Short- and Long-Term Memory Retrieval:
A Comparison of the Effects of Information Load and Relatedness[1]

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Abstract

The separate application of the Sternberg and fact-retrieval paradigms promotes a view that short- and long-term memory are functionally distinct. However, effects of information load and relatedness, observed in both paradigms, support a more unified approach to memory retrieval. The two experiments of this article enable a direct comparison of these effects as observed in a fact-retrieval task, a Sternberg task, and a hybrid precueing task. These experiments are motivated by an associative approach in which performance in all tasks is seen to depend upon a parallel search driven by spreading activation. Decision time data are explained in an *indirect-pathway model* with two important features: 1. *Pre-trial activation levels* of areas in memory can vary to reflect differences between short-term and long-term retrieval. 2. For related material, decisions can be based upon *indirect pathways* that connect the elements of a test probe through pre-experimental associations in memory.

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Introduction

This article describes an attempt to better understand the relationship between retrieval from long-term memory and retrieval from short-term memory. Towards this end, we compare the fact-retrieval paradigm (Anderson, 1976, 1983), which has been used to study long-term memory retrieval, with the Sternberg paradigm (Sternberg 1967, 1969, 1975) which has been used to study short-term memory retrieval. The separate application of these paradigms has reinforced a viewpoint that short- and long-term memory retrieval are functionally distinct. In opposition to this viewpoint, evidence is presented in this article that supports a more unified treatment of memory retrieval. Two experiments are described that enable a direct comparison of performance in a Sternberg task, a fact-retrieval task, and an intermediate precueing task. An *indirect-pathway model* of memory retrieval is advanced to explain these experimental results and a wide range of data arising from experiments in memory retrieval. First, we set the stage by considering effects of information load and relatedness that have been elicited in both the Sternberg and fact-retrieval paradigms.

The fact-retrieval paradigm

In a typical fact-retrieval experiment, a subject might memorize a set of pairings between subject words and predicates (e.g., "John went to college"). The experiment might involve manipulations in *fan* such that the number of pairings (e.g.,"facts") containing a given subject word or predicate is systematically varied. In a speeded recognition test, the subject must distinguish between these pairing and new pairings (often involving these same subject words and predicates).[3] Across a wide range of experiments in the fact-retrieval paradigm, the time to reach a decision regarding a test probe has been found to increase with the fan from each element in the test probe (see Anderson, 1976, chapter 8, for a review). Given a subject-predicate test probe, for example, decision time will increase with the number of predicates associated to the subject word of the probe and with the number of subject words associated to the predicate of the probe.

At a general level, these results indicate that the time to make a decision increases with the amount of information that must be considered or is potentially relevant. The results are consistent with an associative approach wherein retrieval is accomplished through a process of spreading activation. In the fact-retrieval task, activation spreads from nodes in memory corresponding to each element of a presented test probe. This activation tends to converge upon a connecting pathway, if it exists. Once this pathway reaches some threshold of activation, it becomes available for inspection. Fan effects are observed because the activation leaving a node must be partitioned among each of its associations. As a consequence, increases in the fan of a node generally result in a reduction of the activation spreading to a connecting pathway.

A serious limitation of this basic model lies in its inability to accommodate the reductions in fan effect that are often observed when the relevant information is related in some manner. In the fact-retrieval task, fan effects have been reduced through the use of semantic categorical relationships (McCloskey and Bigler, 1980) and thematic relationships (Moeser, 1979; Reder and Anderson, 1980; Reder and Ross, 1983; Smith, Adams and Schorr, 1978). In the Reder and Anderson (1980) studies, for example, there was virtually no effect on decision time for the number of facts associated to a fictitious person when these facts were related (e.g., "Steven called to have a phone installed", "Steven unpacked all of his boxes", "Steven mailed out change of address cards") and foils were unrelated (e.g., "Steven wanted to major in psychology").

Reder and Anderson (1980) explained these relatedness effects by postulating the existence of experimentally created subnodes for related material (e.g., "moving activities"). Decisions can sometimes be made at the subnode level without having to consider individual facts. The subnode approach thus addresses an important reality of information processing. In our judgment of a statement's truth it is apparent that we are not limited to a direct retrieval of that statement's representation in memory.

Instead, we can often make an accurate judgment based upon the retrieval of related information. It has been argued that the formation of such *plausibility judgments* is actually the preferred strategy in most circumstances (Reder, 1982).

The Sternberg paradigm

In a Sternberg task, subjects commit a set of items to memory and are then asked to recognize whether specific target items are in the set. Typically a *set size effect* is observed such that subjects take longer to make these recognition judgements as the size of the memory set increases. This effect can be seen to be analogous to the fan effect of the fact-retrieval paradigm. Also analogous to the fact-retrieval paradigm, relatedness effects have been observed in the Sternberg paradigm.

When set relationships distinguish set items from foils in the Sternberg paradigm, effects of set size are reduced or eliminated. Usable set relationships include letter size and color (Ellis and Chase, 1971), the letter/digit distinction (Lively and Sanford, 1972; Simpson, 1972), and semantic categorical membership (Jones and Anderson, 1982). When all items of a memory set are related to one another, the relationship between decision time and set size in these experiments is often markedly curvi-linear. As the size of such a related set increases to three items, there is an increase in decision time comparable to that observed for unrelated sets; as the size of a related set increases from three to six items, the increase in decision time is much smaller.

These results are well-described by a race model (Ellis and Chase, 1971; Jones and Anderson, 1982) in which decision time is determined by the fastest to complete of two or more independent retrieval processes. For smaller set sizes the retrieval of a direct pathway between the item and the set is nearly always faster than the retrieval of an indirect pathway containing relatedness information. Relatedness effects are only observed when the direct retrieval is sufficiently slowed with increasing set size.

Merging the two paradigms

To compare long-term memory retrieval with short-term memory retrieval, we would like to have some way of merging these two paradigms. One approach to the comparison of short- and long-term memory retrieval has been to use the *item-recognition paradigm* (see Burrows and Okada, 1975; Juola, Fischler, Wood, and Atkinson, 1971), a slightly more general version of the Sternberg paradigm in which the number of items in a memory set sometimes exceeds the capacity of short-term memory.

Burrows and Okada (1975) conducted experiments in which the same subjects were tested on both subspan and supra-span set sizes. The relationship between decision time and set size in their experiments was well described by a bilinear function with slope changing at the limits of memory span. For sets of 2 to 6 words the observed slope was 57 milliseconds/item in one experiment and 37 milliseconds/item in a second experiment; for sets of 8 to 20 words, in contrast, the observed slope was 13 milliseconds/item in both experiments. Although Burrows and Okada interpret this pattern to indicate an involvement of distinct processes in short- and long-term memory retrieval, they also indicate that their data are well fit by a single logarithmic function. Such a function permits a model in which there are no sharp distinctions between short- and long-term memory retrieval.

Unfortunately, there is a serious problem attendant with the use of the item-recognition paradigm as a means of comparing short- and long-term memory retrieval - this approach confounds manipulations in set size with manipulations in the short-term memory/long-term memory nature of the task. In order to compare short-term memory retrieval with long-term memory retrieval in the item recognition paradigm, set size must necessarily be varied from sub-span to supra-span levels. A methodology is needed in which the nature of the retrieval task, i.e., whether it involves active or inactive memory, can be manipulated independently of information load.

One way of doing this is through an extension of the Sternberg paradigm in which subjects are sometimes engaged in a distractor activity between the presentation of an item set and its testing. The distractor activity is designed to prevent subjects from rehearsing the set so that its activity level is comparatively lower when the test probe is finally presented. Using this methodology Sternberg (1969) found that the slope relating decision time to set size was higher when the distractor task intervened. However, Wickens (Wickens, Moody, and Dow, 1982; Wickens, Moody, and Vidulich, 1985) has failed to observe such an interaction in subsequent experiments. In these experiments the slope relating set size to decision time for the secondary memory condition (the condition with the distractor task) is almost identical to the slope for the primary memory condition (the condition without the distractor task). These results suggest that the effects of memory set activity level are additive with respect to the effects of set size.

The approach adopted in Experiment 1 of this article is, in some respects, complementary to that used by Sternberg (1969) and Wickens et al. (1982, 1985). Instead of transforming the short-term memory Sternberg task into a long-term memory task through introduction of a distractor task, an attempt is made to transform the long-term memory fact-retrieval task into a short-term memory, Sternberg-like task through the use of precueing. Subjects are cued with the subject of a sentence and are asked to retrieve into short-term memory all of the predicates associated with the subject word. Then, presumably, they can search these predicates as they would the items in an ordinary Sternberg memory set.

Since set size effects in the Sternberg paradigm are typically measured in the tens of milliseconds while fan effects in the fact-retrieval paradigm are typically measured in the hundreds of milliseconds, we might expect precueing to effect a reduction in the effects of experimental fan/set size. However, typical test items (as well as subjects and procedure) also differ markedly in the two paradigms thus attaching a strong caveat to any conclusions that are reached from a direct comparison of existing data. In fact, Whitlow (1984) found a slight tendency for fan effects to increase with increases in precue duration. However, the interpretation of Whitlow's results is complicated somewhat by his use of a learning phase procedure that imposed a strongly serial, list-like organization onto the total set of learned subject/predicate facts. This organization appeared to override the fan manipulation in some experimental situations and fan effects were sometimes reversed depending upon the order in which the facts were learned.

Putting aside non-essential differences in test items and procedure that are typically found in experimental instantiations of the Sternberg and fact-retrieval tasks, we must consider whether these tasks differ in more fundamental ways that are not captured by the short-term/long-term memory distinction. A Sternberg task, for example, is often described as involving an act of *item recognition* while the fact-retrieval task is generally regarded to require an act of *associative recognition*. In this respect, it is important to distinguish the logical requirements of these tasks from theoretical speculations concerning the processes that are engaged in their completion. A test probe in either a Sternberg task or a fact-retrieval task implicitly references elements that are not physically represented in the test probe itself. Consider a fact-retrieval task involving person-location word pairs. For a given test probe, the subject must decide whether a connection between the person word and the location word was formed during the learning phase of the experiment. The person word and the location word are physically represented in the test probe. In addition, reference to another element or elements, representing the context of the learning phase, is implicit. In the Sternberg task, only one element is explicitly referenced in the test probe (e.g., a letter, digit, word, etc.) while reference to at least one other element, corresponding to the memory set, is implicit. Under this analysis, the nature of the decision required of subjects in the two tasks is actually quite similar - in both tasks, subjects must uncover, or compute, a pathway that connects together the elements of the test probe.

