin and Cook (1978) proposed an alternative model based on associative coding of order information. A major reason Shiffrin and Cook (1978) developed a model that relied on associative bonding to represent order information was to account for experimental findings that demonstrated increasing numbers of transposition errors when spacing between list items is increased. They argued that if items are related to temporal input positions (as assumed by the perturbation model), increased interitem (temporal) spacing would result in temporal distinctiveness between items and produce decreased transpositional errors. Conversely if items are stored via associative links between each other, increased interitem spacing would weaken the associative bonds between items and result in a greater number of transpositional error (Shiffrin & Cook, 1978). In a series of experiments, Shiffrin and Cook varied interitem spacing and observed greater numbers of transposition errors in the condition where items were spaced than in conditions where they were presented close together (massed). They concluded that the greater number of transpositions produced by spacing eliminates the class of models in which order information is associated with positional codes and that the strength of these associations diffuse over time. However, their procedure confounds inter-item temporal spacing and delay to recall.

Shiffrin and Cook's relational model relied on the concept of chaining as originally introduced by Ebbinghaus, with two significant differences. First, Shiffrin and Cook (1978) provided different mechanisms to represent order and item information. Associative or relational bonds that link successive items to each other at the time of input account for all of the information that relates to serial order. These

relational bonds are connected to 'nodes,' where each node contains item information. According to their account, order and item information enjoy distinct representations in memory and are retained or lost from memory independently. The second major difference between original notions of chaining and those of Shiffrin and Cook, has to do with how end items are encoded. In their model, boundary nodes precede and follow the first and last item of a list, respectively. Shiffrin and Cook (1978) admit that these end nodes are included to ensure that the serial position curves show a bowing in the proper direction. This is accomplished by the arbitrary assumption of stronger associations between boundary nodes and end items than exists between adjacent list items. Their account is somewhat less than compelling, since their model required the *ad hoc* introduction of boundary nodes to explain a phenomenon as fundamental as the serial position curve. Shiffrin and Cook themselves admit that the necessary use of boundary nodes introduces a purely **positional** element to their otherwise purely associative model. Their justification for developing a model that relies on two types of encoding mechanisms (relational and positional) to represent serial order, and still another to accommodate item information, is not clear.

Shiffrin and Cook's (1978) model is not the only 'hybrid' theory that relies on both associative and positional information to explain serial order effects. One recently proposed model (Johnson, 1991) makes the assumption that the effective stimulus for a serial list item is the encoding of that item's ordinal position. However, Johnson's model considers learning to be the formation and strengthening of associative bonds between positional codes and serial list items (Johnson, 1991). This use of the terms 'associative' and 'positional' is confusing and can serve to blur the critical distinction between these two types of codes. This distinction rests on which type of information is most critical to the representation of serial order. Specifically, does memory for serial

order depend on associative information that links successive items together, or does it depend upon information linking serial list items to their ordinal positions? There is no reason to believe that memory for serial order depends on only one type of information. That is, it is possible, in principle, for both associative and positional information to play a role in memory for serial order.

Given this possibility, the next step is to examine which type of information is most critical to the representation of serial order. Recent studies have reported that recognition of transpositions of non-adjacent items is superior to that for adjacent items (Angiolillo-Bent & Rips, 1982; Jahnke, Davis, & Bower, 1989; Proctor & Healy, 1985, 1987). Jahnke et al. (1989) have argued that classical associative models which posit direct item-to-item chaining are constrained to predict better recognition of adjacent as opposed to non-adjacent transposed items. That is, if associative chaining plays a critical role in the representation of order information, transposition of adjacent items should be more readily identified than transpositions of non-adjacent items. If associative bonds are indeed stronger between adjacent items than between non-adjacent items, then transpositions of adjacent items should provide more information indicating disrupted order and be more easily recognized than transpositions of non-adjacent items. These investigators also demonstrated substantial correlations between the loss of positional information (indexed by overlap of positional uncertainty gradients) and loss of order information (indexed by transposition errors). On the basis of these data, they argue that memory for order is primarily, if not exclusively, dependent on positional information.

If serial order information were represented primarily by either item-to-item associations (i.e. associative) or item-to-position associations (i.e. positional), one

might expect an accuracy differences between probes that provided either associative or positional information. That is, if a probe is used that provides information in a form not used in the representation of the serial order of items, then it is likely that the subject must perform some transformation or computation on that information for it to be an effective cue. Specifically, cues providing positional information should be more effective than cues providing associative information. Murdock (1976) investigated the relative efficacy of retrieval probes that were associative (e. g., What was the Item that followed Item  $i$  ?), and positional (e.g., What was the Item in serial position  $i$  ?). Although there were differences between serial recall and probed recall, he reported minimal recall differences between the different type of probes. One explanation why no probe effects were observed is that subjects could transform the information provided by either type of probe into usable information. This seems plausible, since both positional and associative probes can elicit recall of serial order information (Murdock, 1976, Waugh & Norman, 1965). However, one would expect that if the task demands were great enough, recall differences between the types of probes would then emerge.

The issue of whether one type of information, either associative or positional, is basic to serial order memory, can usefully be approached from the working memory framework. Craik (1984) has made the distinction between 'primary memory' tasks and 'working memory' tasks. Examples of primary memory tasks include forward digit span and the Brown-Peterson paradigm, while working memory tasks include backward digit span and various dual task paradigms. Most memory tasks require a subject to exert varying degrees of active processing on the part of the subject to encode, store and retrieve information; very few memory tasks (e.g., implicit memory, priming) require little or no activity from the subject. Those tasks which seem to require

extensive operations on materials (e.g. reversal) are thought to tap working memory. Those that require minimal operations (e.g. maintenance rehearsal) are referred to as primary memory tasks. Therefore, this distinction between primary and working memory tasks is largely one of degree and not of kind.

If the proposition made by Jahnke et al. (1989) that serial order is represented primarily through positional codes is correct, then cues providing this information would be more directly usable than cues which provide associative information. Performance differences between associative and positional probes could then be more readily observed in either of two circumstances. First, task demands could be increased such that the subjects' ability to perform such a transformation is diminished which would result in superior recall following positional compared to associative probes. And second, a comparison of young and aged subject groups could reveal a differential effect of probe type since the latter group are thought to have diminished processing resources. Much research done in the area of working memory has suggested the presence of reduced processing capacity in aged subjects relative to young comparison groups. Comparing performance of aged and young subjects could therefore serve as a useful means of addressing the issue of probe effects.

Though the presence of age related differences on working memory tasks is commonly observed (Wright, 1981; Baddeley, Logie, Bressi, Della Sala & Spinnler, 1986; Becker, 1988; Gick, Craik & Morris, 1988; Morris, Gick, & Craik, 1988; Salthouse, Mitchell, Skovronek & Babcock, 1989; Salthouse, 1991), there is not complete agreement regarding the underlying deficit. It has not been established whether observed age related performance differences are due to a diminished general pool of processing resources, deficits in task-specific processing or reduced storage

capacity. Procedures developed for the study of serial memory could be usefully applied to address this issue. Specifically, by equating performance for aged and young subjects on item recall, which would control for differences in storage capacity, memory for serial order could be examined without the problem of confounding differences in processing and storage.

The present experiments addressed three issues important to the study of serial order and working memory, namely, the distinction between memory for order and item information, the relative importance of associative compared with positional information to serial order memory, and age related differences in these phenomena. Experiment 1 examined the reputed distinction between item and order information using partial report techniques. An alternative method (Buschke's missing scan, 1963a) for assessing memory for content and order is presented that is not subject the shortcomings of previous methods and offers the benefit of allowing a direct comparison of serial position curves for item and order memory. A second issue addressed in Experiment 1 regards how memory for order is represented. Specifically, the relative importance of associative and positional information for memory for order was analyzed.

Experiment 2 replicated much of the first experiment, but the unit of analysis was the performance of individual subjects instead of group means. Since memory theories ultimately seek to explain and predict memory functioning for individuals, and not for the aggregated performance of a group, how adequately the general findings from Experiment 1 describe the pattern of performance observed in individuals will be evaluated.

In Experiment 3, age related differences in serial order memory were explored from the perspective of working memory theories. With few exceptions (e.g. Foos, 1989; Light, Zelinski, & Moore, 1982; Wright, 1981), previous research on age-differences in working memory has failed to separate deficits in processing from deficits in storage (Parkinson, Lindholm, & Inman, 1982; Salthouse et al., 1989). The present study focuses on age related processing deficits by equating differences in storage capacity across individuals. The effects of different types of probes (associative vs. positional) and their interaction with task difficulty were examined in the context of theories that claim age associated working memory differences are due to a depletion in a general pool of processing resources. Age related dissociations in memory for item and order information were used to compare the processing demands required for representing and retrieving information of these two types.

Finally, a quantitative model of serial order memory (the Perturbation Model) was applied to both the aggregated data from Experiment 1 and to the data of individuals from Experiment 2. A comparison of the fit of the model to the aggregated and individual data was evaluated and implications for framing and testing formal theories of memory are discussed.

## General Method

**Apparatus.** Stimuli were presented on a computer LCD monitor in front of seated subjects. A Zenith portable computer was used to display the stimuli and to record subject responses.

**Procedure.** The subjects were first given instructions about the general nature of the task. Stimuli (digits ranging from 0-9) were presented sequentially (one at a time) at the center of the monitor, with each digit remaining on the screen for 750 ms and a 500 ms inter-item interval. A trial consisted of presentation of the digit list, after which the subject was engaged by a distractor task for 3 s. The distractor task required the subjects to either (1) say aloud the letters presented on the screen (easy) or (2) say the letter that immediately follows the one presented in the alphabet (difficult). After this distractor task, the subjects were probed to recall a single item.

Retrieval was probed by either an associative, positional or item probe. The associative probe presented the subject with a number followed by a dash (e.g. 4\_\_), requiring the subject to report the digit that immediately followed '4' in the list. The position probe specified a serial position (e.g.  $\overline{6}$ ) and required the subject to name the item that occupied that position in the list. Item probes used the missing scan procedure. Subjects were informed that the number of different digits they could see on any given trial would be equal to one less than the size of the list. So if a subject is being presented with a list of 7 digits for each trial, the possible digits that could be presented on any given trial will range from 0-7 (for a total of 8 different possible digits). Item probes consisted of "MISSING ?" and subjects were required to key in the digit that was not presented on that trial. A sample trial is "2-3-7-0-4-6-1" 'MISSING ?' with "5" being the correct response. Subjects responded by typing their

response on a computer keyboard. Subjects did not know ahead of time which probe would be presented on a given trial.

**Analysis.** The dependent variable for the analysis of recall accuracy was the proportion of digits correctly recalled under the experimental conditions. These accuracy data were subjected to repeated measures analysis of variance (ANOVA), with tests of statistical significance set at the .05 level. Follow-up analyses were conducted using single-degree of freedom contrasts (Rosenthal & Rubin, 1984; O'Brien & Kaiser, 1985; Rosenthal & Rosnow, 1985; Stevens, 1986). For tests of significance on repeated measures effects involving more than 1 degree of freedom, probability values were adjusted using the Huyn-Feldt epsilon correction.

Error data, as opposed to accuracy data, were used for the analysis of the serial position curves, since the item probe only specifies errors, and not correct responses, for serial positions. The number of serial positions for each curve is one less than the list size for position and item probes, because one digit is always omitted from a given trial. Only serial positions 2-6 for 7 digit lists and 2-7 for 8 digit lists are analyzed for the sequential probes, since the first position could never be probed, as there is no item that precedes it. To provide a quantitative description of the serial position curves as well as to assess the effect of distractor difficulty exerted on the shape of these curves, trend analyses (Bray & Maxwell, 1986; Stevens, 1986) were performed on the error data for each probe type. Effects of serial position were decomposed into orthogonal polynomials to assess the unique contributions of the linear and quadratic trend components to the overall serial position effect (Cohen & Cohen, 1983; Rosenthal & Rosnow, 1986; Stevens, 1986; Wilkinson, 1991). A significant quadratic trend would indicated relatively poorer recall for middle position items relative to terminal positions.

A significant linear trend would indicate either a relatively greater primacy or recency effect, depending on the direction of its slope.

## Experiment 1

The first experiment addressed two theoretical issues pertaining to serial order memory. First, it is predicted that, consistent with previous findings (e.g. Jahnke et. al. 1989; Lee & Estes, 1977), positional information is more important to the representation of serial order than is associative information. Recall following associative cues should show a greater deterioration from increasing the difficulty of an intervening distractor task than will positional probes.

The second issue examined is whether differential serial position curves are obtained for probed recall of item and order information. Most research has demonstrated differential serial position curves for item and order information (e.g., Healy, 1974; Hitch, 1974). However, the prediction was made that similar serial position curves for item and order information would be observed. Two reasons lead to this prediction. First, previous work (Buschke, 1963a; Hadley, Healy & Murdock, 1992) has demonstrated serial position effects for item information using the missing scan task and the present experiments are expected to confirm this finding. Second, an analysis of the methods that have been used to separate memory for order from item information reveals methodological limitations of many previously reported findings.

For paradigms where item and order errors have been separated by scoring method (e.g., Bjork & Healy 1974; Hitch, 1974; Lee & Estes, 1981), an item error occurs when two distinct conditions are met; namely, that an order error is made and that the erroneous response indicates an item not part of the to be remembered list. For example, take the string of digits 2-1-5-6-7 as a list of items that must be recalled in

their original order. If a subject were to report the string 2-5-1-6-7, the recall error would be that of order, since all the items reported were on the original list. However, if the subject were to report the string 2-1-5-6-1, both order and item errors would have occurred. One problem with this method of fractionating item and order information is that attempting to recall an early portion of a list in its proper order may interfere with retrieval of subsequent items. Such output effects have been well documented in this and in other areas of cognition (Sperling, 1960; Buschke, 1963a, 1968; Hitch, 1974, Shiffrin & Cook, 1978). Of course, experiments employing effective partial report procedures can to some extent circumvent this problem (e.g., Hitch, 1974). A second problem with this method of studying item and order information is concerned with the prior probability of item and order errors. Most of the tasks described above limit the number of different items which subjects can encounter during the experiment. For example, Hitch (1974) used an eight item list sampled from a set of 12 items, Bjork and Healy (1974) sampled four items from a set of 12, and Lee and Estes (1981) sampled four items from a set of eight. Although the probability of reporting by chance an item correct in position is relatively low in all cases, the probability of reporting an item that was presented on a given trial is astoundingly high, ranging from .25 to .67 for the three examples above. These probabilities are even higher if the plausible assumption is made that on a given trial a subject can use a previous response to limit the pool from which he will make a subsequent guess.

A hypothetical experiment clearly illustrates the severity of this problem.

Assume a subject is presented a list of seven numbers sampled without replacement from the set of single digit whole numbers ranging from 0-9. Take this list to be the following numbers: 2-3-7-0-5-9-1. At testing, the subject only remembers the first two and the last item of the list, and must guess the remaining four items. Since three items

are eliminated from the guessing pool, the subject must guess four unique items from the remaining seven. Since the expected number of successes is equal to  $n \cdot p$  where  $n$  is number of responses and  $p$  is probability of success for each response, the subject would be expected to guess correctly 2.3 of the remaining four items ( $n=4$ ,  $p=4/7$ ). Assuming that none of the guessed items were recalled in their original serial position, the subject's correct in position (order information) score on this trial is .43 (3/7) and correct in any position (item information) is .71 (5/7). However, since approximately two items were correct by chance, 40% (2/5) of the subject's item score is attributable to chance (i.e. measurement error). This is, of course, an oversimplification since in this example we knew exactly how many items the subject guessed. In actuality, the number of items guessed varies across subjects and within subjects across trials and cannot be directly measured.

The two experiments reported by Healy (1974) are not subject to some of these criticisms, since item and order information were separated procedurally for the measurement of retention. However, in the item-only experiment, each of the four serial positions could be occupied by any one of three different items. Healy offered guessing-corrected scores for data from this and from an earlier study (Bjork & Healy, 1974). In fact, many studies offer some sort of guessing-corrected score in an effort to take into account chance or error variability in their measures. However, corrections for guessing are not always applied to all aspects of the data.

None of the early influential studies reporting flat serial position curves for item information (Bjork & Healy, 1974; Healy, 1974; Shiffrin & Cook, 1978) correct serial position data for guessing. Corrections are applied only to the overall proportion correctly recalled for a given experimental condition and the uncorrected position scores

are used to obtain serial position curves. Even if guessing corrections were effective, this is not reflected in serial position data. Since guessing rates are almost always higher for item recall than order recall, serial position curves for recall of item information will be less reliable (i.e. contaminated by more chance variability) than will curves for order information. This raises serious doubts regarding conclusions drawn from the comparison of serial position curves for item and order information. That is, these curves could differ because of the operation of different cognitive processes or because of the exaggerated chance variability in item curves relative to those obtained for ordered recall.

The present experiment used recall probes to measure memory for order item information. The first type of probe was an associative probe that cued the subject to report the item that immediately followed the probe in the list. The second type of probe was positional and required the subject to report the item associated with a given serial position. The third type of probe assessed memory for item information by using a modified version of the missing scan (Buschke, 1963a, 1963b, 1968). This probe is based on a procedure in which subjects are presented with a sample of a known list of items and are required to report which item from the known list was not presented on a particular trial. To accomplish this task, the subject must retain all the items presented on the trial, but need not remember their serial order.

By using probe techniques that require a single response, output effects are reduced and direct comparisons can be made between probes for order and probes for item information. That is, the serial position curves for item and order information are more directly comparable, since maintenance for both types of information are assessed using a partial report probe technique. The most significant advantage of this procedure

is that chance or error variability is comparable among the measures of item and order memory.