Turning now from task requirements to theoretical accounts, it is apparent that many of the models arising from the Sternberg paradigm are non-associative in the following sense: Performance is not seen to involve the attempt to retrieve an existing pathway in memory that connects the test item to the memory set. Under a class of *direct-access models* (Baddeley and Ecob, 1973; Corballis, Kirby and Miller, 1972; Nickerson, 1972) the connection between the set item and the memory set is, instead, inferred on the basis of test-item attributes such as familiarity. Under a variety of matching models (whether these are serial or parallel, self-terminating or exhaustive) the connection between the test item and the memory set is computed (see Sternberg, 1975, for a review). The classic exemplar of this category is Sternberg's original serial, exhaustive scanning model (Sternberg, 1967) which maintains that the test probe is checked against all items of the memory set before a yes/no response is generated.

These conventional models notwithstanding, the Sternberg task can also be seen to involve an associative judgement process in which the attempt is made to retrieve an existing memory pathway that interconnects the elements of the test probe. The linear set-size effect of the Sternberg paradigm is in fact readily explained through a associative, spreading-activation approach as exemplified by the ACT model (see Anderson, 1976, 1983). Figure 1 illustrates one possible representation of a memory set in which item nodes, labeled O_1 through O_S, are simply linked to a common set node T. The set node can be thought of as representing a concept for "the set of items most recently presented". (It should not necessarily be equated with the contents of active memory.) The dotted lines allow for a possibility that nodes have pre-experimental or "other-than-experimental" associations - a point we return to shortly. (In addition, more than one solid line can extend from a given node O_i to indicate, for example, that the corresponding item has been used in more than one memory set through the course of the experiment.)

Insert Figure 1 about here

On a given trial, the activation a spreading to a connecting pathway from the set node is proportional to A / S, where A equals the total activation emanating from the set node and S equals the set node's experimental fan, i.e., set size. If the set node is the only source of activation, then the function relating decision time to set size is of the form, $T = I + B / a$ (where I represents search-invariant aspects of the task such as encoding and response generation and B is a scaling factor associated with search time). This equation predicts a linear set-size effect which remains constant across all ranges of the set-size manipulation.

However, at least one other node, that for the item explicitly represented in the test probe, will also be sending activation to a connecting pathway. This activation i, moreover, is undiminished by increases in set size.[4] According to the ACT model, the following equation more accurately reflects the relationship between decision time and set size: $T = I + B / (a + i)$. This equation predicts that set-size effects will be smaller for the larger memory sets of the item-recognition paradigm without resorting to a distinction in the retrieval dynamics of short- and long-term memory. Of course, this equation generates a relationship between decision time and set size that is negatively accelerated even for subspan variations in set size although this trend may be slight. In fact such a trend is observed more often than not in experiments of the Sternberg paradigm (Briggs, 1974).

In tasks requiring a set membership judgment it is evident that set attributes such as size and organization can vary independently of item attributes such as familiarity, probability of presentation, or ease of encoding. The empirical observation that performance is affected by both set and item attributes (see Mandler, 1980, for a review) has led to the formulation of dual-process models (e.g., Juola, et al., 1971; Mandler, 1980) in which decisions are a product of both set-based and item-based processes. An associative, spreading activation approach suggests that the same mechanisms may underly the expression of set and item attributes during a retrieval attempt.

An outline of the indirect-pathway model

We can outline an instantiation of this approach, the *indirect-pathway model*, that we use to interpret the data from the two experiments of this article as well as data from a range of other memory retrieval experiments. The indirect-pathway model has two important and distinguishing features. First, the *pre-trial activation level* of an area in memory is permitted to vary to reflect differences between short- and long-term memory retrieval. With reference to Figure 1, for example, we expect the pre-trial activation level of T to be considerably lower if, instead of representing a set node in a Sternberg task, it were to represent the subject word of a fact-retrieval test probe. Since no advance notice is given in the standard fact-retrieval task concerning the makeup of an upcoming test probe the pre-trial activation of the node for a subject word should be at roughly the same low level as that for other experimentally relevant nodes.

The indirect-pathway model incorporates a *dominant-node hypothesis* maintaining that a node's influence upon the retrieval process will increase in proportion to the amount of activation it is able to send to a connecting pathway relative to activation from other sources. One prediction of the dominant-node hypothesis is that the decision time effects of a node's fan will generally increase with its level of pre-trial activation. This occurs because a node with a high level of pre-trial activation is more likely to dominate the retrieval process (and hence features of the node such as its fan are made more apparent). We elaborate upon this feature of the indirect-pathway model later in this article in the context of direct comparisons of performance in a Sternberg task, a fact-retrieval task, and a hybrid precueing task.

As a second critical feature of the indirect-pathway model, decisions can sometimes be based upon the most rapidly activated of several pathways connecting the elements of a test probe and these pathways can be *indirect* in the sense that they include relatedness information.[5] In Figure 1, for example, a test probe referring to the top node T and the object node O_1 might be verified through the retrieval of the direct pathway d or through the retrieval of an indirect pathway involving associations x and y - whichever were faster to reach some threshold of activation. The x-association might itself be a complex of associations representing some pre-experimental relation (perhaps of a thematic or categorical nature) between the nodes O_1 and O_S. With this approach, the indirect-pathway model offers more mechanistic elaboration of the race model advanced to account for relatedness effects in the Sternberg paradigm (Ellis and Chase, 1971; Jones and Anderson, 1982). It will be seen that this approach also provides a good accounting of relatedness effects in the fact-retrieval paradigm.

A more formal treatment of the indirect-pathway model, and its ability to handle a range of memory retrieval data, is contained in the discussion section at the end of this article. First, we present a pair of experiments designed to enable the direct comparison of fan/set size and relatedness effects as these occur in a fact-retrieval task, a Sternberg task, and a hybrid precueing task. These experiments indicate that effects of fan/set size and relatedness are comparable in the three tasks and that these effects fall along a continuum.

Experiment 1

In Experiment 1, subjects were tested over the same database of person-object word pairs in three speeded retrieval tasks: A standard version of the fact-retrieval task; a precueing task that was identical to the fact-retrieval task except that each test probe was preceded by an appropriate person-word cue; and a Sternberg task in which the object-word associates of each person word were separately tested as memory sets.

Table 1 presents a portion of the database that one subject might learn. A given subject associated each of 24 person words to a set of one, three, or six object words. This manipulation in set size was crossed with a factor of set relatedness. The object words in half of the sets were selected to be topically or thematically related to one another (see Table 1a) while words in the other sets were comparatively unrelated to one another (see Table 1b).[6] Note that the experimental manipulation in set size equates with the experimental fan of person words. Experimental fan of all object words in a subject's database was constant at two, i.e., each object word was associated to exactly two person words.

`Insert Table 1 about here`

We attempted to minimize the chances that object words in any set might be related to one another in any other than a semantic or thematic manner. No two words in a set began with the same letter and care was taken to insure that word sets were comparable in the distribution of the lengths of their member words. Where the repetition of letter patterns in a set could not be avoided (the word endings "er" and "ess", for example), we tried to insure that these repetitions occurred equally often in related and unrelated sets.

Method

Subjects. Twenty-four subjects (13 female and 11 male subjects) between the ages of 18 and 28 participated in a single 3-hr. session and were paid between $7.50 and $12.00 for their participation.

Stimulus materials and design. The experiment employed a within-subjects, within-items design that crossed the factors of retrieval task (the Sternberg task, the precueing task, and the fact-retrieval task), set relatedness, set size (1, 3, or 6 object words) and response type.

The subjects were divided into two groups of 12 subjects each. A separate set of stimulus materials was used with each group. In each set, stimulus materials consisted of what will be called "person words" and "object words." Person words in one stimulus material set were male names between four and seven letters in length. Person words in the second stimulus material set were names of professions and were between five and ten letters in length.

Object words in the first stimulus material set were drawn from the Toronto Word Pool of 1,080 two-syllable words with a Thorndike-Lorge (1944) count of 20+. Object words were selected from the pool to form 12 sets of six thematically related words each. Object words in the second stimulus material set were simply taken from a dictionary. These words also formed 12 sets of six thematically related words each. All object words in each stimulus material set were between four and ten letters in length. For each stimulus material set, 12 additional sets were formed, each containing of six unrelated words. These unrelated sets were formed by recombining the object words of the related sets. Within a given unrelated set, each object word was drawn from a different related word set.

Each subject worked with a database of person-word, object-word associations involving subsets from each of the 12 related and 12 unrelated six-word sets of a stimulus material set (see Table 1). A given object word in this database occurred in both a related and an unrelated set and was associated to exactly two person words. The size of a subset taken from a given six-word set varied from subject to subject in order to insure that, across subjects, a six-word set was tested in each condition of set size.

Apparatus. The experiment was run on a PDP 11/34 computer using the RSX-11M system. All stimuli were displayed in uppercase letters on a Beehive 100 terminal using a 5X7 (per character) dot matrix. The terminal was modified to display stimuli only at the beginning of a video frame; all stimulus-dependent timing was initiated at the beginning of a frame. Yes/no responses were made through a hand-held, two-button box. The left button was labeled "no" and the right button was labeled "yes".

Procedure. A subject acquired the relevant database of person-word, object-word associations during a learning phase that consisted of a sentence-making task followed by a cued-recall task. A subject was tested over this database during a speeded retrieval phase consisting of Sternberg, precueing, and fact-retrieval tasks. Each of these five experimental tasks began with a familiarization period during which the subjects performed the task on a practice stimulus material set.