The argument was made above that the probability of correctly recalling an item in any position has (in previous experiments) always been very high. Consequently, a large fraction of the a subject's item memory score could be due to guessing or chance. The conclusion was reached that measures of item memory contain more error and are not as reliable as measures of order memory. The procedure described here eliminates this problem since correct recall for either order or item memory requires a specific response, so the probability of correctly recalling an item by chance will not vary as a function of probe type. The present experiment used probe methods that require a single response and specified a single serial position at which a retrieval error occurred for both order and item information. Thus, the above criticism do not apply to the methods used to measure memory for item and order information.

A final purpose of this experiment is to produce data to which a version of Estes' perturbation could be fit (Lee & Estes, 1981).

## **Method**

**Subjects.** Twenty-four young adults (ages 18-26) participated in Experiment 1. There was a single experimental session, lasting about 1.5 hours. Subjects were volunteers recruited from undergraduate students attending classes at Queens College, and employees from Albert Einstein College of Medicine and Mount Sinai Medical Center. An abbreviated version of the WAISR was used to provide a measure of verbal intelligence (Silverstein, 1982). The average age of the subjects was 22 (sd=3) and their average WAISR verbal IQ was 114 (sd=8).

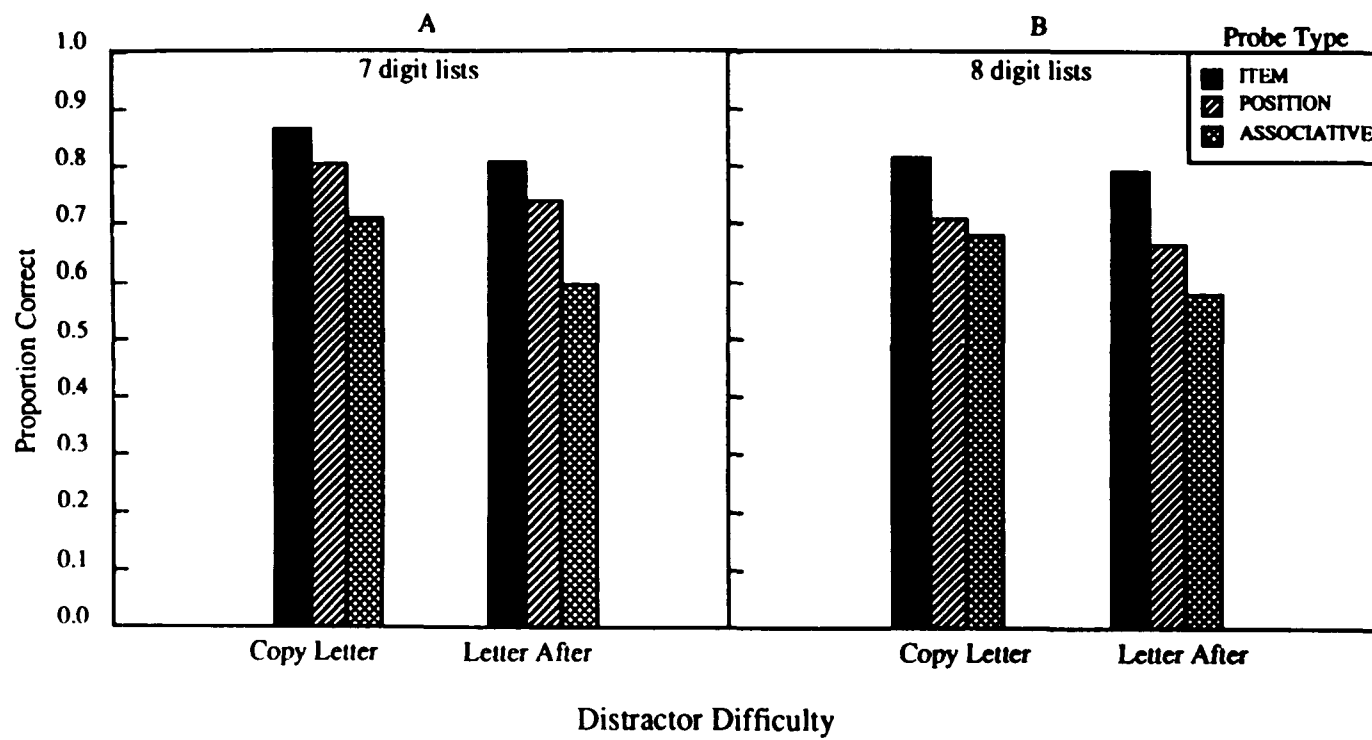
**Procedure.** Subjects were tested on lists of 7 and 8 digits. Each subject was given 6 practice trials in each distractor condition. There were 2 blocks of 24 trials each for each list length, with a single distractor task condition occurring throughout an entire block. Within each block, the 3 different probes were randomly presented to the subject with the constraint that all probes are presented the same number of times. Subjects were given a brief rest between blocks.

**Design and analysis.** For Experiment 1 the design was a 2 (list size 8/ list size 7) x 2 (easy / difficult distractor) x 3 (associative / position / item probe) factorial design, with all factors varied within subjects. The first factor, list size, indicates that subjects was tested on an 8 digit or 7 seven digit list. The second factor, distractor type, refers to whether the task intervening between list presentation and probed recall required the subject to copy a letters (easy) or to specify the letter following the presented letter in the alphabet (difficult). The third factor, probe type, refers to whether the subject's recall was cued with an associative or position probe, in the case where memory for order was to be measured, or a missing scan probe, in the case where memory for item information was to be measured. List size and distractor type were varied across blocks of trials, while probe type varied randomly within blocks. The data were subjected to a 2 x 2 x 3 (list size x distractor type x probe type) repeated measures ANOVA.

## **Results**

**Recall accuracy.** The effects of list size, distractor difficulty and probe type on recall accuracy are reported first, and then the serial position data are analyzed. Figure 2 displays the proportion of digits correctly recalled in each experimental condition. Comparing panels A and B of Figure 2 indicates that the overall level of recall was

Figure 2. Proportion of digits correctly recalled as a function of probe type and distractor difficulty for 7 and 8 digit lists. Data from Experiment 1.



somewhat higher for 7 digit lists than for 8 digit lists. The mean proportion correct for 7 and 8 digit lists was .75 and .70, respectively. A 2x2x3 ANOVA was performed to determine the statistical reliability of these results. This difference was statistically reliable as confirmed by a significant main effect of list size ( $F[1,23]=15.8, p<.01$ ). Recall accuracy was also affected by distractor difficulty, with lower accuracy following the 'letter after' distractor compared with recall following the 'copy letter' condition (.70 vs. .77, respectively). This difference indicated that requiring subjects to report the letter following a target letter in the alphabet was a more effective distractor than was requiring the subjects simply to copy a target letter. A significant main effect of distractor difficulty confirmed this interpretation ( $F[1,23]=26.9, p<.01$ ). The most striking feature of Figure 2 is how recall varied as a function of probe type. As expected, retrieval accuracy was higher for item probes than for either the associative or position probes, regardless of list size and distractor difficulty. Retrieval was also better following position probes compared with associative probes for both list sizes and distractor difficulties. These results were confirmed by a significant overall effect of probe type ( $F[2,46] = 40.7, p < .01$ ), with follow-up contrasts that indicated higher recall following item probes than position probes (.82 vs. .73,  $F[1,23] = 22.1, p < .01$ ), and superior recall following position probes compared with recall following associative probes (.73 vs. .64,  $F[1,23] = 17.5, p < .01$ ).

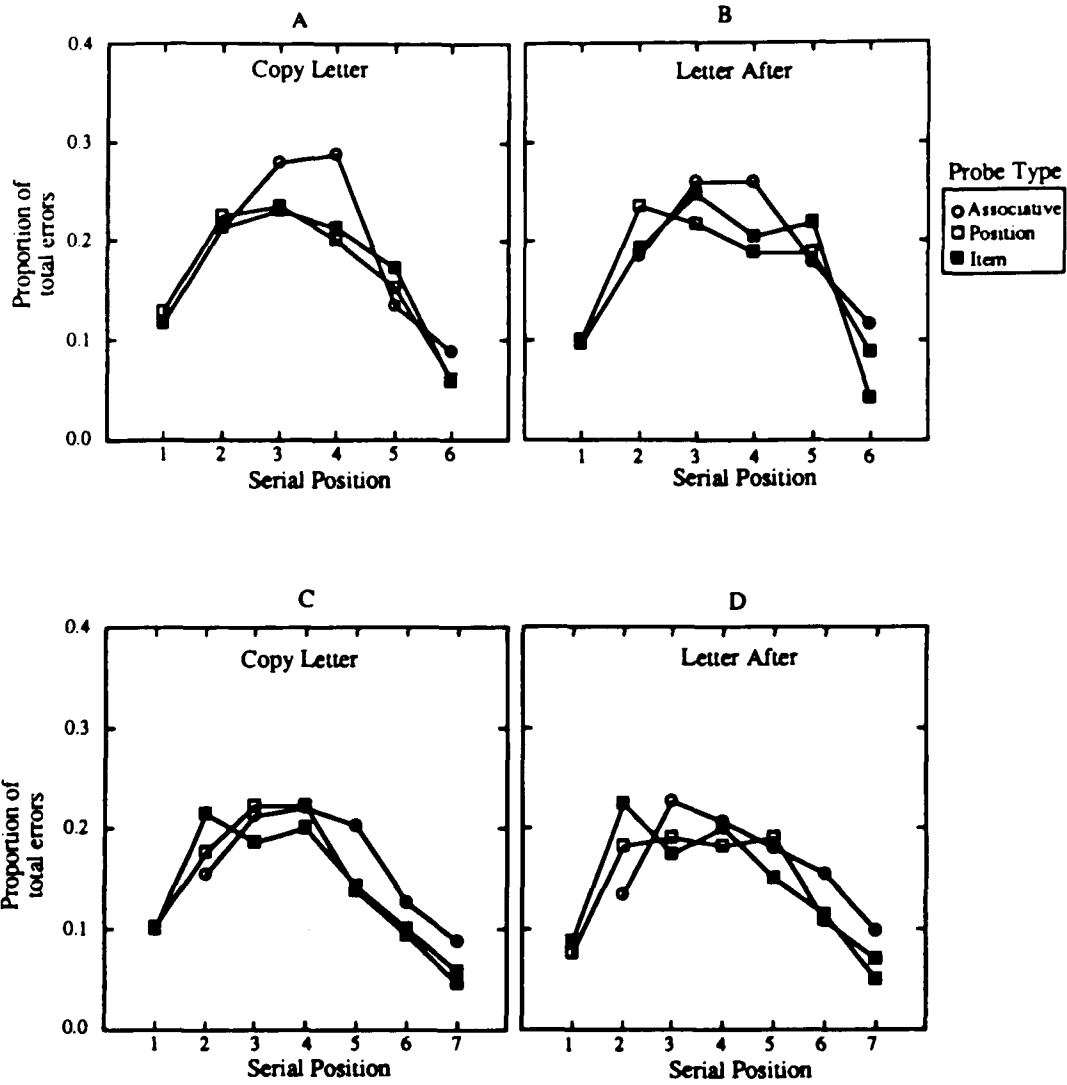
Next the hypothesis that recall following associative cues would show a greater deterioration in the difficult distractor condition than recall following position probes was evaluated. This hypothesis, which predicts a significant probe x distractor interaction, was not statistically significant ( $F[2,46] = 2.9, p=.07$ ). Although the probe x distractor interaction failed to attain statistical significance, a priori contrasts were performed on this interaction. The decline in recall in the difficult (letter after) distractor

condition, relative to the easy (copy letter) distractor condition, following sequential probes (.59 vs. .70) was more than twice the observed decline in recall following position probes (.71 vs. .76), but this contrast also failed to attain statistical significance ( $F[1,23] = 3.8, p = .06$ ). Thus, the hypothesis that recall following relational cues would show a greater deterioration in the difficult distractor condition than would position probes did not receive strong support. A second contrast tested whether recall following the item probe would be less affected by the difficult distractor condition than recall following the order probes. This contrast was also not significant ( $F[1,23] < 1, p = ns$ ), indicating that difficulty of the distractor task does not differentially affect the maintenance and retrieval of item and order information.

When the difference in recall between position and associative probes is compared across list sizes (panel A vs. panel B in Figure 2), the difference appears to be smaller for the longer list size. In fact, the position–associative probe recall difference was twice as large for the smaller list (.12) than for the longer list (.06). The mean proportion of digits correctly recalled for 7 digit lists was .77 for position probes and .65 for associative probes, respectively. However, the difference between position and associative probe recall decreased for 8 item lists, with the mean proportion of digits correctly recalled of .69 and .63 for position and associative probes, respectively. The overall interaction of probe type x list size did not reach statistical significance ( $F[2,46]=3.1, p=.06$ ), but a follow up contrast that specifically compares the position–associative probe recall difference across list sizes provides support for this result ( $F[1,23]=4.2, p=.05$ ).

Associative probed serial position data. Next the serial position (error) data were analyzed. Figure 3 displays the proportional serial position curves for each probe

Figure 3. Serial position curves for recall following all three probe types, for both distractor conditions and list lengths. The value for each serial position reflects the proportion of total errors made for that condition. Panels A and B present the data from 7 digit lists for the 'copy letter' and 'letter after' distractors, respectively. Panels C and D present the same data for 8 item lists. Data from Experiment 1.



type under the easy and difficult distractor conditions for 7 and 8 item stimulus lists. For 7 item lists (panels A and B of Figure 3), the serial position curve for associative probes were characterized by a strong recency effect, and a relatively weaker primacy effect. More pronounced recency compared with primacy were expected for the associative probes since the first serial position was not sampled. These descriptions were supported by trend analyses which demonstrated strong linear and quadratic trends, accounting for 46% and 44% of the between position variability, respectively ( $F_{(linear)}[1,23]=18.1$ ,  $p<.01$ ;  $F_{(quad)}[1,23]=13.3$ ,  $p<.01$ ). By comparing panels A and B, it is apparent that the general shape of this curve did not vary as a function of distractor difficulty. Specifically, neither the linear nor quadratic trends interacted with distractor difficulty ( $F(1,23)< 1$ , ns for both). The same pattern of results were obtained for 8 item lists (panel C and D): a strong serial position effect characterized by a larger recency than primacy component which was constant across distractor difficulty. These interpretations were supported by significant linear and quadratic trends, accounting for 37% and 55% of the variability across serial positions ( $F_{(linear)}[1,23]=10.8$ ,  $p<.01$ ;  $F_{(quad)}[1,23]=12.1$ ,  $p<.01$ ), and by nonsignificant distractor x trend interactions ( $F(1,23)< 1$ , ns for both linear and quadratic trends).

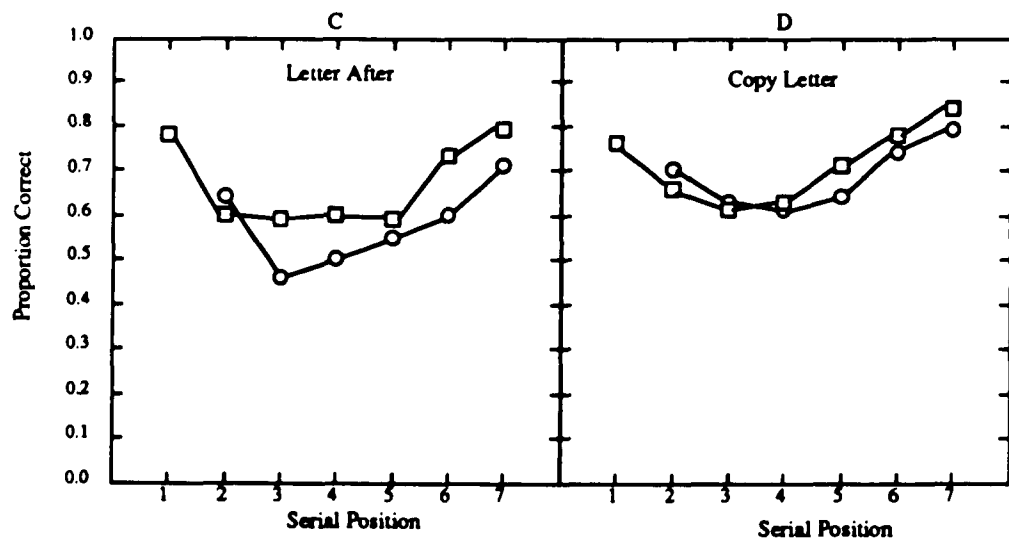
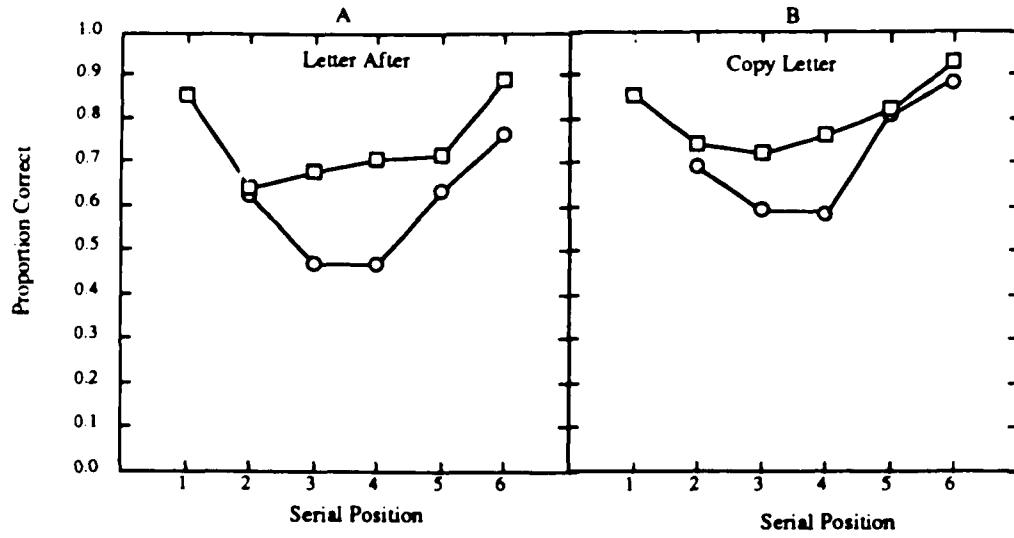
Positional probed serial position data. Similar results were found for retrieval following the position probes. For 7 digit lists (panel A and B of Figure 3), the serial position curve was characterized by strong primacy and recency components, for both distractor conditions. However, in contrast to the curves obtained for associative probes, the magnitudes of the primacy and recency effects were comparable in magnitude. Trend analysis confirmed a strong and significant quadratic component which accounts for 82% of the variability across positions and a non significant linear component which supports these interpretations ( $F_{(linear)}[1,23]< 1$ , ns;

$F_{\text{(quad)}}[1,23]=10.4, p<.01$ ). Comparing panels A and B, no difference in the shape of the curves was observed as a function of distractor difficulty ( $F(1,23)< 1, ns$ ). Position probe data from 8 digit lists showed a similar pattern of results. Recall showed substantial primacy and recency effects, as confirmed by a large and significant quadratic component which accounted for 75% of the variability across serial position ( $F_{\text{(quad)}}[1,23] =35.9, p<.01$ ). Examination of panels C and D of Figure 3 indicates some evidence of slightly more pronounced recency effect, especially for the ‘copy letter’ condition. This observation was supported by a small but statistically significant linear trend, which accounted for 14% of the variability between positions ( $F_{\text{(linear)}}[1,23] =8.3, p<.01$ ). And as observed for 7 digit lists, no difference in the shape of the curves was observed as a function of distractor difficulty ( $F(1,23)< 1, ns$ ).

These analyses indicate that there is somewhat less primacy for the associative as compared to the position probes. This results from not testing recall of the first item with the associative probe. Consequently, the overall higher recall following position probes could be attributed to the reduced magnitude of the primacy effect for the associative probes. Inspection of Figure 4 indicates that such is not the case: the largest accuracy differences occurred for middle items for both 7 and 8 digit lists. Comparison of panels A with B for 7 digit lists and C with D for 8 digit lists shows this to have been the case for both list sizes and levels of distractor difficulty.

Item probed serial position data. Data for retrieval following the item probe paralleled those for the order probes. Examination of Figure 3 (panels A and B) reveals a strong effect of serial position for the item probes on 7 digit lists. Specifically, recall was clearly superior for terminal as compared with middle position items. This observation was confirmed by large quadratic component, accounting for 97% of the

Figure 4. Proportion of digits correctly recalled as a function of serial position for position (squares) and associative (circles) probes. Panels A and B present the data from 7 digit lists for the 'letter after' and 'copy letter' distractors, respectively. Panels C and D present the same data for 8 digit lists. Data from Experiment 1.



variability between positions ( $F_{(quad)}[1,23]=22.8, p<.01$ ). No difference between the size of the primacy and recency components was observed ( $F_{(linear)}[1,23]<1, ns$ ). Distractor difficulty did not exert any detectable influence on the shape of the serial position curve, as the distractor  $\times$  trend<sub>(quad)</sub> interaction was not significant ( $F[1,23]<1, ns$ ). Data from the 8 digit lists provided similar results. Panels C and D of Figure 3 indicate relatively poorer recall for middle position items compared to items occupying terminal positions. The observed primacy and recency components were confirmed by a statistically significant quadratic trend that accounted for 58% of the between position variability ( $F_{(quad)}[1,23]=18.0, p<.01$ ). There was some evidence of a larger recency effect compared with primacy, especially in the 'copy letter' distractor condition. But this observation did not receive strong support from the trend analysis, which indicated that only 17% of the variability across positions is due to this effect ( $F_{(linear)}[1,23]=3.6, p=.07$ ). Finally, there was no evidence that the shape of the serial position curve was affected by distractor difficulty, as indicated by a failure to find a significant distractor  $\times$  trend<sub>(quad)</sub> interaction ( $F[1,23]<1, ns$ ).

Item vs. positional probed serial position data. Two additional trend analyses were performed to test directly whether the serial position curves for an order and item probe differed in shape. The curves obtained from position probes and item probes only were compared, since the serial position curves obtained from the associative probes had one less position (the 1st position was not tested) than the curves generated by the other probes. Only the shape (i.e. trend) and not level (i.e. overall performance) of the serial position curves were compared since the number of errors made at any given position for the position probe was fixed by the experimental design (i.e. each position was tested equally often across subjects), while the number of errors made at a given serial position for the item probe is not fixed. Also, the scoring method of

converting the number of errors at each position to the proportion of total errors removes any difference in level of accuracy. When comparing the shape of the serial position curve for item and position probes across both lists sizes and distractor type, no reliable or striking difference was observed. This observation was tested for both the 7 and 8 digit lists by examining the probe x serial position interaction for statistical significance. This interaction did not approach significance for either the 7 digit list ( $F[5,115] < 1$ , ns) or 8 digit list ( $F[6,138] < 1$ , ns). Since the above trend analyses indicated that both the position and item probe curves are described primarily by a quadratic component, focussed contrasts comparing this component for the two probes were performed. This contrast did not detect any difference in the quadratic component of the serial position curve for these two probe types ( $F[1,23]=1.5$ , ns;  $F[1,23] < 1$ , ns, for 7 and 8 digit lists, respectively). This analysis indicates that there were no detectable differences in the shape of the serial position curves for a test of order information (i.e. position probe) and a test of item information (i.e. the missing scan probe).

Summary of serial position data. To summarize, the major findings from the serial position data are: (1) Retrieval accuracy varied as a function of serial position for all probes, including the probe that assesses memory for item information; (2) The serial position curves were characterized by presence of both a primacy and recency component, as confirmed by trend analyses which revealed reliable and large quadratic trends. In several cases there was a slightly larger recency (as compared with a primacy) effect, as indicated by a significant linear component; (3) The shape of the serial position curves did not interact with the difficulty of the distractor task; (4) And finally, there was no detectable difference in the shape of the serial position curves obtained from the position probe and item probes, showing not only a serial position

effect for item information, but that it did not differ from that obtained from a measure of order information.

## Discussion

The data from Experiment 1 confirm the prediction that retrieval following positional probes would be higher than recall following associative probes. Both probes required retrieval of order information, but cued this retrieval by providing different types of information, i.e. associative or positional. Jahnke et al. (1989) have argued that the representation of order information in memory is a composite of attributes, and that the effectiveness of a cue is determined by the degree to which the cue and target stimulus share common attributes. That positional information provides a more effective cue for retrieval of order information than does associative information is consistent with the idea that memory for order depends largely on memory for position (Jahnke, et al., 1989; Lee & Estes, 1977, 1981). However, this finding must be interpreted cautiously and should not be taken as definitive evidence that order information is represented exclusively by position codes. Two findings justify this caution: First, recall following associative probes was respectable (64% overall accuracy), indicating that associative information could be used effectively to cue retrieval of order information. And second, the expected probe x distractor difficulty interaction was not evident, thus failing to support the prediction that the effectiveness of associative probes would be compromised to a greater extent than would positional probes when cognitive demands are increased. Although the distractor manipulation was effective as evidenced by poorer recall in the letter-after condition compared with the copy-letter condition, even greater cognitive demand might be required to produce the interaction effect. Bearing these *caveats* in mind, the finding that position

information is more important for the representation of serial order in memory than associative information, was still confirmed.

That the level of distractor difficulty did not differentially affect recall following position compared with associative probes requires further explanation. If recall following associative probes requires some active transformation of information into positional codes, then it should be disrupted by tasks that compete for processing resources. This would lead one to expect the differential decrement for associative probed recall when processing resources are occupied by another competing task. By varying the difficulty of a distractor task between a relatively passive operation (i.e. copying a letter) and one requiring a more active operation (i.e. specifying the letter that follows a target in the alphabet), recall performance was reduced. Although the difficult distractor condition produced a decrement in recall following both position and associative probes, this decrement did not differ for the two probes.

The failure to observe an associative-positional probe x distractor interaction could be due to any of several factors. The simplest explanation is that neither the recall task nor the distractor task were not difficult enough to produce an interaction. However, the significant effect of increasing distractor difficulty seems to eliminate the latter of these two possibilities. Another possible explanation for the failure to observe a probe x distractor interaction is that the distractor task does not compete for the same processing resources as do the recall probes. Gick et al. (1988) have provided evidence against the concept of a general pool of processing resources for which cognitive operations compete. The fact that the distractor task did not occur during recall could also explain the failure to observe a probe x distractor interaction. Even if subjects must transform associative cues into positional codes, if this activity occurs only after probe

presentation, then the difficulty of the distractor task would not be expected to interfere with this operation. This interpretation suggests that order information is represented with a single type of code (i.e. positional), and that these codes are transformed into associative information only if necessitated by the recall conditions.

A more interesting explanation for the lack of a probe x distractor interaction is that position information is not more basic to serial order memory than associative information, rather that the relative importance of both types of information depends on specific task characteristics. This interpretation is suggested by the unexpected finding that the positional–associative probe differences are smaller for list length of 8 as compared to list length of 7. This finding is counter-intuitive if the result of overall superior recall following position probes is interpreted as indicating that order information is represented primarily by position codes. Although the available evidence cannot support a definitive answer, it appears that the importance of position codes relative to associative codes may diminish as list length increases. The interpretation is appealing, since it would be seem more efficient to represent extremely long lists of items via item-to-item associations than by item-to-position codes. Consider the difficulty of reporting the 14th letter in the alphabet relative to reporting the letter following 'm'.

A final point of interest regarding probe differences in recall accuracy has to do with the difference between the order and item probes. While it is perfectly reasonable to expect recall of content to be superior to recall of order, most demonstrations of this fact do not provide separate measures of item and order recall. That is, memory for item and memory for order are often separated by using an order-free and order-based scoring procedure. Such a scoring procedure insures that memory for content will

exceed (or at least equal) memory for order. The procedure used in the present experiment provided independent assessments of memory for order and content, and can thus provide a more accurate estimate of the difference between memory for serial order and memory for content than can the order-based/order-free scoring procedure. The difference between memory for order and item information is explored in further detail in Experiment 3.

Analysis of the serial position data demonstrated that retrieval accuracy for the order probes varied as a function of serial position in a way consistent with data reported in the literature (e.g. Lewandowsky & Murdock, 1989). Specifically, retention was better for end positions as compared with positions occupying the middle of the list. However primacy effects were not as strong for the associative probe, since the first position was not tested. This finding could be used to argue that the reason why overall accuracy was superior for the position as compared to the associative probe was that the first position was not tested for the latter, reducing measured accuracy due to a failure to properly assess primacy effects for this probe. However, the finding that recall following positional probes is superior to that following sequential probes does not appear to be due to an under-assessment of primacy in the latter probe condition. Increasing distractor difficulty produced more errors, but did not affect the shape of the serial position curve for either of the order probes.

Serial position data from the item probe paralleled those from the order probes. Strong primacy and recency effects were obtained, indicating that retention of item information is superior for items occupying terminal position compared with items occupying middle positions. Direct comparisons of the serial position data from the item and position probes revealed no substantial differences in their serial position

curves. The present finding that serial position curves for item information are not flat, and do not differ from those obtained for order information, contradicts the prevailing view that memory for order and item information can be dissociated on the basis of differential serial position curves.

## Experiment 2

Experiment 2 replicated much of Experiment 1, but the unit of analysis was based on the data obtained from individual subjects. The purpose of this experiment was twofold. The first was to determine whether the empirical findings reported in Experiment 1 would be observed when the data from individual subjects were analyzed. Specifically, the extent to which recall following position probes was superior to recall following associative probes was examined. Then, the characteristics of the serial position curves for individuals were described and compared to those obtained from aggregated data, with particular attention to (a) whether a serial position effect was observed for item information and (b) whether the serial position curves for item and position probes differed. A second purpose of Experiment 2 was to generate data to which a version of Estes' Perturbation model was fitted. The fit of this model to the data from the present experiment (and Experiment 1) is discussed in section devoted to the Perturbation model (pp. 70-88).

### Method

**Subjects.** Four young adults recruited from undergraduates attending classes at Queens College and hospital lab technicians (ages 18-26) volunteered to participate in Experiment 2. There were four experimental sessions, each lasting about four hours. Subjects were paid \$75 as compensation for the amount of hours spent participating in the study. These subjects had abbreviated WAISR verbal IQs of 120, 112, 108 and 128. Data from a fifth subject was not analyzed due to ceiling effects (the subject's

performance was perfect for all condition except for associative probed recall for the 8 item list).

**Procedure.** Each testing session consisted of 12 practice trials and 16 blocks of 24 trials each, with list size varying across blocks. In each testing session, the subject was presented with six blocks of 7 items lists and six blocks of 8 item lists. The order of presentation was counter-balanced across testing sessions. Within each block, the three different probes were randomly presented to the subject with the condition that all probes are presented the same number of times. Across the four sessions, each subject was probed 42 and 36 times by each of the serial order probes for each serial position for 7 and 8 item lists, respectively. Otherwise, the procedure for Experiment 2 was identical to that for Experiment 1, with the exception that only the difficult (letter after) interference condition was used as a distractor task.

**Design.** The design for Experiment 2 was the same as for Experiment 1, with the exception that only one level of distractor difficulty was studied (letter after), making the design a 2 (list size 7 / list size 8) x 3 (associative / position / item) factorial experiment.

## Results

Table 1 summarizes the accuracy data of each of the four subjects for all three probe types and both list sizes. Comparing these results with those described in Experiment 1, it can be seen that general pattern of findings from the first experiment describes the data obtained from individual subjects. Specifically, retrieval following position probes was better than that following associative probes for all four subjects, for both 7 and 8 digit list sizes. Also consistent with findings from the first experiment

Table 1. Mean proportion correct for individual subjects for each probe type and list size

	<u>Position</u>	<u>Associative</u>	<u>Item</u>
	<u>Mean (SE)</u>	<u>Mean (SE)</u>	<u>Mean (SE)</u>
Subj #1			
7 item list	0.87(.02)	0.71(.03)	0.83(.02)
8 item list	0.78(.02)	0.69(.03)	0.80(.02)
Subj #2			
7 item list	0.76(.03)	0.74(.03)	0.89(.02)
8 item list	0.73(.03)	0.65(.03)	0.81(.02)
Subj #3			
7 item list	0.85(.02)	0.72(.03)	0.82(.02)
8 item list	0.75(.03)	0.66(.03)	0.82(.02)
Subj #4			
7 item list	0.82(.02)	0.78(.02)	0.88(.02)
8 item list	0.73(.03)	0.70(.03)	0.84(.02)

was that this difference was larger for the 7 item as compared with the 8 item list, for three of the four subjects (#1, #3 and #4). Two of the four subjects showed superior recall following item as compared with position probes for 7 digit lists, and all four showed this superiority for 8 digit lists. Recall was higher in all four subjects for 7 digit lists compared with 8 digit lists, regardless of probe type. And although the accuracy of the individual subjects was greater than the average accuracy of the aggregated data from the first experiment, individual subjects were within one standard deviation of the group mean for all experimental conditions.

Figure 5 displays the proportional serial position curves for each subject and list size. Curves obtained for both order and the item probes show a serial position effect, namely relatively more errors are made at middle list positions than at the terminal positions. Evidence for primacy and recency effects was found for each of the four subjects for both 7 and 8 digit lists. The curves resemble those obtained in the first experiment in their general shape and demonstrate that the serial position curves characteristic of data aggregated across subjects are observed for individual subjects as well. These observations were confirmed by the results of trend analyses performed on the serial position data from each subject. Results of these analyses are summarized in Table 2, which displays the proportion of between position variability for each subject that was described by the linear and quadratic trends. For all three probe types, subjects' serial position curves showed large quadratic components indicative of primacy and recency effects, as was found for the aggregated data from Experiment 1. One exception appears to be Subject #3, who demonstrated relatively more recency than primacy, especially for the associative probe recall. This observation was confirmed by the trend analyses, which showed a substantial linear trend for associative probe recall for this subject.

Figure 5. Serial position curves for recall of individual subjects following all three probe types. The value for each position reflects the proportion of total errors made for that condition. Data from Experiment 2.

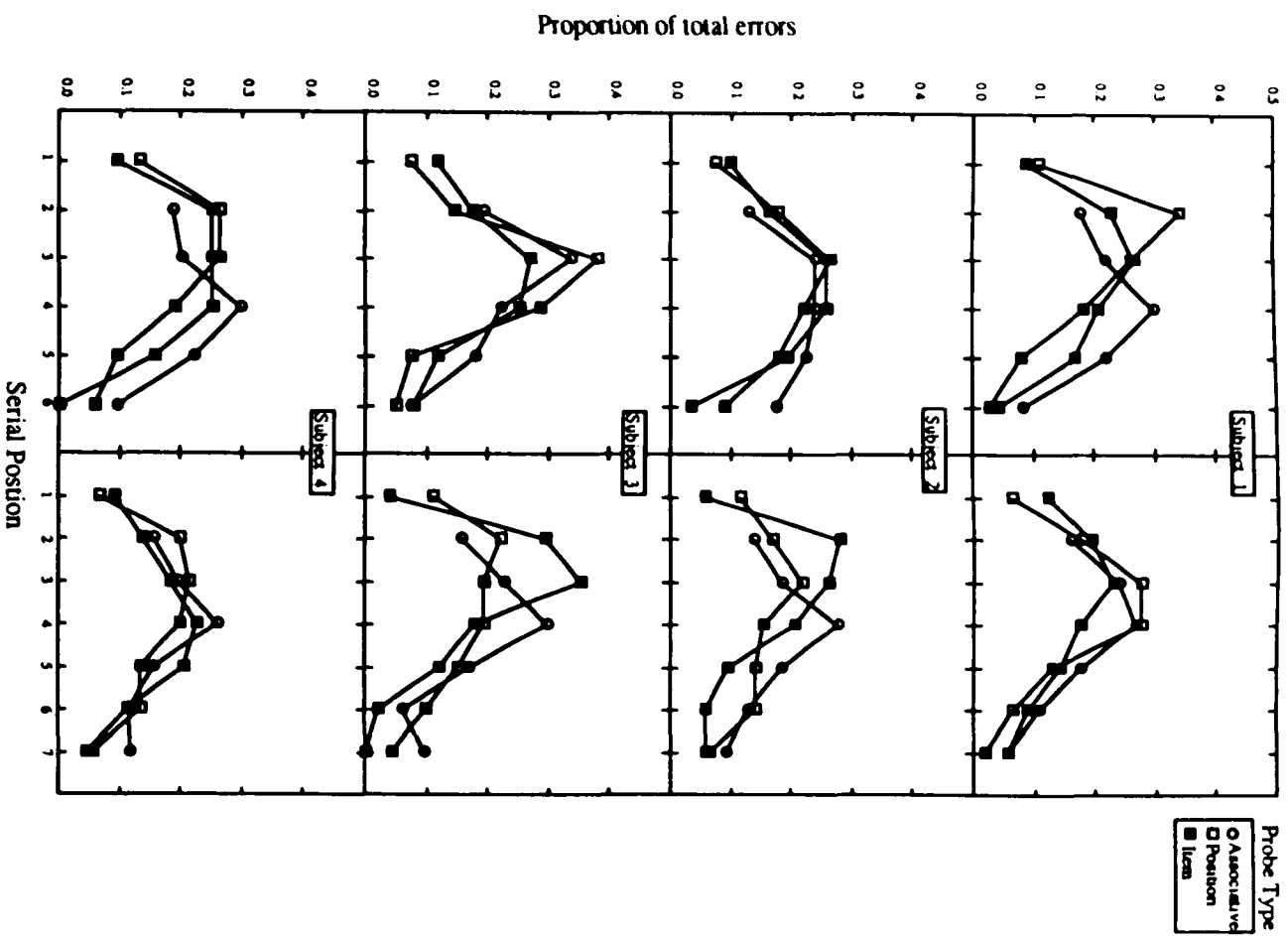


Table 2. Proportion of between position variance accounted for by linear and quadratic trends for data obtained from individual subjects (Experiment 2).