In the sentence-making task, a person word, together with all of its object-word associates, was presented on the terminal screen. The subjects had to formulate and key onto the terminal screen a sentence for each of the object words that directly involved the person word. The cued-recall task used a double dropout procedure and consisted of two test periods. Within a test period, person words were separately presented on the terminal screen in a randomly determined order. For each person word, the subject attempted to type in all of its object-word associates. A subject was then given feedback and his original sentences were presented on the terminal screen. The subject viewed these sentences for as long as he wished before pressing the return key to go on to the next person word. If the subject correctly recalled all of the object words for a person word then that person word dropped out of the test period procedure. Within in a test period, subjects were repeatedly tested, in a randomly determined order, over person words for which object word recall was not perfect. A test period ended when all the person words had dropped out of the procedure. Subjects, therefore, achieved perfect object-word recall to each of the person-word cues exactly once in a test period.

In the retrieval phase, the Sternberg, precueing, and fact-retrieval tasks, were presented in an order that was counter-balanced across subjects. All retrieval tasks used a game format in which subjects were awarded points for fast, errorless performance. These points were converted into money at the end of the experimental session. Subjects earned a half point for each decision time faster than a "time-to-beat" and subjects lost two points for each error. For each task, an initial time-to-beat was set to equal a subject's performance in the task's initial familiarization phase.

The procedure followed in the Sternberg task was very similar to that used in previous experiments (e.g., Jones and Anderson, 1982). The task consisted of 26 test blocks each composed of six targets and six foils. The first two test blocks constituted a familiarization period involving object words from the practice stimulus set. Each of the remaining blocks tested a different set of object-word associates to a person word in the subject's database. Foils in a given test block were also object words from the subject's database that were selected to be unrelated to the object words of the memory set and to each other. Three object-word foils were twice repeated in a test block. A given set item occurred as a target in the test block in inverse proportion to the memory set size (specifically, six divided by the memory set size).

Each test block began with a terminal screen display of the memory set, in a randomly ordered column, and the time-to-beat. The time-to-beat was set equal to the smaller of two numbers: (a) the previous time-to-beat multiplied by 1.05 seconds, or (b) the average of the previous time-to-beat and the actual mean decision time for the previous block. This number was then adjusted for variations in set size by adding the factor, (set size - 3) * 25 milliseconds. A press of the return key cleared the display and the computer then presented a sequence of 12 test probes in a randomly determined order. Preceding the display of each test probe, the prompt "******" appeared on the terminal screen, followed by a 500-millisecond delay. The screen then cleared, a test probe appeared one line below the line upon which the prompt appeared, and the time began. A press of the yes or no response button terminated the display.

In the fact-retrieval task, test probes consisted of person/object words pairs. The first 24 test probes constituted a familiarization period that tested associations in the practice stimulus set. This period also determined an initial time-to-beat. Thereafter, the time-to-beat changed after every 12 test probes in a manner identical to that used for the Sternberg task except that no adjustment was made for set size.

For a given test probe, subjects decided whether they had associated the person word to the object word during the learning phase. Each test probe was preceded by the visual signal "FPFPFP". When the subjects pressed a foot pedal, this signal disappeared and, after a 500 millisecond interval, a word pair appeared. After the subjects responded, the test pair disappeared from the screen and the timer stopped.

Each person word was tested once with each of its object-word associates. A person word was tested an equal number of times with foils that involved the object-word associates of another person word. These object words were selected to be unrelated to the object-word associates of the person word and to each other. A total of 60 target and 60 foil word pairs were tested and these probes were blocked by the factor of set relatedness. The order of the two blocks was counter-balanced across subjects and items. The 30 targets and the 30 foils of a block were presented in a randomly determined order.

The procedure in the precueing task was identical to that used in the fact-retrieval task except that a test word pair was preceded by an appropriate person-word cue instead of "FPFPFP." For example, if the test word pair were "Wayne - baby", this probe would be preceded by "Wayne." Subjects were encouraged to spend as much time as they needed to recall the object-word associates to the person word cue before they pressed the foot pedal.

Results

The relationship between decision time and set size in the three retrieval tasks is presented in Figure 2 for each combination of relatedness by response type. Table 2 presents the corresponding error rate data.

Insert Figure 2 about here

Insert Table 2 about here

Decision times and error rates were submitted to separate analyses of variance for each of the three retrieval tasks. Since each subject experienced a different set of stimulus materials, the design of Experiment 1 avoided the language-as-a-fixed-effects fallacy (Clark, 1973). Parallel analyses, however, were performed on the data that separately treated subjects and items as random effects. When an effect is significant by a subject analysis, both the subject and the item F-ratios are reported. In the fact-retrieval task and the precueing task, trials were excluded from all analyses when these were immediately preceded by a trial involving the same person word. Decision times were also discarded from trials on which an error was made or the time itself was not within a certain range, where this range varied with the task. The analysis of error rates tended to show the same patterns of significance as those of the decision-time analysis and only the decision-time results will be described here.

In the Sternberg task, slightly less than 2% of the correct data were discarded by imposing the restriction that decision times fall within the range of .2 and 1.0 seconds. With respect to decision time, there were significant advantages for related sets (by subjects, $F(1,23) = 43.80$, $P < .001$; by items, $F(1,23) = 18.43$, $p < .001$) and yes responses (by subjects, $F(1,23) = 81.65$, $p < .001$, by items, $F(1,23) = 161.82$, $p < .001$). The effect of set size was also significant (by subjects, $F(2,46) = 350.13$, $p < .001$; by items, $F(2,46) = 175.87$, $p < .001$). A relatedness by set-size interaction, was observed such that the effect of set size was smaller for related sets than for unrelated sets (by subjects, $F(2,46) = 18.71$, $p < .001$; by items, $F(2,46) = 17.52$, $p < .001$). No other decision-time effects approached significance.

In the precueing task, slightly less than 2% of the correct data were discarded by imposing the restriction that decision times fall within the range of .2 and 2.0 seconds. There was a general advantage for relatedness (by subjects, $F(1,23) = 11.27$, $p < .001$; by items, $F(1,23) = 22.07$, $p < .001$) and for yes responses (by subjects, $F(1,23) = 45.17$, $p < .001$; by items, $F(1,23) = 44.69$, $p < .001$). There was also a set-size effect (by subjects, $F(2,46) = 80.51$, $p < .001$; by items, $F(2,46) = 32.53$, $p < .001$). In agreement with the results from the Sternberg task, the effect of set size was smaller for related sets than for unrelated sets. The interaction between set size and relatedness, however, was not significant (by subjects, F(2,46) = 1.22, p > .30; by items, F(2,46) = 1.59, p > .20).

In the fact-retrieval task, slightly less than 2% of the correct data were discarded by imposing the restriction that decision times fall within the range of .2 and 3.0 seconds. There was a significant advantage for yes responses (by subjects, F(1,23) = 55.77, p < .001; by items, F(1,23) = 83.66, p < .001). There was also a marginally significant set-size effect (by subjects, F(2,46) = 3.04; p < .06; by items, F(2,46) = 2.63, p < .09). The factor of set relatedness was not significant as a main effect (by subjects, F(1,23) = 2.12, p > .15; by items, F(1,23) = 2.81, p > .10) or in its interaction with set size (by subjects, F(2,46) = 1.24, p > .30; by items, F(2,46) = 1.67, p > .20). No other effects approached significance.

Planned comparisons involved two separate analyses of variance. In one analysis, decision-time performance in the precueing task was contrasted with performance in the fact-retrieval task. There was a significant interaction involving task and set size (by subjects, F(2,46) = 16.63, p < .001; by items, F(2,46) = 7.98, p < .002). The nature of the task also interacted with response type (by subjects, F(1,23) = 21.95, p < .001; by items, F(1,23) = 28.57, p < .001). In a second analysis, decision-time performance in the precueing task was contrasted with performance in the Sternberg task. There was a marginally significant interaction involving task and set size (by subjects, F(2,46) = 2.73, p < .08; by items, F(2,46) = 4.05, p < .03). An interaction involving task and response type approached significance only with a subject error term (by subjects, F(1,23) = 5.76, p < .03; by items, F(1,23) < 1).

Discussion

Across tasks, effects are observed for the database manipulations of both set size and relatedness that are consistent with previous experimental findings. Although performance generally worsened with increasing set size, this effect is considerably smaller for related material. Despite these general trends, the inter-task variations in effects of both set size and relatedness are considerable. We first consider the differential effects of set size through a comparison of performance in the unrelated conditions of the three retrieval tasks. Relatedness effects will then be compared across tasks.

Decision-time effects of set size for unrelated material in the fact-retrieval task are quite weak and the relationship between set size and decision time is decidedly curvi-linear. As set size increases from one to three, decision time increases by 78 milliseconds for foils and 84 milliseconds for targets. These numbers are roughly of the same magnitude as those observed in experiments by Anderson (1974) using similar materials (person-location word pairings) under similar conditions of fan (i.e., where the fan of one word type varied from one to three while fan of the other word type remained constant at two). However, as set size increases from three to six in the fact-retrieval task of Experiment 1, decision time increases by only 7 milliseconds for targets and actually decreases by 14 milliseconds for foils. This finding may represent an important addition to the fact-retrieval literature. A curvi-linear relationship between fan and decision time has not been obvious in previous fact-retrieval experiments - possibly because the fan of undifferentiated material (as opposed to material that can be partitioned into thematically related subsets) has generally not exceeded three.

This pattern is consistent with predictions of the dominant-node hypothesis we have incorporated into the indirect-pathway model and it follows directly from the model's basic spreading activation, associative approach. The fan of a person node referenced in a test probe of Experiment 1 varied directly with set size while the fan of object words remained constant at two in all conditions. (Similarly, in item-recognition tasks the fan of a set node varies directly with set size while the fan of item nodes referenced in test probes generally remains constant at one). As set size increased, the person node's ability to send activation to a connecting pathway was reduced relative to the object node's ability and increments in set size, consequently, had a progressively weaker impact upon retrieval performance. The curvi-linear relationship between decision time and set size is thus seen to be a consequence of retrieval dynamics involving different elements of the test probe and their relative contributions to the retrieval process.

A considerably stronger case for the dominant-node hypothesis can be adduced from a comparison of set-size effects in the fact-retrieval and precueing tasks of Experiment 1. Materials and procedure in the two tasks were identical except that subjects were precued with the person-word of the test probe in the precueing task. This precueing should increase the amount of activation that the person-node is able to send to a connecting pathway so that the person-node is able to dominate the retrieval process - even at higher set sizes. Set-size effects should then be larger with precueing and the relationship between decision time and set size should be more nearly linear. Both of these results are obtained. The decision-time effect of set size for unrelated (232 milliseconds) material is nearly three times larger in the precueing task than in the fact-retrieval task (81 milliseconds). The linear trend in the relationship between decision time and set size accounts for 91% of the variance in the precueing task while accounting for only 61% of the variance in the fact-retrieval task.