	<u>Position Probe</u>		<u>Associative Probe</u>		<u>Item Probe</u>	
	<u>Linear</u>	<u>Quadratic</u>	<u>Linear</u>	<u>Quadratic</u>	<u>Linear</u>	<u>Quadratic</u>
Subj #1						
7 item list	0.32	0.41	0.15	0.76	0.08	0.87
8 item list	0.15	0.67	0.47	0.41	0.41	0.46
Subj #2						
7 item list	0.00	0.95	0.07	0.85	0.02	0.93
8 item list	0.21	0.57	0.21	0.58	0.22	0.34
Subj #3						
7 item list	0.03	0.67	0.44	0.36	0.07	0.76
8 item list	0.36	0.53	0.33	0.25	0.25	0.38
Subj #4						
7 item list	0.35	0.48	0.14	0.69	0.15	0.83
8 item list	0.09	0.72	0.28	0.30	0.04	0.90

Of note is that each subject displayed a serial position effect for the retention of item information for both list sizes, providing further support for the proposition that serial position curves for item information are not flat, and resemble those obtained for order information. The evidence for this interpretation is strong as shown in Table 2; the quadratic trends account for between 38% and 93% of the between position variability. No formal tests of significance were performed to compare the curves obtained from the position and item probes as was done in the first experiment, since data would need to be aggregated across subjects to carry out such formal testing. However, there were no obvious systematic differences in the general shape of the position curves for these two probe types indicated in Figure 5.

## **Discussion**

The results of this experiment confirmed those reported in Experiment 1. First, serial position curves for item recall were shown to be comparable to those obtained for order recall. Specifically, the curves exhibited a primacy and recency effect that were similar for order and item recall. Second, recall following position probes was higher than recall following associative probes. This indicates that individual subjects were able to use position information more effectively than associative information for recalling serial order. But, as in the first experiment, this difference is not large, with the advantage in proportion correct of position probes versus associative probes ranging from .02 to .16 with an average difference in proportion correct of .08. Therefore, associative information could be used to cue retrieval of order information, but probably would require additional processing that results in an increased opportunity for error.

### Experiment 3

The first two experiments demonstrated that item recall was superior to order recall. If the maintenance of order information requires more processing resources than the maintenance of content information, then it should be possible to produce a differential impairment in order recall by increasing task difficulty. However, there was no evidence that recall of order information was disrupted to a greater extent following a difficult distractor condition than was recall of item information. The possibility of differential processing demands of order and item recall can be further explored by comparing order and item recall in the young with a group of subjects known to exhibit a decline in processing capacity. To this end, the comparison order and item recall between young and aged subjects might reveal differences between order and item recall not observable when only the performance of young subjects is examined.

Craik (1984) has asserted that elderly subjects would be comparable to young adults on tasks that require little active manipulation or transformation of information, that is, on primary memory tasks. In contrast, elderly adults would show markedly inferior performance on working memory tasks that is poorer than young adults. In a series of experiments, Craik and colleagues (Gick, et al., 1988; Morris, et al. 1988) demonstrated age associated differences in processing capacity. They used a modified version of the Daneman and Carpenter (1980) working memory task, which required subjects to verify a series of sentences, and then at the end of the series, recall the last word from each sentence. The scoring method for the memory task was order-based, that is, the words had to be recalled in the order in which they were presented. When

positive grammatical sentences were used, there was no differential decrement in recall due to age, but when negative sentences were used, the word recall of the aged suffered more than did the young. Gick et al. (1988) also examined whether increasing the number of sentences to be verified, and hence the number of words to be remembered, affected word recall, verification accuracy and latency in the aged and young. They found that increasing set size produced more verification errors, longer latencies and poorer word recall, but this variable did not interact with age. These experiments suggest that not all variables known to affect working memory have differential effects in elderly individuals.

These findings raise fundamental questions regarding the nature of age associated changes in short-term and working memory. The hypothesis that aging results in the decline of a general pool of processing resources seems unsatisfactory in light of the findings that not all variables which reduce performance in the young exhibit a greater effect in the elderly. Such a hypothesis would predict that a general deficit in processing resources would exacerbate the effect of any increase in difficulty ( Craik & Byrd, 1982; Gick et al., 1988). The specific characteristics of the type of task complexity or difficulty that interacts with age need to be identified. Unfortunately such issues are rarely addressed, with research more often focussing on tasks or experimental manipulations that are known to have an age effect. That is, the purpose of much research is to demonstrate age differences, rather than to analyze the mechanisms that underlie such differences (e.g. Hultch, Hertzog & Dixon, 1990; Parkinson et al., 1982).

A logical starting point for analyzing mechanisms that underlie age differences in working memory, would be to determine whether such differences are attributable to

an age associated depletion in processing resources and/or reduction in storage capacity (Foos, 1989). However, few studies have attempted to separate age differences due to reduced processing from those due to reduced storage. For example, the adverse effect that dividing attention between two tasks has on aged individuals was clearly demonstrated with a dichotic listening task (Parkinson et al., 1980). When asked to recall information presented simultaneously to both ears, aged subjects recalled fewer items than did young adults. However, since small but reliable differences have been observed in the short-term memory span between young and aged adults, whether the observed difference is due to processing or storage related deficits cannot presently be discerned.

Wright (1981) demonstrated that working memory deficits in aged individuals are found with tasks requiring an internal division of attention. In two experiments she found that when individuals are required to allocate limited resources to competing cognitive processes, the performance of aged individuals suffers to a greater extent than that of young adults. In her first experiment, subjects had to perform a sentence verification task under two conditions. In the control condition, subjects were presented with a string of digits and had to recall them before proceeding to the sentence verification task. In the experimental condition, the sentence verification task intervened between digit presentation and recall. To vary the demands placed on capacity, the number of digits presented was 2, 3, 5 or 6. Recall under the divided attention condition was inferior for all digit string lengths and this effect was greater for the aged subjects than for the young. Her second experiment examined how performing addition was affected by memory load and the number of mental operations required (i.e. carrying ones, carrying ones and tens). Addition accuracy suffered only for the larger memory loads, and there was no differential age effect of memory load for small load

conditions. Although this finding has been interpreted to suggest that age effects are due to diminished storage capacity as opposed to reduced processing resources, performance for both young and old was perfect for low memory load conditions. Therefore, ceiling effects on this task could mask age differences that are present even when demands on processing resources is at a minimum.

A recent study by Foos (1989) directly addressed the issue of whether age differences in working memory are due to diminished processing resources, reduced storage capacity, or both. In his first experiment, subjects were required to solve three addition problems before presenting the answers to any. Elderly subjects showed an exaggerated serial position effect, in that many fewer correct answers were provided for the second problem position. This was interpreted as supporting the reduced storage capacity hypothesis. The reasoning behind this interpretation states that performance on the second problem would be low because with less storage capacity it is the solution most likely to be lost because is not "as recent or fresh" as the third solution and "has not been rehearsed" as much as the first solution (Foos, 1989, p 270). A second experiment by Foos found that stimulus length not stimulus complexity interacted with age, providing additional support for the reduced storage capacity hypothesis.

The problem with most studies that examine the differential effect of divided attention or other working memory variables on young and elderly subjects, is that of differential task difficulty. If the only difference between young and aged adults was related to storage capacity, having the two work with equal memory loads would make the task more difficult for the aged compared to the young. If processing demands are then manipulated, it would be impossible to discern whether effects on performance are due to these manipulations or due to capacity related task difficulty. For example,

assume that the memory span for all young individuals was eight items and for all elderly individuals was six items. A working memory task whose memory load conditions varied from four items to seven items would all be of sub-span length for the young, while two conditions would either be equal to or greater than the span length for the aged. Therefore, the task of remembering the memory load items would not be of comparable difficulty for both age groups. Any differential change in performance of young and elderly subjects associated with varying processing demands (e.g. number of mental operations) could be caused either by the manipulation of processing requirements or its interaction with task difficulty.

In order to infer differential age effects of tasks that vary demands on processing resources, an attempt to equate for capacity differences must be made. One study that is not frequently cited in the aging literature, partly because its primary focus was on dementia and not normal aging, was that of Baddeley et al. (1986). The purpose of their study was to identify the presence of working memory deficits in demented elderly patients. The paradigm used in this study examined subjects' performance on a pursuit tracking task in each of four conditions of varying processing demands. In the control condition, only the tracking task was performed. The other conditions were articulatory suppression (i.e. continuously repeating the word 'the'), reaction time to a tone, and auditory digit span. The authors point out that to infer a working memory deficit attributable to reduced processing resources, the primary (tracking) and secondary tasks (digit span) must be equated for difficulty across subjects, where appropriate. Difficulty was equated for the three subject groups (young, normal elderly, demented elderly) for tracking by varying target speed so that time on target was between 40% and 60%. For the digit span distractor condition, difficulty was equated by using a list length for each subject equal to his or her digit

span. Although the expected effects of dementia on pursuit tracking were obtained, no age associated working memory deficits were observed. Specifically, time on target did not decrease more for the old than for the young, even when digit span was the secondary task.

An additional finding of Baddeley et al. (1986) was that measured recall on the concurrent span task (digit span during pursuit tracking) showed a large effect of concurrent task, but no task by age interaction. The authors conclude that although combining tasks equated for difficulty impairs performance, this impairment is not exacerbated in the elderly.

The results of Baddeley et al. (1986) do not suggest that there are no age associated working memory deficits, only that such deficits do not encompass all aspects of memory and cognition. In this respect, their results are in agreement with those of Craik and colleagues (Gick et al., 1988; Morris et al., 1988) which indicate that certain forms of task complexity produce a differential age effect, while others do not. Although short-term serial order memory is poorer in aged adults relative to young adults (Parkinson, 1982), no study has ever examined whether this finding is due to reduced storage capacity or processing resources. That is, elderly individuals could remember less on serial memory tasks because they do not have the capacity to remember the same amount of information as do young individuals, or because the information they do retain is more easily 'disorganized', or both.

The present experiment examined age associated differences in the processing resources needed to maintain serial order information in short-term memory. An attempt was made to remove the effects of differential storage capacity between young and aged subjects so that performance differences could be attributed to age related differences in

processing capacity. If aged adults show a deficit relative to young adults in the ability to retain and retrieve order information that is not attributable to a loss of item information, then two implications will be evident. First, a specific age associated deficit in the ability to maintain the organization of information in short-term memory would be indicated. That is, if age differences in capacity are experimentally minimized, as evidenced by comparable recall of item information, any differences in recall of order information would reflect an age related impairment in the processing required to maintain order information in addition to content information. Second, the processing requirements of order retention would be shown to differ from those of item retention either in amount or kind.

The present experiment also explored whether aged subjects would exhibit a larger effect of distractor difficulty than young subjects. The bulk of previous research would predict that there should be an age x distractor interaction. However, the only study which equated for task difficulty across young and aged subjects did not show a differential effect of increased demands on processing capacity for young and aged subjects (Baddeley et al. 1986). This finding leads to the prediction that if the age differences in storage capacity can be minimized, then there should be no distractor x age interaction.

## **Method**

**Subjects.** Twenty-four young adults (ages 18-26) and twenty-four elderly adults (ages 65-80) volunteered to participate in a single experimental sessions, lasting about 1.5 hours. The young subjects were volunteers recruited from undergraduate students attending classes at Queens College, and employees from Albert Einstein College of Medicine and Mount Sinai Medical Center. All of the elderly subjects have

participated in an ongoing study of aging and memory conducted at the Albert Einstein Medical Center. Consequently, all the elderly subjects have been screened for dementia, neurological pathology and have received an abbreviated WAIS-R as a measure of their verbal intelligence. There was no difference in mean abbreviated WAIS-R scores between the young (114.4,  $sd=7.6$ ) and the aged (113.5,  $sd=8.2$ ). The data from eight young subjects from Experiment 1 who had digit spans of 8 were used in the present experiment, since they received the proper length lists (see Procedure below). The data from two aged subjects were excluded after it was discovered they had a prior history psychiatric illness.

**Procedure.** Since task difficulty was to be equated across subjects, memory capacity for digits was assessed using the digit span task from the WAISR. Digit span measured by the WAISR determined the maximum list length for each subject according to the following rule: for digit spans less than 6 the maximum list length was 6, for digit spans of 6 or 7, the maximum list length was 7 and for digit spans greater than 7 the maximum list length was 8. Subjects were exposed to lists equal to their maximum and one less than their maximum, as determined by the above rule. So, for example, a subject with a digit span of 6 would be tested on list lengths of 7 and 6. For each list length, there were two blocks of 24 trials, with a single distractor task condition occurring throughout an entire block. Subjects were given a brief rest between blocks. Other aspects of the experimental procedure are as described in the General Method section above.

**Design.** The design was a 2 (aged / young) x 2 (list size long/ list short) x 2 (easy / difficult distractor) x 3 (associative / position / item probe) experiment, with age being the between-subject factor and all factors varied within subjects. The first

within-subject factor, list size, indicates that the subjects was tested on a long or short list of digits, the exact length of which depended on each subject's digit span. The second within-subject factor, distractor type, indicates that the task intervening between list presentation and probed recall required the subject to copy a letters (easy) or to specify the letter following the presented letter in the alphabet (difficult). The third within-subject factor, probe type, indicates that the subject's recall was cued with an associative or position probe, in the case where memory for order was to be measured, or a missing scan probe, in the case where memory for item information was to be measured. List size and distractor type were varied across blocks of trials, while probe type varied randomly within blocks.

## Results

Although the experimental task did not focus on age differences in retention capacity, WAISR digit spans can be compared. The average digit span for elderly subjects was lower than that of the young (5.8 vs. 6.8,  $t[46]= 3.1$ ,  $p<.01$ ), which is consistent with previous research (Parkinson, 1982).

Recall accuracy. The mean proportions correct for the aged and young for each experimental condition are reported in Table 3. The young showed higher overall recall across all conditions than the aged, with the mean proportion of digits correctly recalled of .74 and .66 for the young and aged, respectively. Closer examination of Table 3 indicates that this overall difference is entirely due to the young's superior recall on both order probes. This was confirmed by a significant main effect of age ( $F[1,46]=32.7$ ,  $p<.01$ ), and a follow-up contrast which revealed that this main effect was due to age differences on order probes, ( $F[1,46]=64.4$ ,  $p<.001$ ), indicating poorer recall of order information for the aged compared to the young (.56 vs .69,

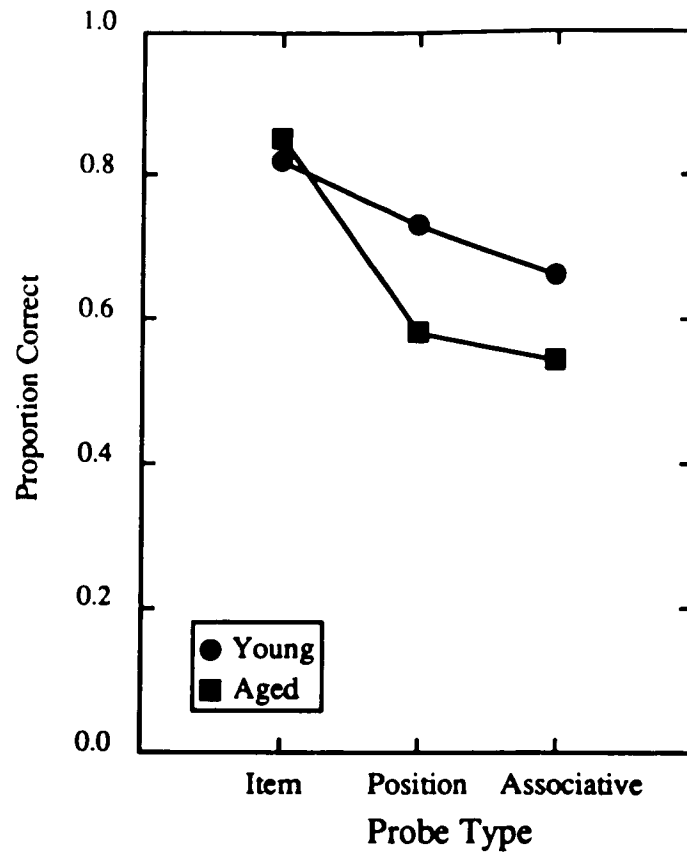
Table 3. Mean proportions correct for young and aged subjects by probe type for list length and distractor conditions. Data from Experiment 3.

<u>Probe Type</u>	<u>Young subjects</u>		<u>Aged subjects</u>	
	<u>Copy Letter</u>	<u>Letter After</u>	<u>Copy Letter</u>	<u>Letter After</u>
			<u>Short Lists</u>	
Associative	.72(.03)	.60(.02)	.62(.02)	.52(.03)
Position	.82(.02)	.77(.02)	.65(.02)	.58(.04)
Item	.86(.01)	.77(.02)	.90(.03)	.83(.03)
			<u>Long Lists</u>	
Associative	.67(.03)	.62(.04)	.56(.03)	.45(.02)
Position	.69(.01)	.65(.01)	.60(.04)	.50(.04)
Item	.81(.02)	.80(.01)	.87(.04)	.81(.03)

respectively). However, no reliable age differences for recall on the item probe ( $F[1,46]=2.8$ , ns) were found. The mean proportion recalled was lower following the letter-after distractor compared with the copy letter distractor (.66 vs. .72, respectively) and for long lists compared to short (.63 vs. .68, respectively). Significant main effects of distractor ( $F[1,46]=49.1$ ,  $p<.001$ ) and list length and ( $F[1,46]=20.5$ ,  $p<.001$ ) confirmed these results. Recall accuracy also varied with probe type, as shown by clearly superior recall for item probes (.83) compared with the order probes (.62). A significant main effect of probe type ( $F[2,92]=136.4$ ,  $p<.001$ ), and a follow-up contrast which compared recall following the item with recall following order probes ( $F[1,46]=94.5$ ,  $p<.001$ ) confirmed these interpretations. Position probe recall was better than associative probe recall (.65 vs. .60, respectively). This was supported by a follow-up contrast of the position probe compared to the associative probe ( $F[1,46]=9.4$ ,  $p<.001$ ).

The age x distractor interaction was not significant ( $F[1,46]=1.7$ , ns), indicating that the difficult distractor condition had a comparable effect on recall for both young and aged subjects. No interaction was found between age and list length ( $F[1,46]<1$ , ns). The significant effect of probe type described above indicated that recall was higher following item as compared to either of the order probes. This difference between item and order recall was much larger for the aged compared to the young (.29 vs. .12). That is, the aged found it much more difficult to recall order information than did the young, even though recall of item information was comparable for the two groups. Figure 6 displays this effect graphically. A significant interaction between age and probe type supported this description of the data ( $F[2,92]=22.7$ ,  $p<.001$ ). Follow-up orthogonal contrasts comparing differences between order and item recall ( $F[1,46]=41.2$ ,  $p<.001$ ), and differences between positional and associative

Figure 6. Proportion digits recalled correctly for young (circles) and aged (squares) subjects as a function of probe type. Data from Experiment 3.



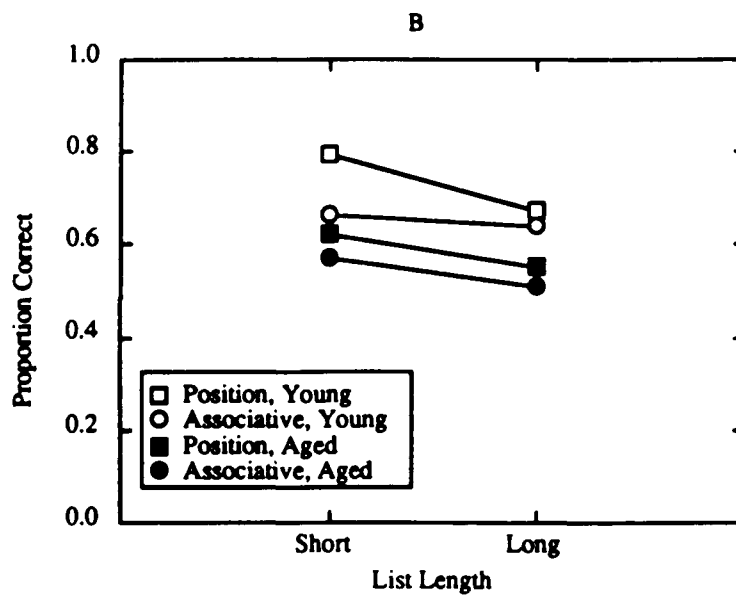
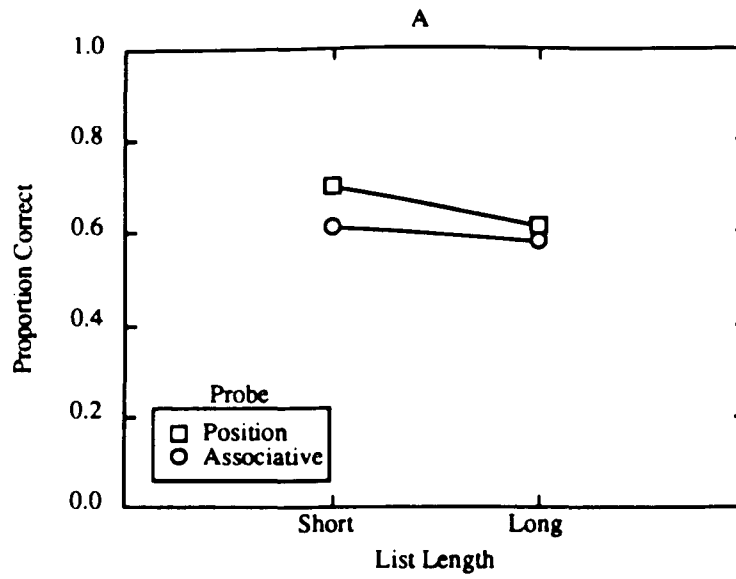
probed recall ( $F[1,46]= 1.0$ , ns) for young and aged confirmed that this interaction was due to item–order probe differences and not to positional–associative probe differences.

The greater recall following positional compared with associative probes was moderated by list size. Panel A in Figure 7 displays this effect graphically. If the data are collapsed across the young and aged subjects, the positional–associative probe difference was much larger for the short lists than the long lists (.09 vs. .03, respectively). This result is supported by a significant probe x list length interaction ( $F[2,92]=5.8$ ,  $p<.01$ ) and is consistent with the finding from Experiment 1 which indicated that the positional–associative probe recall difference was twice as large for 7 item lists and for 8 item lists. However, panel B in Figure 7 indicate that this interaction is further modified by age. That is, young subjects showed a larger position–associative probe difference for small lists sizes than for long lists sizes (.13 vs. .02), while aged subjects do not (.05 vs .04). A significant probe type x list size x age interactions confirmed this interpretation of the data ( $F[2,92]=3.7$ ,  $p=.02$ ), as did a follow-up contrast that specifically tested the positional–associative x list x age effect ( $F[1,92]=6.0$ ,  $p<.02$ ).

Serial position data in the aged. The following analyses focused on the serial position data for the aged subjects since serial position data from young adults were analyzed in detail in Experiment 1<sup>1</sup>. Because not all elderly subjects were tested on the same list size, the number of subjects comprising each curve is different. Fifteen aged subjects were tested on the 7 digit list and all 24 were tested on the 6 digit list. Since

<sup>1</sup> Preliminary analyses indicated that although noisier, the serial position data from these additional young subjects conform to those described in Experiment 1.

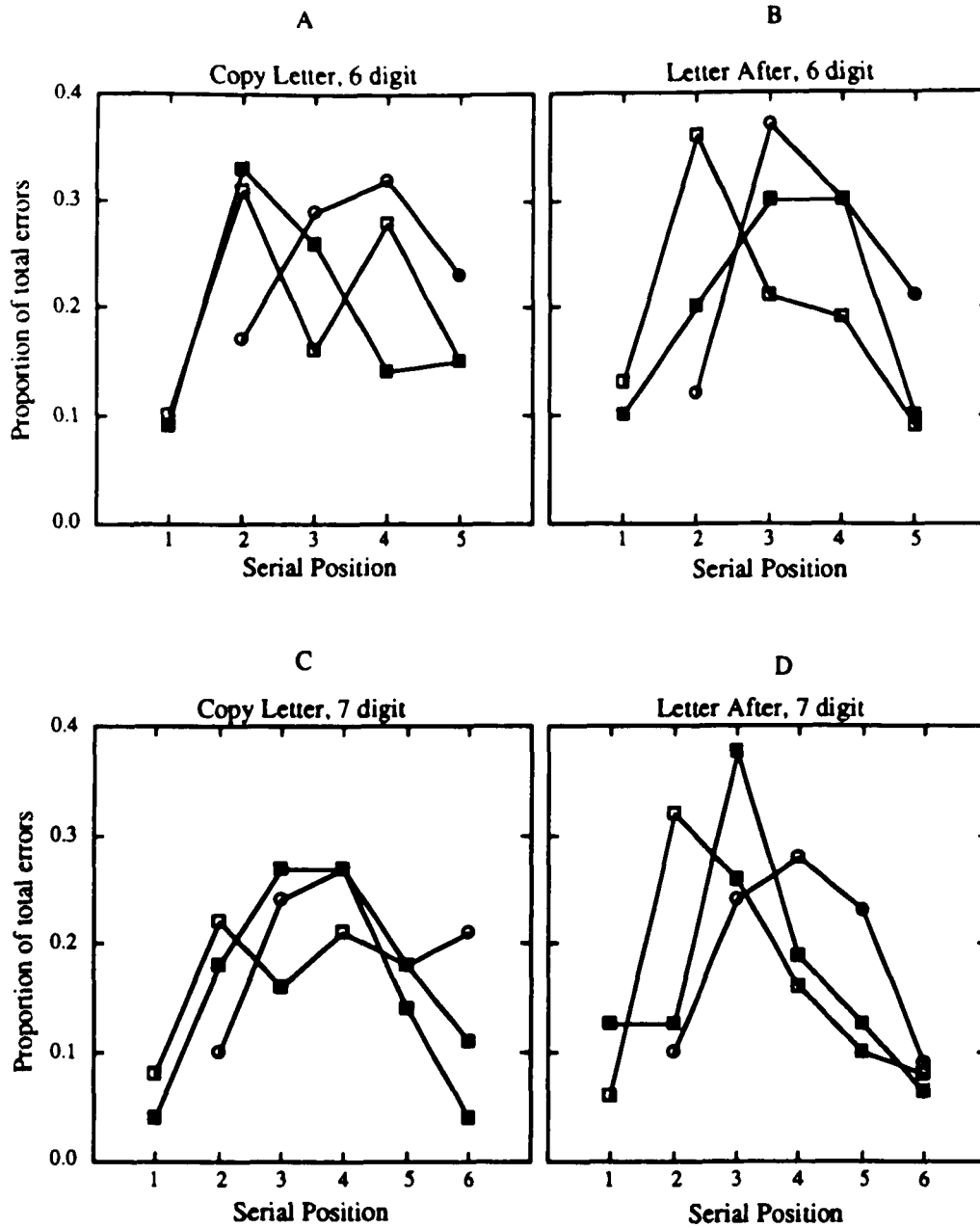
Figure 7. Proportion of digits correctly recalled following position (squares) and associative (circles) probes. Panel A displays the difference in proportion correct between position and associative as a function of list length, collapsed across age. Panel B displays the same effect for young (open symbols) and aged (closed symbols) subjects separately, which indicates that the interaction shown in Panel A is due to the young subjects. Data from Experiment 3.



only 9 subjects were tested on 5 digit lists, there were not enough data points to construct reliable serial position curves or perform a trend analysis on data from this condition.

Figure 8 displays the proportional serial position curves obtained from the aged subjects. The serial position data from both the 6 and 7 digit lists for the aged subjects were similar to those of the young subjects from Experiment 1, in that the curves were characterized by a substantial primacy and recency components. Although there is some noise evident in the data plotted in Figure 8, a clear serial position effect is evident for all three probes that is similar to that obtained for young adults. This characterization of the data was confirmed by trend analyses. Retrieval following associative probes showed strong primacy and recency effects, as indicated by significant quadratic trends which accounted for 87% of the between position variability for 6 digit lists ( $F_{\text{qued}}[1,23] = 21.1$   $p < .01$ ), and 73% of the between position variability for 7 digit lists ( $F_{\text{qued}}[1,14] = 14.8$ ,  $p < .01$ ). Data from the position probes were similar to those from the associative probe. The quadratic trends were large and significant, accounting for 46% and 57% of the variability across positions ( $F_{\text{qued}}[1,23] = 21.0$   $p < .01$ , and  $F_{\text{qued}}[1,14] = 41.1$   $p < .01$ ), for 6 and 7 digit lists, respectively, indicating substantial primacy and recency effects. No effect of distractor difficulty on the shape of the serial position curves or significant linear trend was detected for either probe type. The curves for recall of item information displayed in Figure 8 show serial position curves similar to those for order information, extending the findings from Experiments 1 and 2, that properly measured serial position curves for item information are not flat, to elderly adults. The observation that serial position curves for item information are not flat was supported by quadratic trends similar in magnitude to those obtained for the order probes. Specifically, the quadratic trend

Figure 8. Serial position curves for recall by the aged, following all three probe types, for both distractor conditions and list lengths. The value for each serial position reflects the proportion of total errors made for that condition. Panel A and B present the data from 6 digit lists for the 'copy letter' and 'letter after' distractors, respectively. Panel C and D present the same data for 7 item lists. (Symbols: open circles= associative probe; open square= position probe; filled square= item probe). Data from Experiment 3.



accounted for 87% of the between position variability for 6 item lists ( $F_{(quad)}[1,23] = 12.9$   $p < .01$ ), and 77% for 7 item lists ( $F_{(quad)}[1,14] = 12.8$   $p < .01$ ). No effect of distractor difficulty on the shape of the serial position curves or significant linear trend was detected for item probe recall.

Comparison of serial position data for the young and aged subjects. Direct comparison of the serial position curves of the young and aged subjects is complicated by the fact that not all subjects received stimulus lists of the same length. Therefore, the linear and quadratic trends in the serial position data of the young and aged were compared by using coefficients for orthogonal polynomials to compute contrast scores that represented both of these trends (Rosenthal & Rosnow, 1986). Independent samples t-tests were then be used to compare the contrast scores of the young with those of the aged to determine if there are differences in the linear and quadratic trends between these groups. In order to maximize power, the stimulus list lengths that were used were those which the greatest number of young and aged subjects received. Twenty-two of the 24 young subjects were tested on 7 digit lists and all 24 aged subjects were tested on 6 digit lists. The contrast scores were constructed such that negative scores indicated more primacy than recency for linear trends and a more pronounced bowing of the serial position curve for quadratic trends.

The aged subjects showed less recency than did the young subjects on associative probed recall (.59 vs. -.44), but this difference did not obtain statistical significance ( $t_{(linear)}[44] = 1.92$ ,  $p = .06$ ). The magnitude of the bowing of the serial position curves was comparable for the young and aged (-.76 vs. -.85) for associative probed recall. This interpretation of the data was supported by a non-significant quadratic trend ( $t_{(quad)}[44] < 1$ , ns). Recall following positional probes was

characterized by significantly less recency for the aged than for the young ( -1.9 vs. -.41;  $t_{\text{linear}}[44] = 4.30, p \leq .05$ ), but no difference in the overall bowing of the curves (-1.1 vs. -1.6;  $t_{\text{quad}}[44] = 1.2, p = .23$ ) was observed. There was no detectable difference between the young and the aged for either the linear ( -.29 vs. -.57;  $t_{\text{linear}}[44] = 1.30, p \leq .19$ ) or quadratic trends (-.79 vs. -.94;  $t_{\text{quad}}[44] < 1, \text{ns}$ ) for recall following the item probes.

## Discussion

The results from Experiment 3 demonstrated that elderly subjects performed more poorly than young adults when required to maintain and retrieve order information. This finding is especially compelling, since the elderly performed just as well as the young on recall of item information. Equivalent item recall for the young and aged indicate that the differential loss of order information could not be attributed to loss of item information resulting from reduced storage capacity. Since it is plausible that maintaining and retrieving order information requires more processing resources than item information, this finding has implications for age associated differences in working memory. Viewed in the context of working memory, this result suggests that maintenance and retrieval of order information, as compared to content information, places greater demand on processing capacity. Furthermore, this finding also suggests there is an age related impairment in the ability to execute the specific processing required to maintain and/or retrieve serial order information.

Results of the present experiment are consistent with the view that not all types of task complexity have similar effects on performance (Gick et al., 1988). If the age x probe interaction were due to a depletion in general pool of processing resources in the aged, then it should have been exacerbated by a task that competes for processing resources. This would lead one to expect the differential deficit for order memory found in the elderly to be more pronounced when processing resources are taxed by another competing task. By varying the difficulty of a distractor task between a relatively passive operation (i.e. copying a letter) and one requiring a more active operation (i.e. specifying the letter that follows a target in the alphabet), recall performance was

reduced. Although the difficult distractor condition produced a decrement in recall for both young and aged subjects, this decrement was equivalent for the two groups. Thus, having to divide limited processing resources between maintaining information in primary memory and performing a secondary task does not produce an age dependent impairment in probed recall. The age x probe interaction was not modified by complexity of the distractor task, providing additional evidence that age associated deficits in processing capacity are specific to certain types of processing.

The major findings of Experiment 3 support the hypothesis that at least some age associated performance decrements in working memory are due to deficits in processing capacity. An alternative explanation that cannot be discounted is that the age x probe interaction is evidence of a disassociation between memory for item and order information. It is possible that distinct and relatively independent systems or processing modules are responsible for item and order memory. If this were true, then aging could exert independent effects on memory for item and order information. Regardless, the results described require a more specific and detailed account of age associated deficits than one which simply attributes them to an impairment in a general pool of processing resources. Adequate explanations will require a more thorough understanding of the types and characteristics of processing on which aged individuals exhibit difficulties.