The linear trend for unrelated material is even stronger in the Sternberg task where it accounts for 98% of the variance. On the other hand, the decision-time effect of set size for unrelated material in the Sternberg task is somewhat smaller than in the the precueing task (194 vs. 232 milliseconds).

If subjects could in principle reduce the precueing task to a Sternberg task, a comparison of decision times, in absolutes and in patterns, makes it evident that they did not. In general, performance in the precueing task is intermediate between that of the fact-retrieval task and the Sternberg task. Time measurements of the interval between presentations of a precue and the test probe in a trial, as well as comments volunteered by subjects in a post-experimental debriefing, indicate that subjects sometimes gave only a cursory examination of the precue before pressing the foot pedal to initiate test probe presentation.

Turning now to a consideration of relatedness effects in the three tasks, decision-time performance over related material is superior to that for unrelated material and this effect is significant in both the precueing and Sternberg tasks. Set-size effects are also smaller for related material than for unrelated material in all three retrieval tasks. However, this interaction is significant only for decision times in the Sternberg task.

Experiment 2

Experiment 2 was basically a replication of the Sternberg and a fact-retrieval tasks of Experiment 1. However, the procedure of the Sternberg task was changed in order to increase its similarity to that used in the fact-retrieval task. In the Sternberg task of Experiment 1, a memory set was tested in a block of six targets and six foils, regardless of its size. This was done so that the procedure would be similar to that used in previous explorations of the relatedness effect in the Sternberg paradigm (e.g., Jones and Anderson, 1982). However, the procedure is different from that used in the fact-retrieval task and the precueing task. In both of these tasks, a person word occurred in a test probe exactly once with each of its object-word associates. A person word also occurred an equal number of times in foil probes. This meant that a given person word was tested proportion to the size of its associated set of object words. In Experiment 2, object-word sets were also tested in proportion to their size in the Sternberg task.

Procedures for the grouping of test probes and for the determination of the time-to-beat were also modified in the Sternberg task of Experiment 2 in order to achieve greater agreement with corresponding procedures of the fact-retrieval task. In the Sternberg task of Experiment 2, each trial began with the presentation of the relevant memory set and trials over various memory sets were randomly intermixed, i.e., unlike Experiment 1, trials over the same memory set were not grouped together. Also unlike Experiment 1, the time-to-beat was no longer adjusted to reflect differences in memory set size. (This would not have been a straightforward adjustment in any case since test probes over various sized memory sets were randomly intermixed in a given block of trials.)

Experiment 2 also included a blocking manipulation across experimental tasks in an attempt to determine the extent of a potential conflict between processes applied to related material and those applied to unrelated material. In some test periods, for both the fact-retrieval and Sternberg tasks, test probes over related material occurred in one test block while test probes over unrelated material occurred in a second block. In other test periods, blocking was arbitrary so that probes over related material were randomly intermixed with probes over unrelated material.

Method

Subjects and items. Twenty-four subjects (14 male and 10 female) between the ages of 18 and 28 participated in a single 3-hr. session and were paid between $7.50 and $12.00 for their participation.

Stimulus materials, design, and apparatus. The experiment employed a within-subjects, within-items design that crossed the factors of retrieval task (the Sternberg task and the fact-retrieval task), blocking (arbitrary or by relatedness), set relatedness, set size (1, 3, or 6 words) and response type. The stimulus materials and the apparatus were identical to those used in Experiment 1. All differences between Experiment 1 and Experiment 2 will be discussed in the procedure section.

Procedure. The learning phase was identical to that used in Experiment 1. The retrieval phase consisted of two test periods. In each of these periods subjects completed a Sternberg task and a fact-retrieval task. In one test period, all test probes in both tasks were blocked by relatedness; in the other test period, all test probes in both tasks were blocked in an arbitrary manner. The order of the two types of test period was counter-balanced across subjects and, independently of this counter-balancing, the order of the two retrieval tasks within a test period was also counter-balanced across subjects.

The procedure used in the relatedness-blocking condition of both tasks was identical to that used in the fact-retrieval task of Experiment 1. All test probes over related sets were randomly ordered in one block; all test probes over unrelated sets were randomly ordered in the other block. A block in the arbitrary-blocking condition contained an equal number of test probes over related and unrelated sets.

The composition of test probes in the fact-retrieval task of a test period was identical to that of Experiment 1. Each person word in the subject's database occurred exactly once in a target probe with each of its object-word associates. A person word occurred an equal number of times in foil probes containing the object-word associates of another person word in the database.

A similar approach was used in the composition of test probes in the Sternberg task of each test period. Each set of object-word associates (to a person word) in the subject's database was tested with each of its object words occurring exactly once in a target probe. A set was tested an equal number of times with foil probes containing the object-word associates of other person words in the database. A given trial began with the presentation of the relevant object-word set and trials over a given object-word set were randomly intermixed with trials testing other object-word sets in the database (in the same way that trials involving a given person word in the fact-retrieval task were intermixed with trials involving other person words.) Also in contrast to Experiment 1, the time-to-beat in the Sternberg task was not adjusted to reflect changes in memory set size.

On a given trial, the procedure in the fact-retrieval task was identical to that used in Experiment 1. Changes in the Sternberg task procedure were made, however, in order to make it more comparable to that used in the fact-retrieval task. The following format was followed in a trial of both tasks:

1. A trial was initiated with the presentation of a visual signal. In the Sternberg task, this signal was the relevant object-word set; in the fact-retrieval task, this signal was the string, "FPFPFP." Presentation of the signal started the timer.

2. Subjects pressed the foot pedal when they were ready for the test probe. A press of the foot pedal cleared the terminal screen and stopped the timer.

3. After a delay of 500 milliseconds, the test probe appeared and the timer was started. This test probe was an object word in the Sternberg task and a person/object-word pair in the fact-retrieval task.

4. Subjects stopped the timer with a press of either the yes or no button and terminated the trial.

Results

There was no main effect of the blocking manipulation in either the Sternberg or fact-retrieval tasks ($F < 1$). The blocking manipulation did interact with the relatedness manipulation in the Sternberg task (by subjects, $F(1,23) = 6.75$, $p < .02$; by items, $F(1,23) = 10.38$, $p < .01$). In comparison to the arbitrary blocking condition, times for related sets were faster in the relatedness blocking condition and times for unrelated sets were slower. It is possible, therefore, that the blocking of materials in the relatedness blocking condition induced subjects to adopt general strategies that differed from block to block. However, the same general trends are apparent in under both conditions of blocking across the experimental tasks and we offer no further discussion of the blocking manipulation in this article.

The relationship between decision time and set size in the two retrieval tasks is presented in Figure 3 for each combination of relatedness by response type (collapsing across the blocking manipulation). The corresponding error rates for these conditions can be found in Table 2.

`Insert Figure 3 about here`

Decision time data were submitted to separate analyses of variance. Since each subject experienced a different set of stimulus materials, the design of Experiment 2 avoided the language-as-a-fixed-effects fallacy (Clark, 1973). Parallel analyses, however, were performed on the data that separately treated subjects and items as random effects. When an effect is significant by a subject analysis, both the subject and the item F-ratios are reported. In both the fact-retrieval task and the Sternberg task, trials were excluded from all analyses when these were immediately preceded by a trial involving the same person word (or person-word associates). Decision times were also discarded from trials on which an error was made or the time itself was not within a certain range, where this range varied with the task. The analysis of error rates tended to show the same patterns of significance as those of the decision-time analysis and only the decision-time results will be described here.

In the Sternberg task, slightly less than 2% of the correct data were discarded by imposing the restriction that decision times fall within the range of .2 and 1.2 seconds. Decision-time performance was better for related sets (by subjects, $F(1,23) = 53.62$, $p < .001$; by items, $F(1,23) = 68.38$, $p < .001$) and for yes responses (by subjects, $F(1,23) = 22.11$, $p < .001$; by items, $F(1,23) = 109.83$, $p < .001$). A set-size effect was observed (by subjects, $F(2,46) = 258.03$, $p < .001$; by items, $F(2,46) = 124.12$, $p < .001$) and the effect of set size was smaller for related sets (by subjects, $F(2,46) = 9.51$, $p < .001$; by items, $F(2,46) = 11.66$, $p < .001$).

In the fact-retrieval task, slightly less than 2% of the correct data were discarded by imposing the restriction that decision times fall within the range of .2 and 2.5 seconds. There were significant advantages for related sets (by subjects, $F(1,23) = 17.26$, $p < .001$; by items, $F(1,23) = 25.49$, $p < .001$) and for yes responses (by subjects, $F(1,23) = 59.99$, $p < .001$; by items, $F(1,23) = 112.01$, $p < .001$). A set-size effect was observed (by subjects, $F(2,46) = 5.71$, $p < .01$; by items, $F(2,46) = 2.79$, $p < .08$). The set-size effect was smaller for related sets than for unrelated sets (by subjects, $F(2,46) = 3.76$, $p < .04$; by items, $F(2,46) = 4.22$, $p < .03$). In addition, there was an interaction involving the factors of relatedness and response type (by subjects, $F(1,23) = 13.51$, $p < .002$; by items, $F(1,23) = 8.80$, $p < .01$). (There was a 52 millisecond advantage for related sets on foil trials and a 121 millisecond advantage for related sets on target trials.)

In an analysis of the combined decision-time data from the two retrieval tasks, the factor of task interacted with set size (by subjects, $F(2,46) = 22.43$, $p < .001$; by items $F(2,46) = 16.77$, $p < .001$) and response type (by subjects, $F(1,23) = 33.15$, $p < .001$; by items, $F(1,23) = 46.88$, $p < .001$). In addition, a three-way interaction was observed that involved task with the factors of relatedness and response type (by subjects, $F(1,23) = 13.74$, $p < .002$; by items, $F(1,23) = 10.29$, $p < .004$).

Discussion

Experiment 2 replicates all of the basic findings of Experiment 1. As in Experiment 1, set-size effects are significantly larger in the Sternberg task. Relatedness effects are again larger in the fact-retrieval task, although this difference is again not significant, i.e., there are no significant interactions involving the factors of task and relatedness.