### **Perturbation Model**

The present experiments have supported the prediction that recall following position probes would be higher than recall following associative probes. Given this result, it would be interesting to determine to what extent a theory based on position codes would be able to account for the data generated from the associative as well as the position probes. The argument has been made above that if position codes are primary to the representation of serial order in memory, then some transformation would have to take place for associative information to be an effective retrieval cue. If a theory which relies on positional codes to represent serial order does not explicitly account for the use of associative information in the retrieval of serial order, a specific bias in its prediction of serial order recall would be expected. Specifically, such a theory would be expected to overestimate associatively probed recall, since it could not model the operation which transforms associative cues into more directly usable information.

One such quantitative theory that relies on positional codes for serial order is Estes' Perturbation model. This model was fitted to the data from Experiments 1 and 2 to determine whether it can account for the essential characteristics of data generated from associative as well as position probes. Previous studies which have evaluated this model have only used aggregated data (group means). Comparing the model's fit to the data from Experiments 1 and 2 will aid in determining how adequately the Perturbation model can account for group and individual performance on a serial memory task.

Formal aspects of the Perturbation Model. To understand how the Perturbation model is fit to experimental data, a brief explication of the formal aspects of the model is required. The theory underlying the formal aspects of Estes' Perturbation model was discussed above. To review, Lee and Estes (1981) proposed a model of short-term

serial order memory in which information is encoded hierarchically. At the highest level of abstraction information about trial position is encoded. At the lowest level, information regarding the position of items within a particular trial is encoded. Once encoded, this information is repeatedly reactivated, and with each reactivation there is a probability that information regarding the relative positions of items (and trials) will perturb and interchange. This perturbation process occurs independently at the item and trial level.

This perturbation model has been extended by Healy et al. (1987) to incorporate the entry of information into secondary memory. This extended perturbation process can be described mathematically by the following recursive equation (Healy et al., 1987):

$$X_{i,n+1} = (1 - \alpha)X_{i,0} + \alpha[(1 - \theta)X_{i,n} + (\theta/2)X_{i+1,n} + (\theta/2)X_{i-1,n}] \quad (1)$$

where  $X_{i,0}$  is the probability of initially encoding the item in the  $i$ th position of the segment (usually taken to equal 1.0),  $X_{i,n}$  is the probability that during the  $n$ th time interval the item is remembered to have occurred in the  $i$ th position of the segment,  $\theta$  is the probability that a perturbation of item position information occurs during a reactivation, and  $\alpha$  is the probability that an item will be subject to the perturbation process (i.e. that a reactivation will occur). The exact form this equation depends on the number of items in the serial list. Equation 1 describes the perturbation process only for the middle two items of a four item segment since perturbation can occur in only one direction for the end items. The parameter  $\theta$  reflects task-specific conditions which affect the likelihood that the relative position of items are confused. For example, previous work has found that setting  $\theta$  to a value of .04 fits data obtained from 4 item

segments. If the number of items in a segment is increased, the probability of a perturbation of an item's position information might also increase. Healy et al. (1987) argue that the  $\alpha$  parameter is the secondary memory component of the model, and reflects probability that an item is encoded in secondary memory storage, and hence immune to the perturbation process. The model would account for the difficulty or effectiveness of distractor tasks that intervene between encoding and recall with this parameter. For example, If the subject is allowed continuous maintenance rehearsal the probability that any item presented on a trial would be subject to perturbation would be minimal. If a task of some difficulty intervened between encoding and retrieval, items would more likely be subject to perturbation. The  $\alpha$  parameter would reflect this by taking on larger values (approaching 1.0) for task conditions that effectively reduce or prevent continuous rehearsal.

The X-process described above specifies the probability that information regarding the serial position of an item will be retained. The probability of retaining information that an item occurred on trial  $t$  at the  $n+1$ th time interval,  $Z_{t,n+1}$ , is

$$Z_{t,n+1} = (1 - \alpha)Z_{t,0} + \alpha(1 - \theta_2)Z_{t,n}, \quad (2)$$

where  $\theta_2$  is trial perturbation probability. The probability that an item in position  $i$ , on trial  $t$  is correctly recalled is determined by the joint probability that the position of an item within a segment and the trial position information of the item have been retained,  $X_i Z_t$ . The following equation describes this probability:

$$P_{it} = X_i Z_t + (1 - Z_t)/G, \quad (3)$$

where  $(1 - Z_t)$  is the probability of perturbation on the trial level, and  $G$  is the number of

items per segment. The end term of the equation attempts represent guessing that results in chance recall (Healy et al. 1987).

An important starting point for application of this model to experimental data involves what rule is to be adopted that determines the number of times to apply the recursive functions. The rule that has been adopted in the past has lead to considerable success in fitting experimental data: apply two reactivations during the presentation of the recall prompt and during the presentation of each interpolated item. However, no reactivations occur within a segment (or experimentally defined “chunk”) until all items in that segment have been presented. This prevents an advantage for items occurring later in a segment and produces a symmetric, concave-upward serial position function (see Figure 1). The primary justification for this recursion rule is that it will produce a bowed, symmetrical recall function. Therefore, aside from the fact (albeit an important one) that this rule leads to an excellent fit to the data, it enjoys no theoretical preference.

Lee and Estes (1981) have reported the failure of the Perturbation model to account for data obtained in the absence of experimentally demarcated chunks. Though not invalidating the model, this finding does question whether it is stated in a general form. In order to apply the model to the data obtained from the present experiments, the previously used recursion rule was modified. The modified recursion rule assumed that a reactivation occurred upon presentation of every list item and upon each interpolated item. A variable number of reactivations at presentation of the recall probe was permitted depending on whether the probe was positional or associative. These modifications ensured that the advantage enjoyed by the end items have (in terms of perturbation occurring in only one direction) is reduced for the first item of the list compared to the last. Thus, the modified recursion rule will result in a graded serial

position function with greater recency than primacy effects (for probed recall). Further details on how the model was fitted to the data are provided in the Appendix.

Application of Perturbation Model. Figure 9 displays the observed and predicted serial position curves for 7 digit lists from Experiment 1. The model provides an excellent fit of the position probe data for both the copy-letter (panel A) and letter-after (panel B) distractor conditions, accounting for 94% and 98% of the variance in the data. The only parameter that varied across distractor conditions was  $\alpha$ , which was .945 for the copy-letter and .975 for the letter-after distractor conditions. The values for  $\theta$  and  $\theta_2$  were .03 and .01 for both distractor conditions, respectively. Therefore, the model could successfully account for the difference in distractor conditions by assuming the probability that a given item will be subjected to the perturbation process (i.e. transposition error) is higher for the difficult (letter-after) distractor condition than for the easy (copy-letter) condition. However, the model is less successful in predicting recall for the associative probes, accounting for 54% and 70% of the variance in the data for the copy-letter (panel B) and letter-after distractors (panel D), respectively. End positions are well predicted, but the model systematically overestimates recall for middle list items.

The same pattern of results was obtained for 8 item lists as evidenced in Figure 10. The only parameter to change was  $\theta$ , which was set to .04 for the 8 item lists. The model predicts relatively well position probe recall for both distractor conditions, accounting for 78% and 84% of variance in the data for copy-letter (panel A) and letter-after (panel C) conditions, respectively. Predictions were considerably less accurate for associative probe data, accounting for 66% and 53% of variance in the data for copy-letter and letter-after conditions, respectively. Inspection of Figure 10

Figure 9. Observed proportion of digits correctly recalled (open circles) as function of serial position and model-based predictions (closed circles) for 7 digit lists. Panels A and B present the data from the 'copy letter' distractor for position and associative probes, respectively. Panels C and D present the same data for 'letter after' distractor condition. Data from Experiment 1.

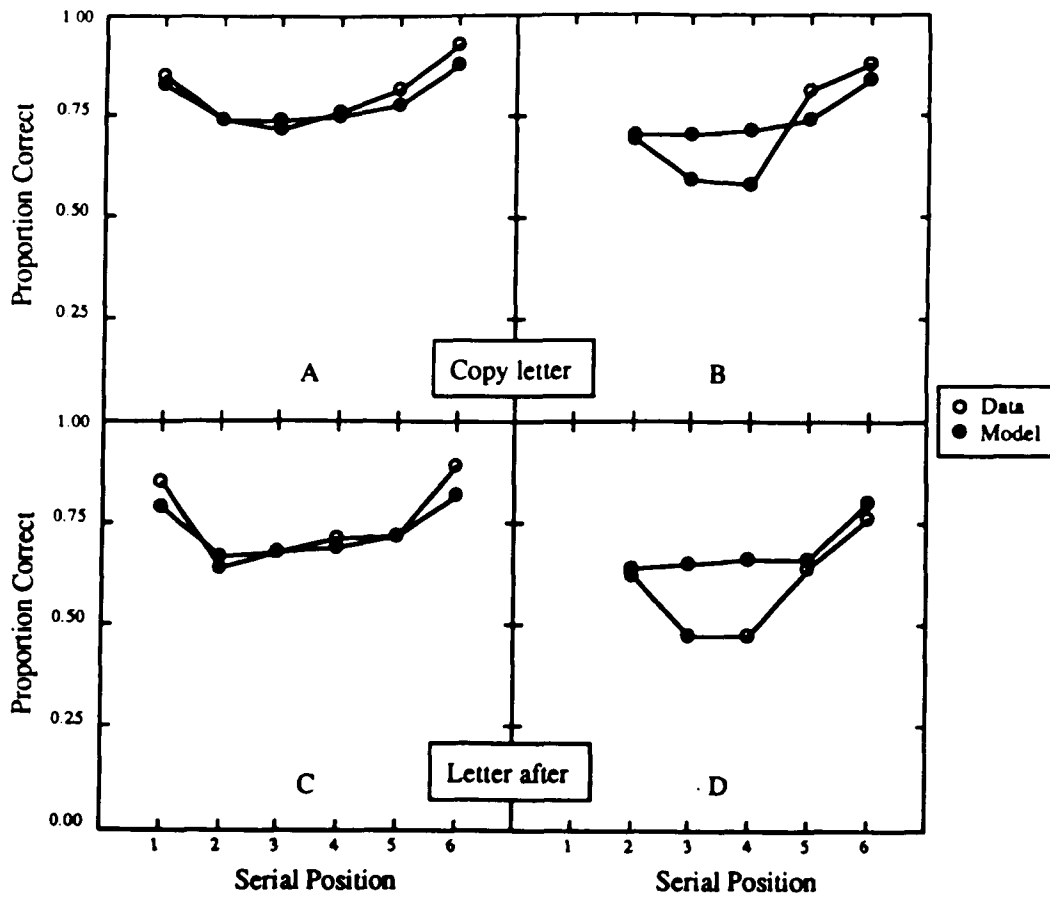
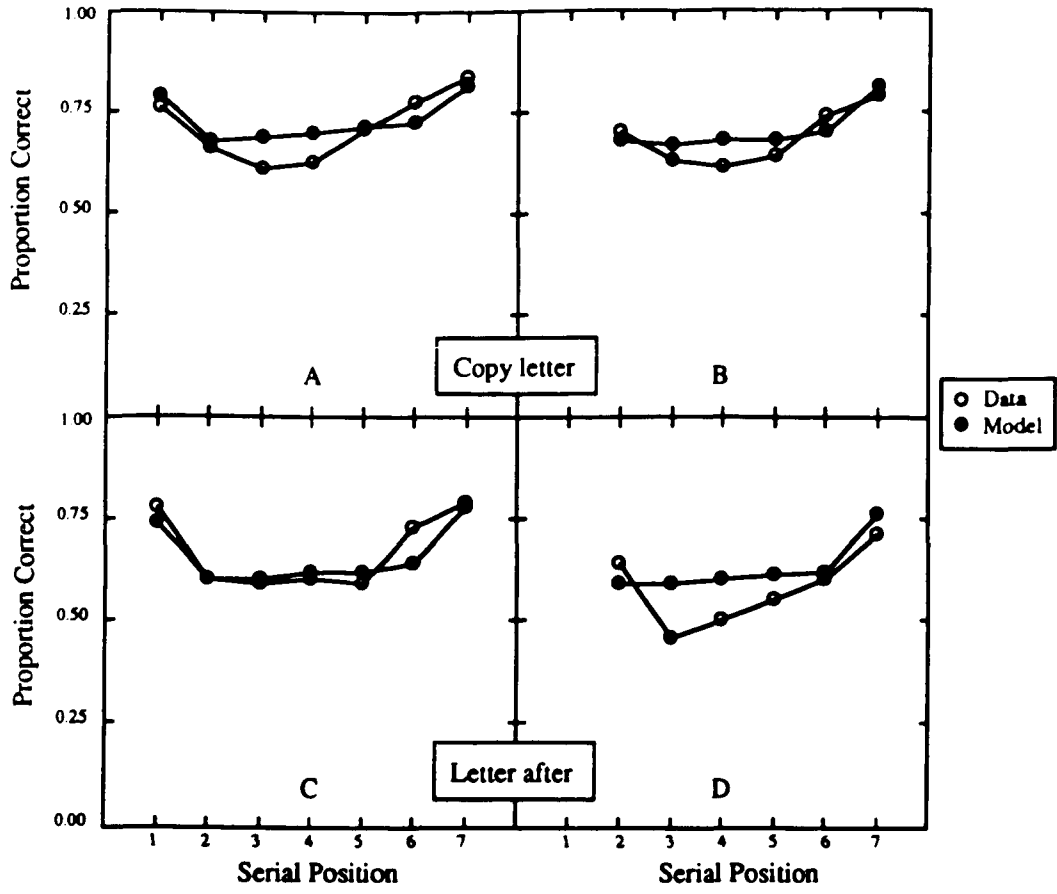


Figure 10. Observed proportion of digits correctly recalled (open circles) and model-based predictions (closed circles) as function of serial position for 8 digits lists. Panels A and B present the data from the 'copy letter' distractor for position and associative probes, respectively. Panels C and D present the same data for 'letter after' distractor condition. Data from Experiment 1.

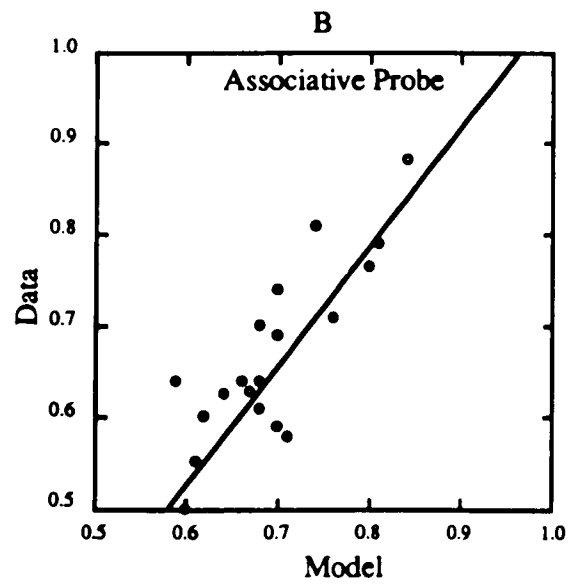
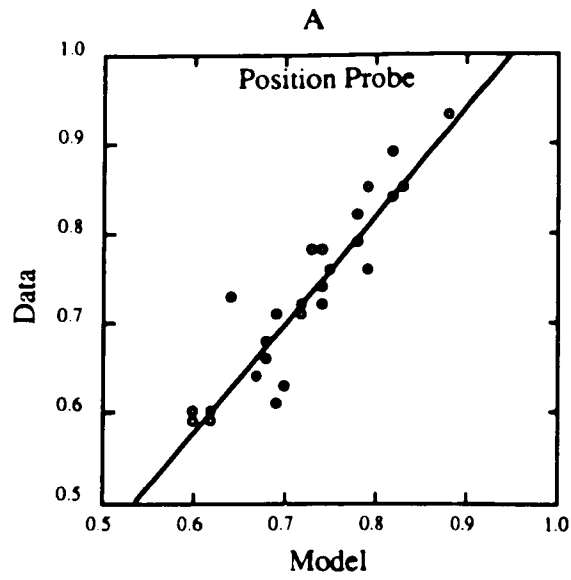


indicates that, as for the shorter list, model estimates are accurate for the end items but overestimate observed performance for the middle positions.

The model's success in predicting recall under the various experimental conditions and probe types is summarized in Figure 11. Observed recall for all 4 experimental conditions (7 and 8 item lists; copy-letter and letter-after distractors) is plotted against the model's predictions for position probes (panel A) and associative probes (panel B). The fitted line in both plots represents the regression of observed recall on predicted recall for each serial position. If model predictions were accurate and unbiased (i.e. differed from observed data only by random error), the regression of observed on predicted recall would have an intercept of 0 and a slope equal to 1. The regression for the position probe data approximates these conditions relatively well, although the intercept is slightly negative (int=-.16, slope=1.2), with the model's predictions accounting for 86% of the variance in the data. However, bias in the model's predictions of associative probe recall is clearly evident, with the model overestimating recall, especially for the letter-after distractor conditions where recall was poorest (int=-.26, slope=1.4), with the model's predictions accounting for only 66% of the variance in the data.

The perturbation model successfully predicts serial position curves for position probed recall, indicating that the revised recursion rule allows the model to be extended to describe serial position functions of more than four positions. However, accuracy was substantially better for 7 as compared with 8 digit lists. Also, the model can account for the effect of an intervening distractor task as altering the likelihood that information reaches secondary memory (i.e. the value of  $\alpha$ ), as opposed to changing the probability that items are transposed (i.e. the value of  $\theta$ ). However, the model has

Figure 11. Summary of model fits for the aggregated data from Experiment 1. Observed proportion correct is plotted against the model's predictions for each serial position, list length and distractor condition for position (panel A) and associative (panel B) probes. The fitted line represents the regression of observed data on the model's predictions.



considerably less success in predicting associatively probed recall by assuming that more reactivations occur upon presentation of the associative probe as compared with the position probe.