It is apparent that the changes introduced into the Sternberg task of Experiment 2 (to bring its procedure into closer agreement with that used in the fact-retrieval task) did little to alter the important result patterns. Specifically, decision-time effects of set size are virtually identical in the Sternberg tasks of Experiments 1 and 2 - both for related and unrelated material. The benefits of relatedness are again most apparent for six-word sets.

Differences in decision-time performance between related and unrelated material are also apparent in the fact-retrieval task for all ranges of set size. The curvi-linear relationship between decision-time performance and set size for targets in the fact-retrieval task is quite similar to that of Experiment 1. The largest increase in decision time occurs as set size increases from one to three. For targets over unrelated material, decision time increases only slightly as set size increases from three to six; for targets over related material, decision time actually decreases as set size increases from three to six. However, decision time data for foils in the fact-retrieval task are considerably less well-behaved. For both related and unrelated material, the sharpest increases in decision time occurs as set size increases from three to six.

General Discussion

Under a spreading activation model, such as ACT (Anderson, 1976, 1983) or this article's indirect-pathway model, presentation of the test probe initiates a simultaneous spread of activation from nodes in memory corresponding to elements in the test probe. Activation spreading from a node in memory is partitioned among each of the node's links according their strengths. When a sufficient quantity of activation converges upon a connecting pathway, the contents of this pathway are then available for inspection. Less activation spreads to a connecting pathway from a given node as the number of its links or fan increases. From this perspective, therefore, the generally detrimental effect that set size had upon decision-time performance in both experiments of this article resulted because increases in set size served to increase the fan of an indexing node.

The dominant-node hypothesis states that a node's influence upon the retrieval process will increase in proportion to the amount of activation it is able to send to a connecting pathway relative to activation from other sources. Variations in a node's fan, therefore, will generally have a larger impact upon decision-time performance when the fan of other nodes involved in the retrieval process is high. This is a basic finding of the fact-retrieval paradigm (see Anderson, 1976, pgs. 276-278).

A corollary to this prediction is that increases in a node's fan will have a progressively smaller impact upon decision-time performance when the fan of other nodes involved in the retrieval process remains constant. Such a pattern is generally observed across tasks in both Experiments 1 and 2, i.e., increases in decision time are proportionally smaller for set size increases of three to six than for increases from one to three. This pattern is also apparent in the curvi-linear relationship between decision time and set size that is observed in the item-recognition paradigm (Burrows and Okada, 1975). Again, the notion is that a memory set in a Sternberg or item-recognition task is represented as an associative structure in which a set node is linked to nodes for each item in the set (see Figure 1). The fan of the set node will thus increase with increases in set size while the fan of item nodes remains constant. For larger values of set size, the item node referenced in a test probe will come to dominate the retrieval process so that effects of set size are minimal.

In the experiments of this article, set-size effects changed with the task involved. The relationship between decision time and set size was much stronger and more nearly linear in the Sternberg and precueing tasks than in the fact-retrieval task. This can be explained to result from the relationship between a node's dominance of the retrieval process and its level of pre-trial activation. In the fact-retrieval task, subjects had comparatively little advance knowledge regarding the areas of memory that would be relevant to an upcoming test probe, so all nodes referenced in a test probe (including the person node whose fan was affected by set size) had roughly equal and low levels of activation at the outset of a trial. By contrast, the pre-trial activation levels of relevant nodes in the Sternberg and precueing tasks were much higher. More importantly, pre-trial activation levels of a set node in the Sternberg task and of a precued person node in the precueing task were comparatively much higher than pre-trial activation levels of associated object nodes.[7] These set and person nodes were thus able to dominate the retrieval process - even at higher levels of set size.

It is important to note that the indirect-pathway model, with its use of pre-trial activation is single- rather than dual-process (as opposed to models proposed by Atkinson and Juola, 1974, and Mandler, 1980) and, in particular, that it maintains no fundamental distinction between short- and long-term memory retrieval - the same mechanism of spreading activation operates on both the set and item nodes over all ranges of set size and under all conditions of pre-trial activation.

The indirect-pathway model is intended to handle effects of relatedness as well as effects of set size/fan. Advantages of relatedness were present in all tasks of the two experiments and set-size effects were smaller for related material. These effects of relatedness were generally larger in the fact-retrieval task, but they were more reliable in the Sternberg task. None of the possible interactions involving relatedness and task approached significance in either Experiments 1 or 2.

As we have already noted, the indirect-pathway model's approach to relatedness is a mechanistic elaboration of the race model approach (Ellis and Chase, 1971; Jones and

Anderson, 1982) that was developed to explain relatedness effects in the Sternberg paradigm. In one version of the race model (Jones and Anderson, 1982) two decision processes, an *item-by-item process* and a *relatedness-judgment process*, proceed in parallel and decision time is determined by the first of these processes to reach completion. In the indirect-pathway model these processes translate into simultaneous attempts to uncover direct and indirect pathways, respectively, that connect the elements referenced (either implicitly or explicitly) in the test probe. However, it is important to note that, in contrast to original race model proposals, the same mechanism of spreading activation is in effect in the retrieval of both direct and indirect pathways. The indirect-pathway model is thus single process in its approach to both task-induced and relatedness-induced differences in the set size effect. In the next section we provide a more detailed development of the indirect-pathway model and we assess the extent to which the model is able to account for effects of set size/fan and relatedness across memory retrieval tasks.

The Indirect-Pathway Model

The *indirect-pathway model* of memory retrieval adopts an associational, spreading activation approach with two features of interest:

- The *pre-trial activation levels* of nodes referenced in a test probe is permitted to vary to effect observed differences between short- and long-term memory retrieval. Variations in pre-trial activation can be seen to reflect expectations concerning the composition of the test probe.

- A decision regarding a probe of information in a newly acquired set can sometimes be based upon the retrieval of an *indirect pathway* in which the connection of probe elements is partially accomplished through the use of pre-experimental relatedness information. In the model, overall benefits of relatedness and specific reductions in the effects of set size/fan result from the use of indirect pathways.

In the indirect-pathway model, presentation of a test probe initiates a simultaneous spread of activation from the nodes that are referenced in the probe. This activation will converge upon pathways connecting the probe elements in memory (if these connecting pathways exist). When the activation received by a pathway exceeds some threshold, the pathway becomes available for inspection. At this point it is possible to exert some control over the use of relatedness information.[8] The selection of foils in Experiments 1 and 2 of this article minimized the need for such control, e.g., subjects were not required to distinguish between targets and related foils. Under this circumstance, decision time in the model is determined by the fastest pathway to be retrieved and this pathway may be indirect. In Figure 1, for example, a connection between nodes T and O_1 might be affirmed via retrieval of the direct pathway d or retrieval of the indirect pathway composed of parts x and y.

It should be emphasized again that the top node, T, in Figure 1 can represent either the memory set of a Sternberg task or the person word of a fact-retrieval or precueing task. Nodes O_1 through O_3 represent the object words that are experimentally associated to the top node T. Since negative effects of the experimental set size manipulation are expressed through the top node's fan, their magnitude depends upon the top node's domination of the retrieval process. The dominance of the top node, in turn, depends upon its fan relative to the fan of other nodes referenced in a test probe. The indirect-pathway model predicts that continued increases in set size will have a progressively smaller negative impact upon performance as the object node increasingly comes to dominate the retrieval process. This dominance also depends upon the nature of the task. In the indirect-pathway model, the task variations of Experiments 1 and 2 determined the level of the top node's *pre-trial activation*. Both the top node and the object node referenced in a test probe had equal and low levels of pre-trial activation in the fact-retrieval tasks. The pre-trial activation level of a top node was considerably higher in the precueing and Sternberg tasks.

When decisions are based upon indirect pathways, there are two independent and opposing effects of set size. On the one hand, the fan of the top node increases with set size so that less activation spreads from this node to any single connecting pathway. On the other hand, the number of inter-item associations (and hence the number of pathways indirectly connecting elements of a target test probe) also increases with set size. In related sets, the strength of inter-item associations is high and indirect pathways play a large role in the retrieval process. This leads to a reduction and, in some cases, a reversal of the standard negative effects of set size. Performance will begin to improve with set size at that point where the decreasing negative effects of the top node's fan on performance are offset by benefits resulting from an increase in the number of indirect pathways.

A reversal of set-size effects, although not significant, is apparent in the fact-retrieval tasks of Experiments 1 and 2. Reder and Ross (1983) have observed a similar, and significant, effect in a fact-retrieval experiment that involved judgments of thematic consistency. Under the indirect-pathway model these reversals occur because the impact of a node on the retrieval process rapidly declines as its fan increases relative to the fan of other nodes in a test probe. With reference to Figure 1, this occurred for the top node in the fact-retrieval tasks of Experiments 1 and 2. On the other hand, the top node was able to maintain its dominance in the precueing and Sternberg tasks, over the range of set sizes used in the experiments, as a consequence of its high pre-trial activation level. Negative effects of set size were reduced for related sets in these tasks but there was no reversal.

In the indirect-pathway model, the representation of experimentally acquired information is relatively unstructured. In particular, no new structure is created to highlight pre-experimental relations among items in contrast, for example, to the subnode model (Reder and Anderson, 1980; Reder and Ross, 1983). As we shall shortly see, such a structure does not appear necessary in order to explain the relatedness effects we have considered in this article. Instead, set-level effects of relatedness can arise from the direct involvement during the retrieval process of individual, pre-experimental associations among items.

Nothing has been said thus far about foil rejection. Performance curves for foils roughly parallel those for targets in the tasks of Experiments 1 and 2 (with the notable exception of the fact-retrieval task of Experiment 2 and the possible exception of the precueing task of Experiment 1). This pattern is consistent with a *waiting mechanism* for foil rejection (Anderson, 1976; King and Anderson, 1976) in which subjects allow some amount of time for the retrieval process to uncover a connecting pathway before executing a default no response. It is assumed that this waiting time is adjusted to reflect factors that govern the speed of target recognition, such as fan, so that premature rejections of target probes are avoided.

Anderson (1983, pgs. 111-114) discusses one possible way of implementing such a waiting mechanism. Under this implementation, some of the activation emanating from nodes referenced in the test probe accumulates at one or more productions generating a no response. These productions have mutually inhibitory connections to "yes-response" productions that acquire activation via pathways in memory connecting the elements of the test probe. Under this model of foil rejection, the speed of a no response is directly affected by the fan of test probe elements.

Anderson's waiting model of foil rejection can also explain the general ease with which unrelated foils are rejected in this article's experiments and in previous experiments in both the Sternberg paradigm (e.g., Ellis and Chase, 1971; Jones and Anderson, 1982) and the fact-retrieval paradigm (e.g., Reder, 1982; Reder and Anderson, 1980; Reder and Ross, 1983). Unrelated foils are less likely to activate spurious connections in memory which delay the emission of a no response by sending some activation to yes-response productions (which, in turn, acts to send inhibitory activation to no-response productions).

Note that an elaboration of this second feature of the waiting model might enable us to dispense with the supposition that elements of the test probe directly send activation to no-response productions. We might maintain, instead, that increases in the fan of elements in a foil generally brings about an increase in the potential number of spurious connections among elements of the foil. This, in turn, sends activation to yes-response productions and so indirectly delays the emission of a no response via the inhibitory connections between yes-response and no-response productions.

This notion that spurious connections delay the process of foil rejection might be expanded upon to generate a number of predictions. We should expect, for example, to be able to vary the ease of foil rejection in a more or less continuous fashion as a function of the relatedness of the elements in a foil. It should also be possible to differentiate nodes not only on the basis of their number of connections to other nodes in memory (i.e., their fan), but also on the basis of the relative strengths of these connections. Other elaborations yield error rate predictions as well. This waiting model seems to predict, for example, that error rates are likely to increase with the variability of activation patterns during the retrieval process. Spurious connections among the elements of a foil are more likely to trigger an incorrect yes response; and productions generating a no response are more likely to incorrectly fire before activation connecting the elements of a target has had time to trigger a yes response. Given the increase in variability that typically accompanies an increase in decision time means, this elaboration correctly predicts the generally high correlation between error rates and decision times observed in both the Sternberg and fact-retrieval paradigms. Unfortunately, a more detailed treatment of these and other possible elaborations of the waiting model is beyond the scope of this article.

The indirect-pathway model is explained more formally with reference to Figure 1. The strength of any given link in Figure 1 in can vary independently of the strengths of other links in the representation. When there is no possibility of confusion, the same symbol that labels a particular link or node will also represent its activation level. Variations in the strengths of pathways directly connecting the top node to the object nodes will produce certain effects of serial position and testing frequency. Individual variations in the strengths of inter-object associations will influence the pattern of relatedness effects.

Upon presentation of a test probe, activation spreads from both the top node and the object node referred to in the test probe. The activation leaving a node will be partitioned among its outgoing links according to their strengths. In general, the activation going to a particular link is characterized by the following equation:

$$a_i = A * s_i / \Sigma_j s_j \tag{1}$$

where s_i is the strength of the link, A represents the total activation leaving the node, and the term in the denominator sums across the strengths of each link extending from the node.

To simplify matters for the purposes of modeling the situation in Experiments 1 and 2, it is assumed that all experimentally created direct pathways (the solid lines in Figure 1) have a strength of one. In Figure 1, therefore, the amount of activation going to the direct pathway d from the top node T can be characterized by the following specific version of equation 1:

$$d = T / (S + P) \tag{2}$$

In Equation 2, T refers to the activation originating from the top node, S is the experimental fan of the top node (equivalent to set size), and P is the combined strength of the pre-experimental links (perhaps more appropriately labeled "other-than-experimental" links) extending from the top node.

Upon presentation of the test probe, link d will also receive the following portion of the object node's activation:

$$O_1 / (2 + P) \tag{3}$$

The "2" is included in Equation 3 because each object word is associated to exactly two person words during the learning phase of the experiments. The total direct activation coming to link d will be:

$$d = T / (S + P) + O_1 / (2 + P) \tag{4}$$

The activation of link d, therefore, varies inversely with set size. The magnitude of this effect, however, will depend upon the relative amounts of activation originating from node T and node O_1. It will be assumed that each node referred to in the test probe receives one unit of activation when the test probe is presented. (In the Sternberg task, a top node is implicitly referred to when the test probe is presented.) In addition, a top node in both the Sternberg task and the precueing task may already have several units of activation when the test probe is presented. Pre-trial activation of the top node will increase the effects of set size in this equation.

In the indirect-pathway model a decision can also be based upon indirect pathways. The links x and y in Figure 1 combine to form one such pathway. If the strength of this indirect pathway q is s_q then the amount of activation it receives when the test probe is presented can be characterized by the following equation:

$$q = T * s_q / (S + P) + O_1 * s_q / (2 + P) \tag{5}$$

To avoid needless complexity in the model, it will be assumed that all indirect pathways in the memory structure for a related set have the same strength s_r and that all indirect pathways in the memory structure for an unrelated set (if they exist) have a separate strength s_u. On any given trial over a memory structure of S object nodes, a yes response can be based upon any one of S-1 potential indirect pathways.

It will be assumed that the time it takes for a given pathway (whether direct or indirect) to reach some threshold of activation B is exponentially distributed[9] with a mean time of B/a (where a is the amount of activation the pathway receives). The mean time for a direct pathway to become active, therefore, is B/d and the mean time for an indirect pathway to become active is B/q. (Again, the same symbol refers to both a pathway and its activation level where no possibility of confusion exists.)

Decision time is assumed to be a function of the fastest to reach activation threshold of S pathways where S equals set size and S-1 of these pathways are indirect.[10] Assuming that the exponentials for these pathways are independent of one another then the time for the fastest of these to reach a threshold of activation is characterized by the following equation:

$$\textit{retrieval time} = B / [d + (S-1) * q] \tag{6}$$

The expected decision time for a target probe is expressed by the following equation:

$$Dt(targets) = I + retrieval\ time \tag{7}$$

I, the intercept, reflects the time to encode a test probe and the time to execute a yes response.

In agreement with the general waiting mechanism approach, as it was discussed above, the time to reject a foil in the indirect-pathway model is somewhat longer than the expected time to recognize a target. This is accomplished through the addition of the parameter F to the decision time equation for targets and leads to the following decision-time equation for foils:

$$Dt(foils) = I + retrieval\ time + F \tag{8}$$

The retrieval process is, therefore, given an additional period of time F in order to make sure that no connection exists among the items in the test probe.

The activation level T of the top node is permitted to vary to reflect the nature of the retrieval task. This activation level can be higher in the Sternberg and precueing tasks to reflect the fact that the top node is already active in these tasks at the beginning of a given trial. When a top node has a high pre-trial activation level it will dominate the retrieval process and performance will depend upon its features. Specifically, the effects of set size will increase with increases in the pre-trial activation level of the top node.

The model was fit to the combined decision-time data of Experiments 1 and 2 using the program STEPIT (Chandler, 1964). This program found values for the parameters the model that gave the best fit to the data by minimizing the value of a chi-square statistic. Note that we might expect estimates of I, B, and, most especially, T to vary with the task in order to reflect inter-task differences, respectively, in the time of encoding and response generation, search rate, and the activation level of the top node.

We might also expect the values of these parameters to vary somewhat with inter-experimental variations in task procedure and experimental design. Consequently, the parameters I and B were separately estimated for each of the three experimental tasks in Experiment 1 and the two experimental tasks in Experiment 2. In addition, the parameter T (the activation level of the top node) was separately estimated for the precueing task and each of the Sternberg tasks. The value of T in each of the fact-retrieval tasks was set to equal one unit of activation. This enforces the assumption that, in the absence of precueing, person and object nodes referenced in a fact-retrieval task test probe have the same low level of activation at the onset of a trial.

Within the framework of the indirect-pathway model, there is no reason to expect inter-task or inter-experimental variations in the values of s_u, the strength of indirect pathways for unrelated material, s_r, the strength of indirect pathways for related material, or P, the strength of pre-experimental links. These parameters reflect the strengths of existing associations corresponding to material that remained the same across experiments and tasks. Consequently, only a single estimate was made of s_u, s_r, and P.

Consistent with the assumed waiting mechanism, a simplifying assumption was made concerning parameter F that its value in a given task would always equal some constant times the task's intercept, I.[11] A single value for this constant, F^*, was estimated and used to form the F for each of the experimental tasks. The model makes no provision for predicting the rather weak effects of blocking that were observed in the Sternberg and fact-retrieval tasks of Experiment 2.[12]

In all, 17 parameters were used to fit the decision-time means from the 36 conditions of Experiment 1 (defined by a factorial combination of retrieval task, relatedness, set size, and response type) and the 48 conditions of Experiment 2 (defined by a factorial combination of retrieval task, blocking, relatedness, set size, and response type). With 84 data points being fit and 17 parameters being estimated, the chi-square statistic has 67 degrees of freedom. The least chi-square value obtained by the indirect-pathway model was 82.35, $p < .10$. The model accounts for 99.4% of the variance in decision time means.

Figure 4 displays both observed (points) and predicted (lines) decision-time values for the Sternberg, precueing, and fact-retrieval tasks of Experiment 1. Figure 5 displays comparable values for the Sternberg and fact-retrieval tasks of Experiment 2 (collapsing across the blocking manipulation)

Insert Figure 4 about here

Insert Figure 5 about here

The indirect-pathway model produces all the major trends observed in the decision-time data of Experiments 1 and 2. In particular, the model is able to generate important inter-task variations in the set size effect and it is able to generate interactions involving set size and relatedness that are observed across retrieval tasks. In the model, the use of indirect pathways can sometimes result in a net positive effect of set size on decision-time performance. Perhaps one of the most interesting features of the model is its ability to generate the inverted U-shaped relationship between decision time and set size that is observed for related material in the fact-retrieval tasks of Experiments 1 and 2.

Discrepancies between observed and predicted decision times are relatively small for all experimental tasks except the fact-retrieval task of Experiment 2. The discrepancies in this task are due, in part, to the blocking manipulation whose effects were not modeled. They are also due to a potentially anomalous pattern in the observed decision times for foils. For foils over both related and unrelated material, decision times are minimally affected as set size increases from one to three; there is then a comparatively precipitous rise in decision time as set size increases from three to six. We can offer no explanation for this pattern.