Figures 12–15 display the fit of the model to the individuals' data from Experiment 2. The model performed adequately in predicting serial position curves for position probed recall for the individuals (top graphs for Figures 12-15). There appeared to be little difference in the model's success as a function of list size, performing equivalently for list lengths of 7 and 8 digits. However the model failed to predict performance following the associative probe (panels C and D for Figures 12–15). The number of probe related reactivations was in some cases increased to 20 (10 times that for position probes), but the model still overestimated performance. This finding suggests that the perturbation model cannot account for recall differences due to probe type simply by increasing the number of probe related reactivations.

One evident failing of model in predicting position probe recall is the systematic overestimation of recall for middle position items and underestimation of the recency effect (see in particular Figures 12 and 13). This bias can be summarized by plotting the observed data against the models predictions for each subject together in one plot. If predictions were accurate and unbiased, the point should fall along a regression line that has a slope of 1 and intercept of 0. The amount of variance in the data accounted for by the predictions would likewise summarize the model's accuracy for predicting individuals' performance. Figure 16 displays these plots for position and associative probe recall. For position probe recall, predictions are accurate for the majority of the data, but are biased in the direction of overestimating low values. This is reflected in an intercept that is significantly different from 0 ( $int = -.27, p < .01$ ) and a slope that is

Figure 12. Subject # 1 observed proportion of digits correctly recalled (open squares) and model-based predictions (closed squares) as function of serial position for position and associative probes. Data from 7 digits lists are displayed on the left and data from 8 digit lists on the right. Data from Experiment 2.

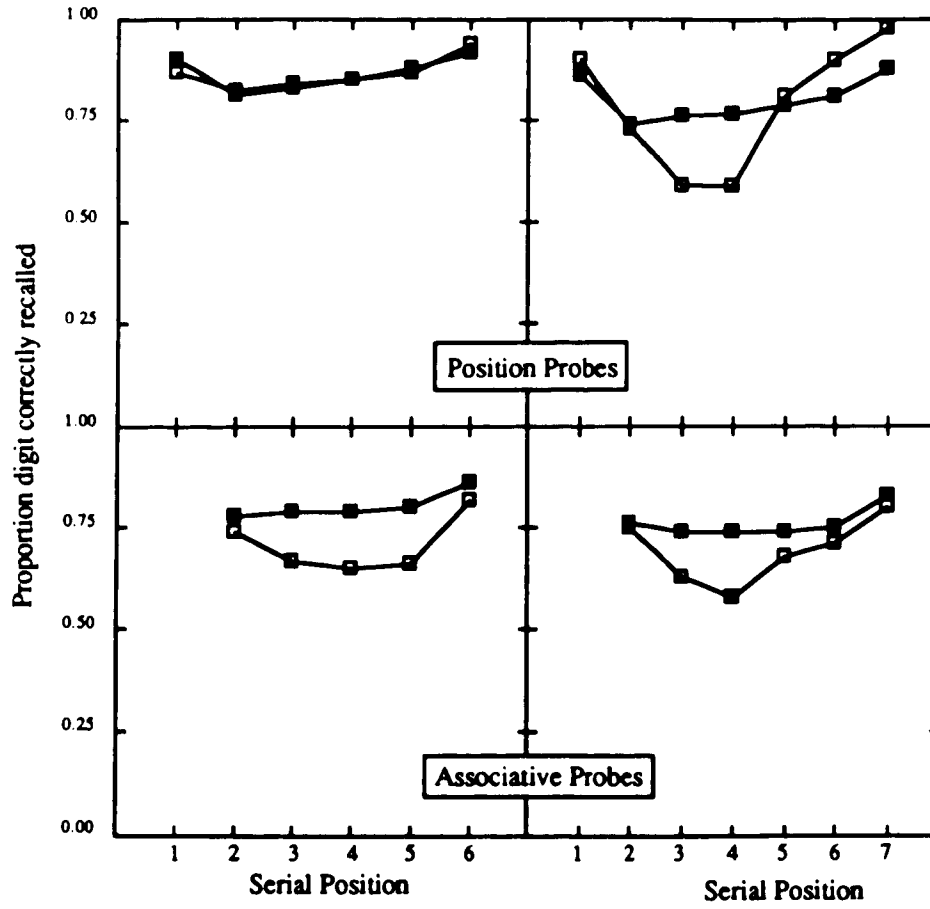


Figure 13. Subject # 2 observed proportion of digits correctly recalled (open squares) and model-based predictions (closed squares) as function of serial position for position and associative probes. Data from 7 digits lists are displayed on the left and data from 8 digit lists on the right. Data from Experiment 2.

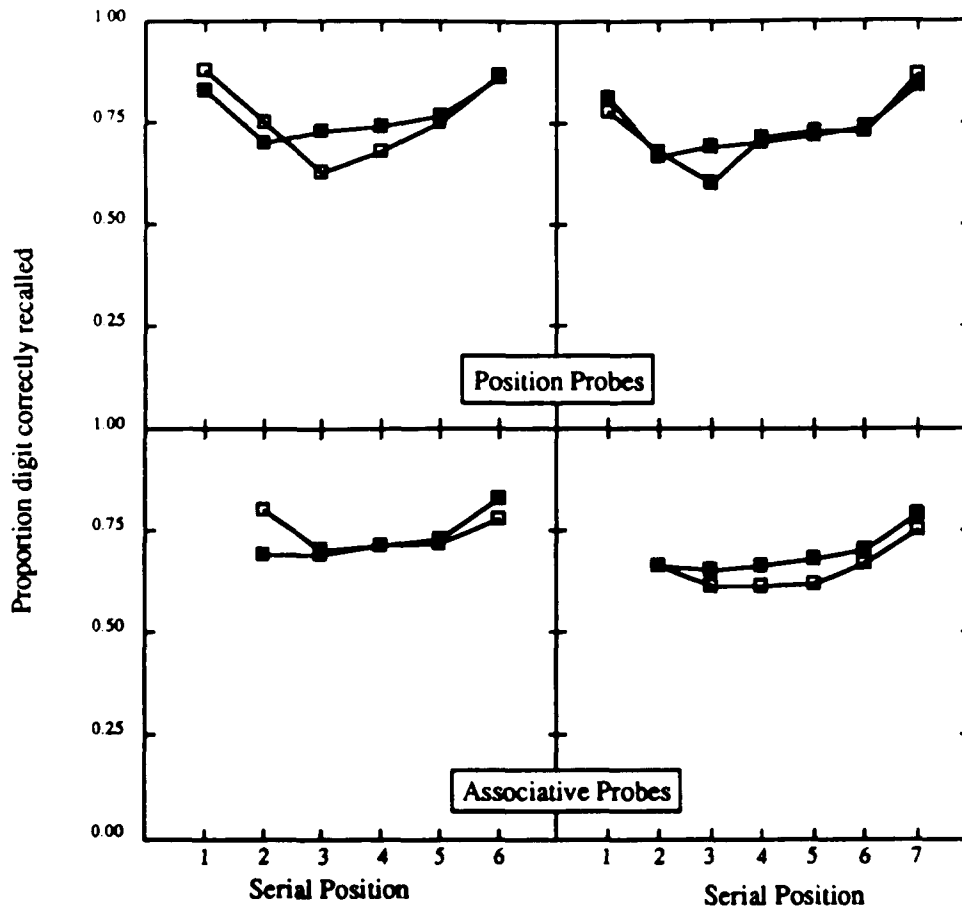


Figure 14. Subject # 3 observed proportion of digits correctly recalled (open squares) and model-based predictions (closed squares) as function of serial position for position and associative probes. Data from 7 digits lists are displayed on the left and data from 8 digit lists on the right. Data from Experiment 2.

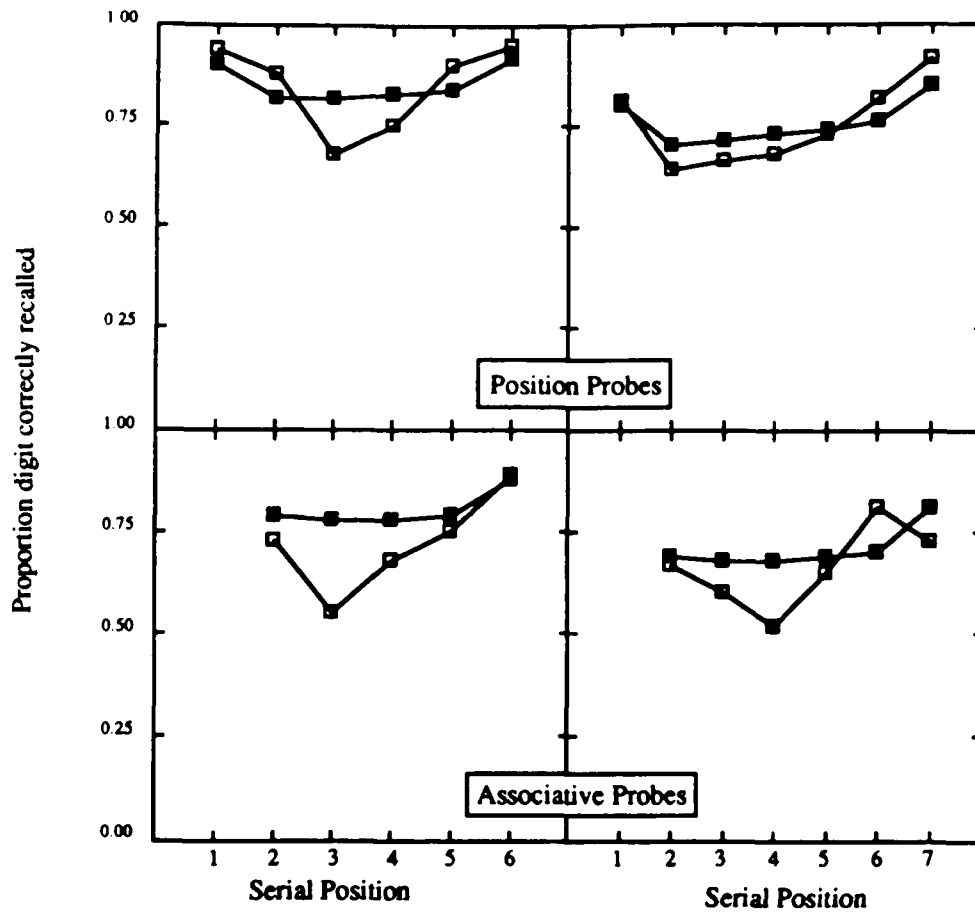


Figure 15. Subject # 4 observed proportion of digits correctly recalled (open squares) and model-based predictions (closed squares) as function of serial position for position and associative probes. Data from 7 digits lists are displayed on the left and data from 8 digit lists on the right. Data from Experiment 2.

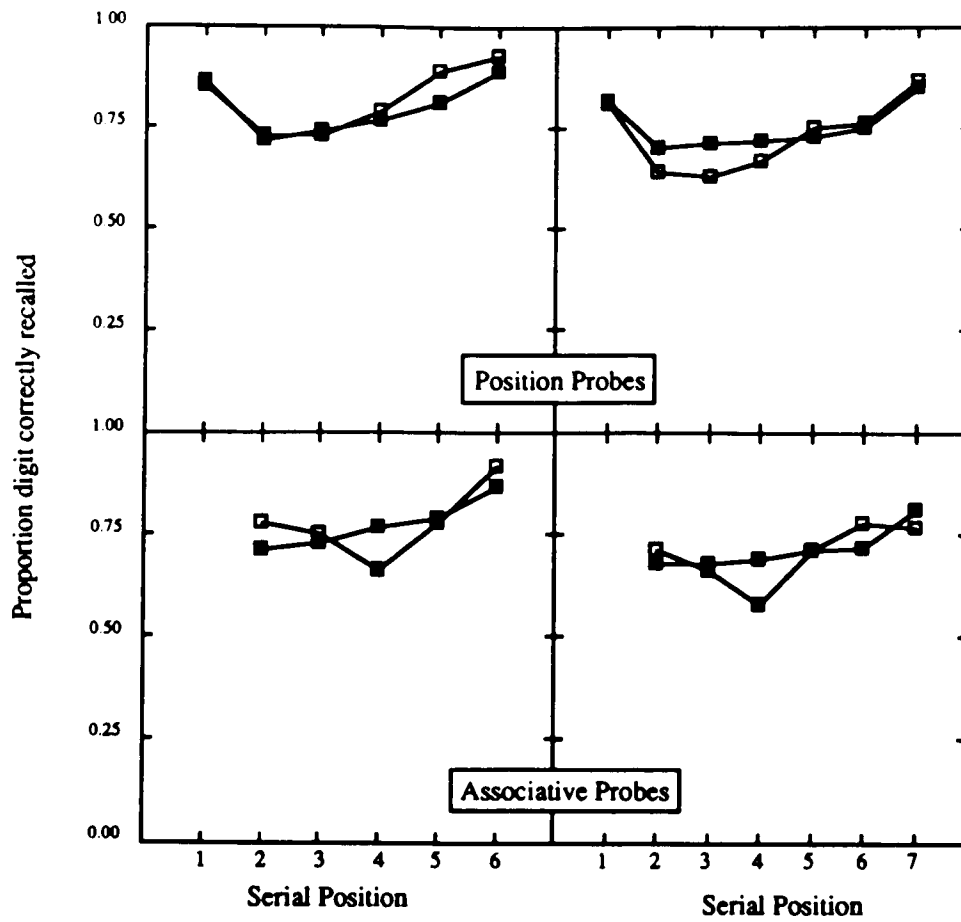
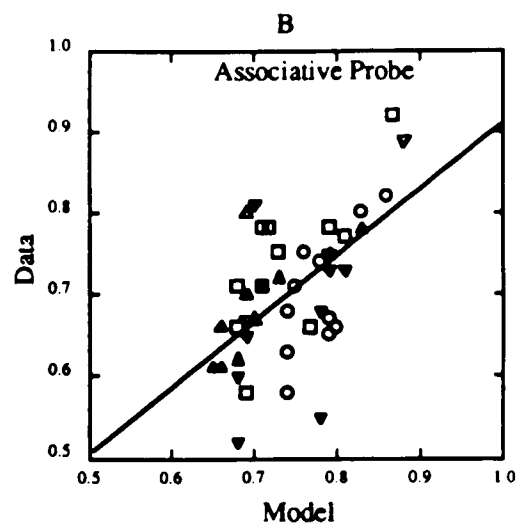
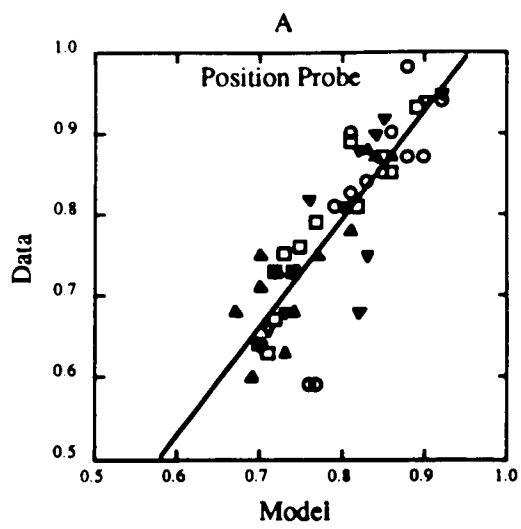


Figure 16. Summary of model fits for the individual subject's data from Experiment 2. Observed proportion correct is plotted against the model's predictions for each serial position and list length for position (panel A) and associative (panel B) probes. The fitted line represents the regression of observed data on the model's predictions. (Symbols: ▲=Subject #1; ▼=Subject #2; □=Subject #3; ○=Subject #4)



significantly greater than 1 (slope=1.3,  $p < .01$ ). The overall accuracy of the model as assessed by the percent of explained variance was low (72%). The failure of the model to predict associative probe recall is clearly evident in the right graph of Figure 16. Only 34% percent of the variance in the data was accounted for by the model predictions.

Evaluation of model fit. The explanatory power of the Perturbation model in accounting for the serial position curve under a variety of conditions was examined. When applied to the aggregated data from Experiment 1, the model captured the general pattern of probed serial order recall for position probes. The model could also account for the effect of distractor difficulty by altering the likelihood that information could reach a more stable store in secondary memory (Healy et al., 1987). This was modeled by increasing the value of  $\alpha$  for the difficult distractor, increasing the probability that a reactivation would take place, exposing the item to a perturbation. Estes originally proposed  $\alpha$  as the 'long-term memory' component of the model, since it was thought that items reaching long-term memory would be immune to the perturbation process described by the model. However, another interpretation is possible. If no distractor task intervenes stimulus presentation and retrieval, an individual could execute a control process, such as maintenance rehearsal, to avoid the loss of any order or item information. A simple distractor task might be partially effective in preventing such control processes, while an extremely difficult distractor task might completely prevent such maintenance. Within the context of the perturbation model, such controlled maintenance would protect information from the perturbation process just as would storage in secondary memory. Distractor difficulty could then be viewed as one factor that affects the probability that reactivations occur which introduce error into the encoding of items.

The model failed to predict the differences in serial order recall due to the type of probe presented. As it is currently formulated, the model cannot account for probe differences only by adjusting the number of probe related reactivations; it consistently overestimates recall following associative probes. The observed pattern of overestimating associatively probed recall is consistent with the notion that the Perturbation model does not represent the process by which associative information is transformed into position codes. This inability of the model to predict associative probed recall does not necessarily indicate a failure of the Perturbation model to account for serial order recall. Rather, it specifies a limitation of the model and points out the possibility that processes external to short-term memory are responsible for the translation of associative into position codes.

The perturbation model fits the aggregated recall data for position probes from Experiment 1 relatively well, accounting for 86% of the variance in the data. Since this model seeks to explain the mechanism underlying memory, the ultimate test is to determine how well it can predict recall performance of individuals. Assessing how well a theory predicts the performance of individuals is the best test for virtually any memory theory, however, most do not permit such tests since many theories cannot provide point predictions. Testing theory based predictions on individual subjects' data is essential, since a theory of must be able to accommodate variations in performance across individuals if it is to be informative at the level of individual functioning. That is, a theory may be framed such that it can predict the average performance of many individuals, but cannot adequately model the performance of single individuals whose data contribute to that average.