Table 3 presents the parameter estimates of the indirect-pathway model for each experiment. It is curious that B, the activation threshold, is estimated to be largest in the Sternberg task and smallest in the fact-retrieval task. One explanation for these estimates follows from the role that the activation threshold might play in tradeoffs between speed and accuracy. As the threshold is lowered, the likelihood improves that some connecting pathway will be retrieved and the speed of this retrieval also improves. However, the likelihood also increases that this pathway is spurious. Error rates were much lower in the Sternberg tasks than in the fact-retrieval tasks and it is possible that a surplus of activation in the relevant memory structure afforded subjects the luxury of raising the activation threshold in the Sternberg tasks to insure greater accuracy without much sacrifice in speed. In the fact-retrieval task, on the other hand, pathways might never have reached a high activation threshold, particularly if processes of decay or forgetting were at work between the learning phase and the retrieval phase.

Insert Table 3 about here

The interpretation of all other task specific parameters is relatively straight-forward. The estimates of I, the intercept, are smallest in the Sternberg task and largest in the fact-retrieval task; I assumes an intermediate value in the precueing task. The estimate of T, the pre-trial activation level, is quite high for the Sternberg tasks of both experiments, in comparison to the assigned value of one for the fact-retrieval tasks. The estimate of T in the precueing task of Experiment 1 is intermediate. (Recall that, on the basis of retrospective reports and measurements of the the subject-determined cueing interval, we concluded that subjects did not always make complete use of the person-word precue).

Inter-experimental variations in these task specific parameters are relatively slight with one striking exception: The estimate of pre-trial activation level T in the Sternberg task of Experiment 2 is less than half of its corresponding estimate in Experiment 1. Perhaps the most reasonable explanation for this discrepancy revolves around an inter-experimental difference in procedure. Recall that a memory set in the Sternberg task of Experiment 1 was tested in a single block of 12 test probes. In contrast, the procedure followed in the Sternberg task of Experiment 2 more closely resembled that of the fact-retrieval task. In particular, trials over a given memory set were randomly intermixed with trials over other memory sets. It is possible that the blocking of trials over a memory set in Experiment 1 enabled a much larger buildup of pre-trial activation.

In fitting the model to the data, separate parameters s_u and s_r were used to estimate the average strength of an indirect pathway for unrelated and related material, respectively. These values of .060 for s_u and .111 for s_r are considerably smaller than the arbitrarily chosen strength of 1.0 for direct pathways and the estimated value of 2.03 for the combined strength of all pre-experimental associations of a given node. The non-zero estimate for s_u reflects a notion that even object words in an unrelated set are, to some extent, connected to one another in memory. It is important to note that, based upon these estimates, the strength of an indirect pathway is only slightly stronger in the related condition. We might not expect this difference to be very large given the subtle, thematic nature of the relatedness manipulation employed in the experiments. However, as an important advantage of the indirect-pathway model, even this small difference in the average strength of an indirect pathway can have substantial effects upon decision-time performance. It might be said that the pre-existing associations among the items of a newly formed set are given considerable leverage (in terms of their effects on retrieval) through their incorporation into indirect pathways.

The positive estimate of F^* seems to do an adequate job of generating the longer duration of foil rejections (with the already mentioned exception of foil rejection in the fact-retrieval task of Experiment 2). Finally, the estimate of P, the combined strength of pre-experimental associations, agrees closely with previous estimates (see Anderson, 1976, chapter 8).[13]

Conclusion

This article's direct experimental comparison of performance in Sternberg and fact-retrieval tasks and in a hybrid precueing task is motivated by an associational, spreading activation approach. Under this approach decisions regarding a test probe are seen to involve parallel searches that attempt to uncover pathways connecting the elements of the test probe. Reference to some of these elements is explicit, i.e., they are physically represented in the test probe, whereas reference to other elements (e.g., the experimental context, the memory set of the Sternberg task) is implicit. Each of these elements can be used as an index to gain entry to relevant information in memory.

In Experiments 1 and 2, manipulations in set size/fan (i.e., information load) had a larger impact upon performance in the short-term memory Sternberg and precueing tasks than in the longer-term fact-retrieval task. Consistent with research in both the Sternberg and fact-retrieval paradigms, advantages for related material were observed in all experimental tasks and effects of set size/fan were smaller for related material. The proposed *indirect-pathway model* of memory retrieval allows the pre-trial activation levels of areas in memory to vary in order to generate inter-task differences - both in overall performance and in the effects of set size. Relatedness effects arise in the model because decisions can sometimes be based upon the fastest to reach activation threshold of several possible pathways connecting the elements of the test probe. Some of these connecting pathways can be indirect in the sense that they include pre-experimental relatedness information.

The indirect-pathway model integrates a complex set of results involving phenomena associated with short-term memory and other phenomena associated with long-term memory. It suggests that short-term memory retrieval and long-term memory retrieval need not be regarded as separate processes, but rather as a single process applied to network structures having different levels of activation. This process, through its use of indirect pathways, can also produce relatedness effects in both short- and long-term memory retrieval.

Table 1:
Related material (a) and unrelated material (b) in a portion of a sample database of Experiment 1. (The person word in a line is associated to the object words in the same line during the learning phase.)

(a)

JOHN	COLLEGE	LECTURE	RESEARCH	STUDENT	TEACHER	GENIUS
HENRY	WITNESS	MOTIVE	POLICE			
MIKE	RIFLE	HUNTER	FOREST			
GARY	NAVY					
JACK	GARDEN					
DAVID	PUBLIC					

HARRY	BUSINESS	COMMERCE	DEALER	EXPORT	MERCHANT	SHIPPING
PETE	MUSIC	OPERA	SINGER			
FRANK	PASSION	BEDROOM	LOVER			
CHARLES	KINGDOM					
RICHARD	ANGEL					
MARK	LUNCHEON					

(B)

BILL	COLLEGE	WITNESS	RIFLE	NAVY	GARDEN	PUBLIC
KARL	LECTURE	MOTIVE	HUNTER			
DICK	RESEARCH	POLICE	FOREST			
BRUCE	STUDENT					
GEORGE	TEACHER					
ROBERT	GENIUS					

STEVE	BUSINESS	MUSIC	PASSION	KINGDOM	ANGEL	LUNCHEON
EDDIE	COMMERCE	OPERA	BEDROOM			
PAUL	DEALER	SINGER	LOVER			
JERRY	EXPORT					
DAVE	MERCHANT					
FRED	SHIPPING					

Table 2:
Percentage error rates for the retrieval tasks in Experiments 1 and 2.

	Unrelated Sets			Related Sets		
Set Size >	1	3	6	1	3	6
			Sternberg Task, Exp. 1			
Foils-	4	8	8	4	6	8
Targets-	5	7	8	4	5	5
			Precueing Task, Exp. 1			
Foils-	3	6	16	4	9	12
Targets-	8	10	16	6	8	8
			Fact-Retrieval Task, Exp.1			
Foils-	15	14	20	8	13	18
Targets-	11	19	17	8	9	7
			Sternberg Task, Exp. 2			
Foils-	3	5	10	2	3	3
Targets-	3	4	13	2	4	5
			Fact-retrieval Task, Exp. 2			
Foils-	5	6	14	9	6	9
Targets-	8	16	17	7	10	4

Table 3:
Parameter estimates for the indirect-pathway model.

	Exp. 1	Exp. 2
Sternberg task		
I	0.150	0.126
B	0.940	0.647
T	11.811	5.868
Precueing task		
I	0.212	
B	0.610	
T	3.602	
Fact-retrieval task		
I	0.609	0.443
B	0.282	0.350
General Parameters		
s_u	0.060	
s_r	0.111	
P	2.032	
F*	0.303	

Key: I - intercept (in seconds), B - activation threshold, T - top-node activation (equal to 1 unit of activation in both fact-retrieval tasks), s_u - average strength of an indirect pathway for unrelated material, s_r - average strength of an indirect pathway for related material, P - average combined strength of pre-experimental links (an experimental link is given a strength of 1.0 in the model), F* - multiplied by I in order to form F, the added time to execute a no response.