When the perturbation model was fitted to the recall data from individual subjects, overall accuracy was somewhat poorer than when it was fit to group means, accounting for only 72% of the variance in the individual's data (compared with 86% for the group means). This finding taken by itself could simply indicate that there is more noise in the individual subjects' data than in the aggregated data. If the poorer fit to the individual's data were attributable to noise (i.e. random error) alone, then the regression of observed on model predicted values would have a slope of 1 and intercept of 0. That is, the value of observed data points would deviate from prediction randomly and would not show any systematic bias. The results from fitting the aggregated data approximated these conditions, but showed some indication of bias in the direction of overestimating recall of middle position items. Applying the model to the data of individual subjects revealed this bias more clearly. Compare the position probe plot in Figure 11 with that of Figure 16 and the greater bias (overestimation of low recall probabilities) for the individual subject fits is evident. Therefore, noisy data does not explain inaccurate prediction of the model for the individual subjects serial position curves. It appears that the Perturbation model did not capture some important features of serial order memory, at least when it was applied to the data of individuals.

## General Discussion

These experiments examined several factors that underlie short-term memory for serial order. Typical serial position curves were observed for all probe types, for two levels of distractor difficulty and for two list lengths. This was the case for aggregated data obtained from young subjects, aged subjects and for data obtained from individual subjects. This finding suggests the presence of a basic process or mechanism inherent in short-term memory that is robust across specific experimental manipulations.

Although there was evidence of a common process operating across all the experimental conditions, important differences among the recall probes were also observed. While the comparison of serial position curves from the probed recall of order and item information did not reveal any significant differences, there was a considerable difference in recall accuracy. This difference between recall accuracy of item and order information was exaggerated in the aged, suggesting a specific impairment of memory for order in aged. Consistent with previous findings, positional codes were found to be more basic than associative codes for serial order memory. However, there was some indication that additional encoding operations came into play for the long stimulus lists. Application of a quantitative model which relies on positional coding of serial order met with mixed success. The model fit the serial position data from the positional probe well, especially for the short stimulus list. However, the model had difficulty predicting recall for associative probes and the long stimulus lists, providing a further indication that there are important aspects of serial order memory not captured by an exclusively positional account.

Positional vs. Associative encoding. These experiments confirmed the findings of previous research (e.g. Bower, 1971; Bjork & Whitten, 1974; Baddeley & Hitch, 1977) that short-term memory for serial order depends largely on positional information. Recall following positional probes was higher than recall following associative probes when performance was collapsed across experimental conditions. If positional information is indeed basic to the representation of serial order, then it is likely that associative cues would need to be transformed into position codes in order to effectively cue recall. Since it is also likely that such a transformation would require the expenditure of processing resources, the prediction was made that associatively probed recall would suffer under a difficult distractor condition to a greater extent than would positionally probed recall. However, this expected probe x distractor interaction was not observed. Evidence was also obtained to suggest that the advantage of positional cues over associative cues was diminished for the long stimulus lists.

These latter two findings are counter-intuitive if one adopts the view that memory for serial order is represented exclusively by positional codes. Such a view would predict that positional cues would not only be more effective than associative cues, but would be increasingly advantageous in conditions of increased task difficulty (as was the case for the letter-after distractor and longer stimulus list conditions in the present experiments). The present findings clearly do not support this view. An alternative interpretation is one that emphasizes flexibility in adopting strategies for encoding serial order information in short-term memory. It is possible that for short stimulus lists positional information is more relevant to the encoding of serial order, while for long lists associative information is more important. This possibility can be addressed by the present experiments only with respect to list length, since list length was the only dimension on which the stimuli were varied (but only over two lengths).

Therefore, it is important to examine whether there is any theoretical basis for expecting positional codes to be more effective for encoding short lists than long lists.

There is evidence from the present experiments that a positional theory of serial order met with less success for long stimulus lists. The perturbation model was fitted to the data obtained from the present experiments. To review, this model assumes that information regarding serial order is represented through the encoding of list items by their linkage to ordinal positions. When applied to data from short lists, the model was able to predict with a high degree of accuracy the serial position curves for positionally probed recall of the short stimulus lists. However, the model fit to data from the long stimulus lists was considerably worse. This pattern of results describes both the aggregated data from Experiment 1 and the individual subjects' data from Experiment 2. A previous study offers additional support for these findings. Lee and Estes (1977) examined the ability of an early version of the perturbation model to account for recall of serial order. The experimental procedure often used to study this model involves the presentation of an eight item list that is separated into a pair of four item chunks. Lee and Estes (1977) found that their model could not be applied to data generated from an experimental condition in which a long stimulus list (12 items) was not separated into smaller chunks. They argued that the model could not be applied to data generated from experimental conditions in which the subjects' chunking of the stimulus list was uncontrolled. That is, if the size of a subject's chunk is unknown, then it is impossible to know the ordinal position occupied by a given list item for that subject. Only if the stimuli are limited to a manageable number can they be associated with well-defined ordinal positions.

The present experiments are limited in that only two list lengths are examined. However, there are both theoretical and empirical considerations to suggest that it becomes increasingly difficult to encode items in terms of their ordinal positions as list size increases. The example was provided earlier of how reporting the 14th letter in the alphabet is more difficult than reporting the letter following 'm'. Another possibility why positional cues are less effective for long lists is that long lists might not be represented as a single structure in short-term memory. If a list is too long to be represented in short-term memory as a single structure, the ordinal positions lose their original referents. For example, if a subject were presented with a 12 item list, but could only maintain a chunk of seven elements (e.g. Miller, 1956), the 10th item in the list might not be associated with the 10th ordinal position. Instead, the subject might encode the 10th item as occupying the third position of the second segment or chunk. This raises the possibility that another encoding mechanism comes into play for longer lists, since positional encoding becomes less efficient as the length of the stimulus lists increases. While there may be many possible encoding mechanisms, the use of associative codes and chunking are two likely candidates. Associative encoding may play a more important role in representing serial order as list size increases. The present results indicating that the advantage of positional cues over associative cues may diminish for the long lists are consistent with this view. Individual differences in chunking strategies would also become an important factor in explaining serial order memory for long stimulus lists.

The present experiments cannot resolve whether the decreased effectiveness of positional cues for the retrieval of serial order is joined by a concomitant increase in the importance of another encoding mechanism. However, the findings reported suggest that a factor (or factors) other than positional codes become more involved in the

encoding of serial order as list length increases. Individual differences in mnemonic strategies is one consideration that has not received adequate attention in theoretical accounts of serial order memory. As the size of the list increases beyond span length, subjects may adopt encoding strategies that are not used (or required) to encode shorter lists. Previous research has established that individuals “chunk” information differently, depending on factors such as experience, information in long-term memory, and the structure of the stimuli (Simon, 1974; Simon & Chase, 1973). The results from the present experiments indicate that theoretical accounts of serial order memory should address the use of encoding strategies as well the more basic encoding mechanisms.

Serial order effects for item and order memory. Previous studies have suggested a disassociation between memory for item and memory for order information. The major evidence for this proposed disassociation has been differential serial position curves for item and order memory. Bowed-shaped recall functions have been obtained for recall of order information, but flat functions have been found for recall of item information (e.g. Healy & Bjork, 1974; Healy, 1975; Hitch, 1974). The results of the present experiments are in contrast to those previously reported in that similar serial position curves were observed for the item and order probes. The finding that the missing scan probe (i.e. the item probe) produces a bowed serial position curves is not new (Buschke, 1963a; Hadley et al., 1992), but the functions thus obtained had never been directly compared to those obtained from a comparable probe of memory for order.

The present results indicating that the serial position curves for item and order memory do not differ when comparable probes are used to cue recall indicates that

previous findings may reflect the method used to assess item memory, rather than any fundamental characteristic of the underlying phenomenon. It is important to note that the missing scan procedure is not the only method for demonstrating serial position effects for the retention of item information. Bowed serial position functions have been observed for free recall (Murdock, 1962; Postman & Phillips, 1965); these findings provide another demonstration that memory for content can display characteristic serial position curves. It was previously argued that the flat serial position functions that have been reported for item memory may be due to methodological limitations of previous studies (Bjork & Healy, 1974; Healy, 1974; Hitch, 1974). Specifically, the guessing rates are typically much higher for item recall than for order recall. A common feature of the missing scan and free recall procedures is the low guessing rate. The fact that procedures which are not hampered by high guessing rates produce bowed serial position functions strongly suggests that flat serial position curves for item memory are largely due to limitations in the procedures used to measure item retention.

Whereas the serial position data emphasize a fundamental similarity between recall of item and order information, the overall accuracy of recall underscores an important difference. Recall accuracy for item information was uniformly better than recall for order information as measured by either positional or associative probes. Although this finding is hardly surprising, many previous studies have not compared item and order recall under comparable conditions. Buschke (1963a) reported that digit span measured by the missing scan probe is longer than when measured by serial recall. However, as Buschke argued, the missing scan probe reduces output interference by requiring a single response. Therefore, the observed difference between the missing scan probe and serial recall could be attributed to output interference. Other comparisons of item and order recall have used two scorings of the items recalled to

separate memory for item and order information (Bjork & Healy, 1974; Hitch, 1974). Such procedures which rely on order-based and order-free scoring of serial recall necessitate that recall of item information be higher than (or at least equal to) recall of order information. When memory for item and order information were separated experimentally (e.g. Healy, 1974), the guessing rates were usually much higher for item recall than for order recall, which complicated comparisons of recall accuracy between the two. By using probes which required a single response to measure either item or order recall, the present study attempted to avoid complications which might arise from output interference and differential guessing rates.

Following the reasoning used to evaluate the relative importance of positional and associative codes, better recall following item probes may indicate that memory for item information is more basic than memory for order information. This possibility has face validity, since the order in which an item occurred can be forgotten without forgetting that it occurred. The present findings of similar serial position curves combined with overall higher accuracy for item compared to order recall place certain constraints on theories of short-term memory. There is evidence that, at a fundamental level, parallel mechanisms produce the serial position effect for both item and order memory. That is, the processes involved in generating the serial position effect are not inherent to memory for order, but are fundamental to short-term memory for both content and order information. Conversely, the absence of a serial position effect is not intrinsic to memory for item information, as has been previously conjectured (e.g. Bjork & Healy, 1974; Healy, 1974). Therefore, instead of addressing only order recall, theoretical accounts of the serial position effect should apply to recall of both item and order information.

Age differences in serial order memory. Parkinson (1982) has observed that digit span tasks are the most common measure of memory capacity. He argues that there are small, but reliable differences between the digit span of young and aged adults. The data from Experiment 3 also demonstrated that young subjects have a slightly longer digit span than aged subjects. This experiment controlled for storage differences by using each subject's digit span to determine the list lengths on which that subject was tested. If this control was successful, then age differences in processing capacity that are uncontaminated by differences in storage capacity could be studied. Equivalent recall of item information in the young and aged indicated that this control was effective. The aged subjects exhibited a deficit in the recall of order information compared to the young. This differential impairment of order recall in the aged was taken as evidence of an age related decline in processing capacity, since differences in storage capacity were not operative. However, the failure to detect any age x distractor or age x list size interaction suggests that the nature of this age related processing deficit is quite specific recall following order probes.

Craik and Byrd (1982) have argued that age related performance decrements are due to a general deficiency in processing resources in the aged. This theoretical viewpoint would predict age related interactions with any variable that affects performance, since a general deficit in processing resources should exacerbate any type of difficulty (Gick et al., 1988). However, recent studies have demonstrated that age related interactions occur with some but not all variables known to affect working memory (Foos, 1989; Gick et al., 1988; Morris et al., 1988). The present results are consistent with the view that not all forms of task difficulty have equivalent effects on working memory. Such a view demands an understanding of the processes that underlie the tasks used to study age differences in working memory.

In order to explain the age x probe interaction, the processing differences between memory for item and order information must be examined. An impairment at the level of encoding for the aged is one possible explanation for their poorer recall of order information. Previous research has established that aged individuals tend not to encode stimuli as thoroughly as young adults (e.g. Grober & Buschke, 1986). Although both item and order memory require the encoding of contextual information, order memory requires a more fine-grained appreciation of context than does item memory. Estes' perturbation model captures this by assuming multiple levels of encoding. At the highest level of abstraction, information regarding the trial in which a particular item occurred is encoded. This level of encoding would be responsible for item memory. At the lowest level, information regarding the position of items within a particular trial is encoded; order memory is determined at this level of encoding. Once encoded, trial and position information are continuously updated, and with each update there is a probability that information regarding the relative positions of items (and trials) will be re-encoded incorrectly. Previous discussions of this model have assumed that information at both levels (i.e. trial and position) is **initially** encoded without error. Perhaps this assumption approximates the truth well for young adults, but does not apply to the aged. Aged individuals might initially encode order information less accurately than young individuals resulting in their poorer recall of serial order. This possibility could be tested experimentally by devising a procedure that would ensure adequate encoding on the part of aged and young (control) subjects (Buschke, 1984; 1987). If such a procedure could ameliorate the aged's deficit in order memory, then an impairment in encoding would be indicated. However, if the aged's deficit in order recall persisted, then an impairment in maintenance or retrieval would be suggested.

At a broader level, the present finding that the aged are impaired in order recall relative to the young suggests some important disassociation between the processes required for item and order recall. The involvement of two encoding mechanisms has already been discussed as one possible difference between item and order memory. Another explanation is that maintenance and retrieval of order information requires more cognitive 'effort' than is needed for item information. The suggestion that these processes might differ in terms of the amount of cognitive activity they require is consistent with the account of Gick et al. (1988). They presented the argument that aged individuals have difficulties with the ongoing active processing that certain tasks demand (e.g. sentence span), but have an easier time with the passive holding of information in short-term memory. This viewpoint is consistent with that of Craik (1984), which asserted a differential effect of aging on memory tasks that require active processing and manipulation of information. It has become increasingly clear, from the present findings and those of others (Foos, 1989; Gick et al., 1988; Morris et al., 1988), that age effects are quite specific and do not produce a generalized impairment in all types of processing which demand the expenditure of cognitive resources.

Explaining age differences in terms of the deficits in cognitive resources has become quite popular (e.g. Gick et al. 1988; Morris et al. 1988; Foos, 1989; Light, Zelinski, & Moore, 1982). However, it is unclear what different investigators mean by terms such as 'effort' and 'resources' in this context. Typically, such terms are defined by performance on specific tasks. For example, task manipulations that produce a decrement in performance are, for that reason alone, often assumed to require more cognitive effort. Also, subject groups that exhibit performance deficits are assumed to have diminished processing resources. Thus, using the term "processing capacity" to explain performance differences is often theoretically uninformative. For constructs

such as processing capacity to become informative, they must be linked to specific cognitive processes involved in the performance of specific tasks (e.g. the encoding order information). Ultimately the understanding of age differences in memory for serial order will require an understanding of the mechanisms underlying performance on serial order tasks. Therefore, the analysis of age associated impairments in working memory should proceed in parallel with the study of the processes that are basic to the experimental tasks we use.

The results discussed above suggest that there are important features of serial order memory that cannot be accommodated by the positional encoding account. Theories should allow for the possibility that a variety of encoding operations and strategies could be involved in memory for serial order, instead of assuming that only one type of encoding process is involved (e.g. positional or associative coding). The distinction between memory for item and order information has not been appreciated by many investigators who study age related memory impairment (but see Dannenbaum et al., 1988). The present demonstration of an age related deficit specific to the recall of order information suggests possible directions for future studies of age effects that could enhance our theoretical understanding of both cognitive functioning and aging. Specifically, it would be of great interest to identify the cognitive operations that could explain the difficulty aged subjects have in recalling order information relative to recalling item information. The findings from the present experiments indicate that the study of serial order memory can serve two purposes. First, the study of serial order memory provides a potentially useful means by which to further our knowledge of basic cognitive mechanisms, such as encoding. And second, the study of serial order effects can provide a framework for understanding the changes in those mechanisms

that occur with advanced age. Thus, research on serial order memory can inform theoretical development in diverse topic areas important to cognitive psychology.

## Appendix

The following theory-based constraints were made when setting parameter values: (1) values for  $\theta$  must be constant across probe and distractor type for a given list size; (2) for data from Experiment 1, only the  $\alpha$  parameter could vary across distractor type; (3) the value for  $\theta_2$  was held constant, since there was no a priori reason to expect the experimental manipulations to differentially affect this parameter; and (4) the number of reactivations for each probe type must remain fixed across both list sizes and, for Experiment 1, across both distractor conditions. The aggregated data from Experiment 1 were modelled first and the obtained parameter values were used as starting values for modelling the individual subject's data from the second experiment. The 'best-fitting' parameter values were set to minimize the average squared residual discrepancies between the data and predicted values. Parameter values were set to fit the data from the position probe and only the number of reactivations occurring at probe presentation was allowed to vary for fitting the associative probe data. The adequacy of the fit was evaluated by visual inspection of the model based predictions plotted with the observed data and by the amount of variance in the observed data accounted for by the model.

Though different in form, the perturbation model is similar to other theories of memory that specify and describe underlying mechanisms. All such theories are framed to explain the mechanisms that produce performance of individual persons, even though they are rarely tested at that level. Since the model has never been used to predict individual's performance, the constraints on setting parameter values specified above were relaxed in order to determine if the model is flexible enough to capture the

variability in performance across individuals. That is, patterns of **average performance** may not be representative of the majority of individuals, and it therefore important to assess the model's ability accommodate this possibility. Consequently, when applying the model to individual subject's data, all parameters were permitted to vary in order to attain an optimal fit. The one constraint held in place was that the difference in recall performance attributable to probe type (i.e. positional vs. associative) could be modelled only by varying the number of probe-related reactivations.

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