List of Figures

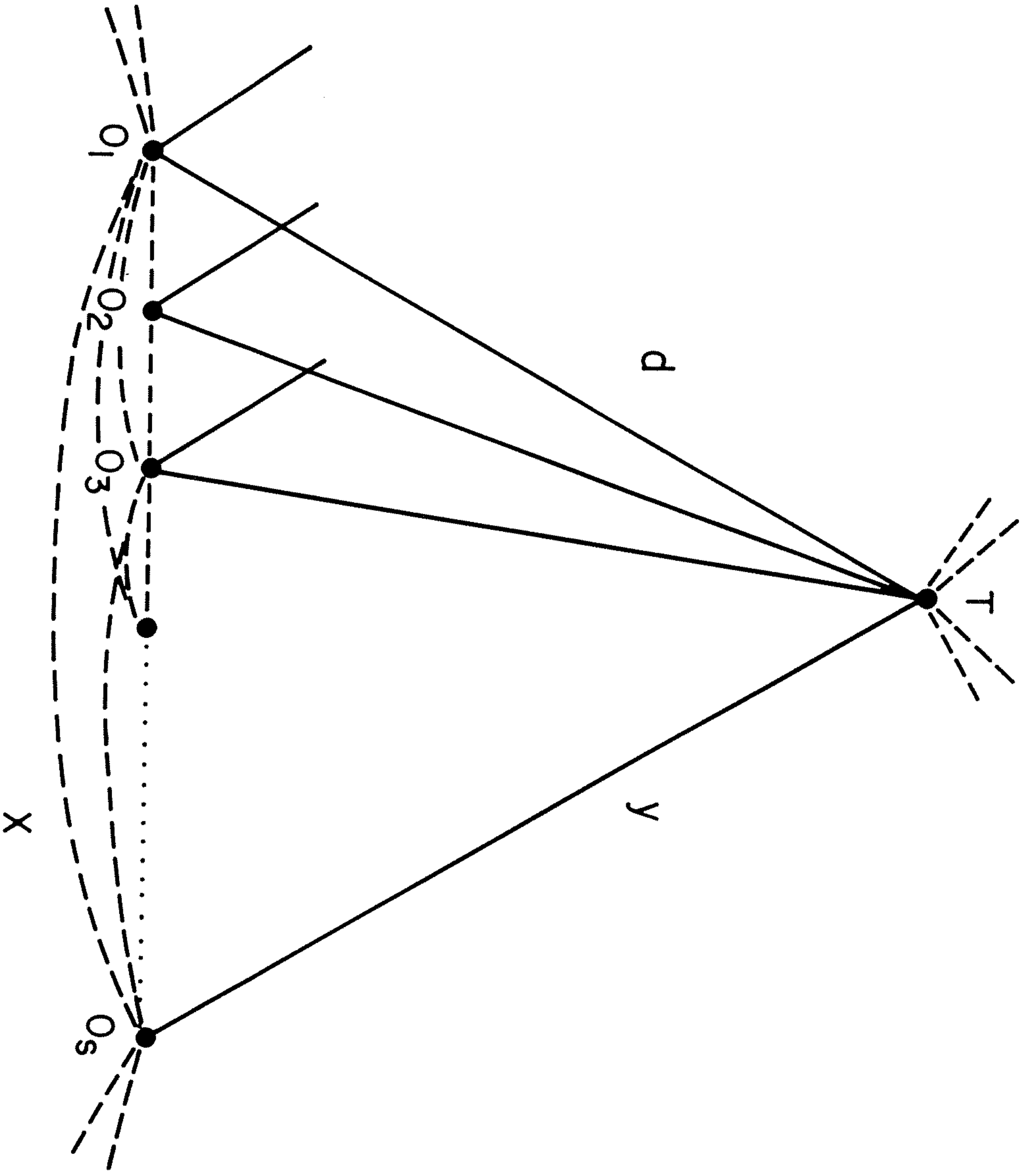
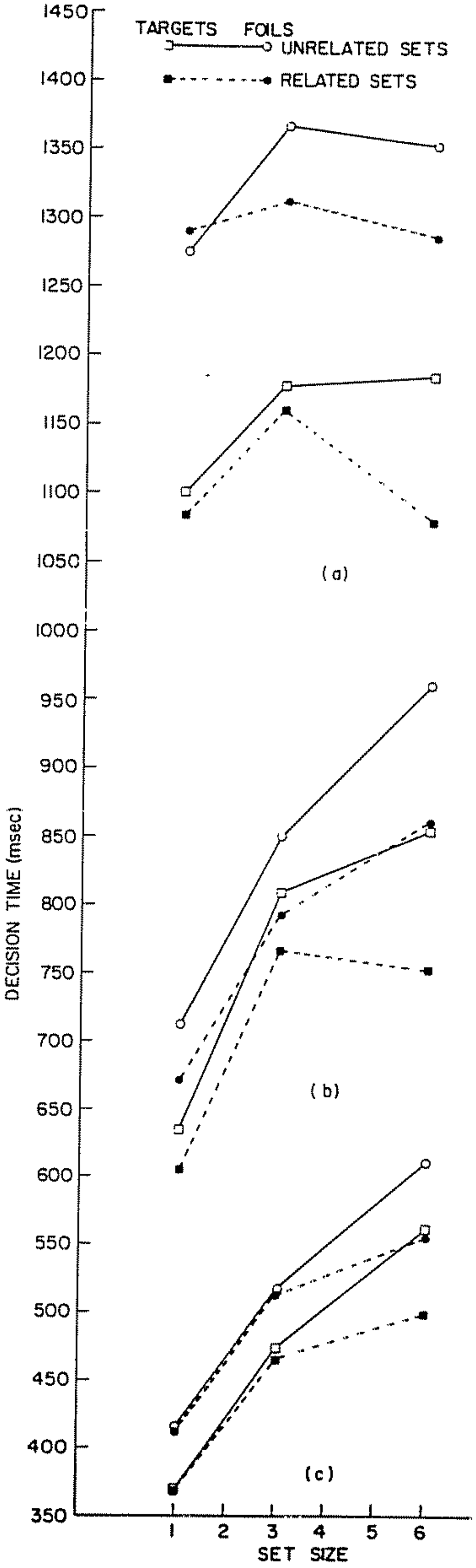


Fig 1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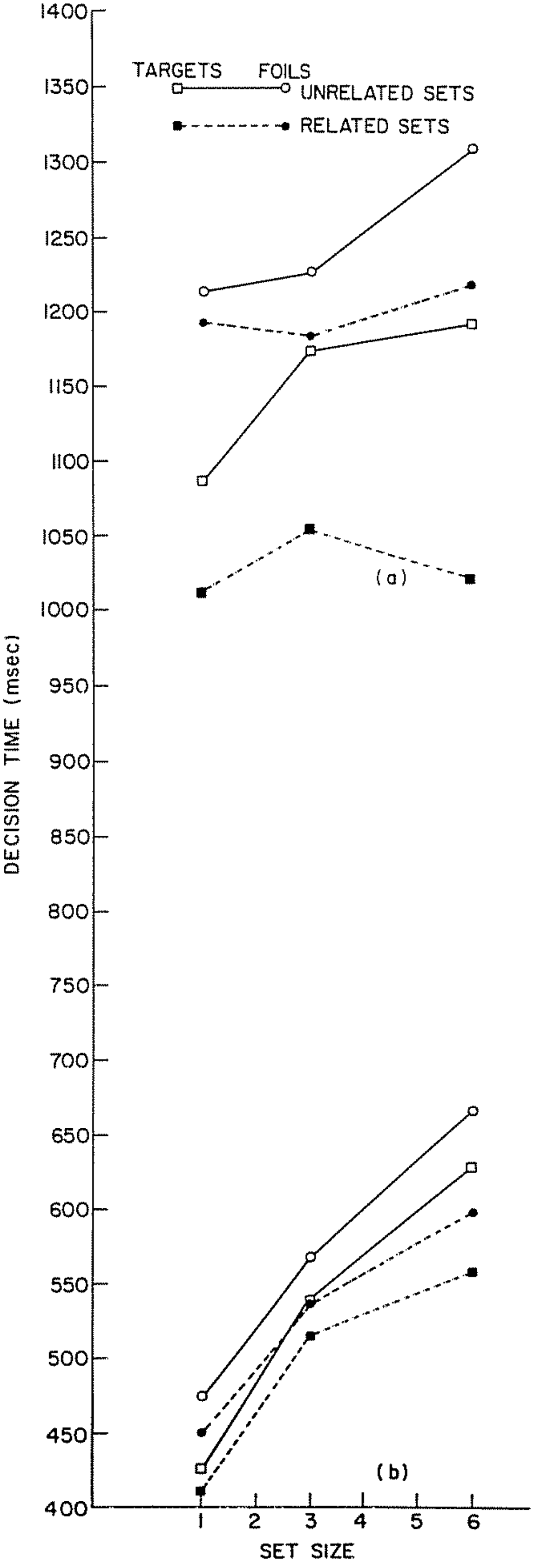
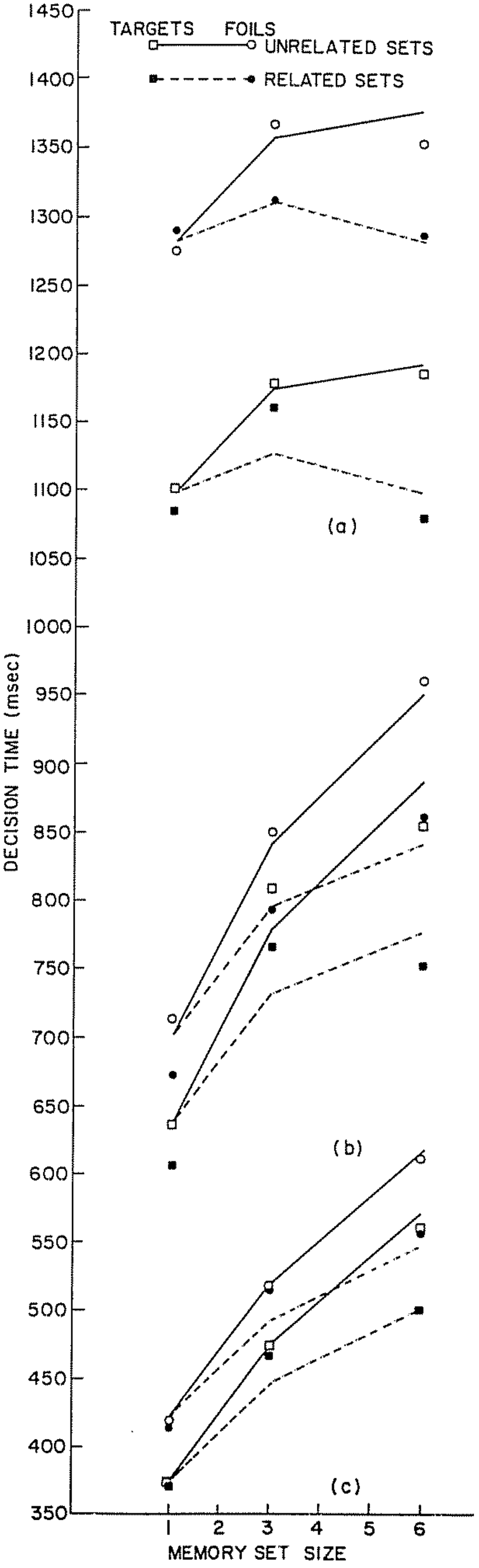
FOILS
UNRELATED SETS
RELATED SETS
DECISION TIME (msec)
1450
1400
1350
1300
1250
1200
1150
1100
1050
1000
950
900
850
800
750
700
650
600
550
500
450
400
350
(a)
(b)
(c)
1
2
3
4
5
6
SET SIZE

Fig 2



TARGETS
FOILS
UNRELATED SETS
RELATED SETS
1400
1350
1300
1250
1200
1150
1100
1050
1000
950
900
850
800
750
700
650
600
550
500
450
400
DECISION TIME (msec)
(a)
(b)
1
2
3
4
5
6
SET SIZE

Fig 3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UNRELATED SETS
RELATED SETS
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1150
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750
700
650
600
550
500
450
400
350
DECISION TIME (msec)
(a)
(b)
(c)
1
2
3
4
5
6
MEMORY SET SIZE

Fig 4

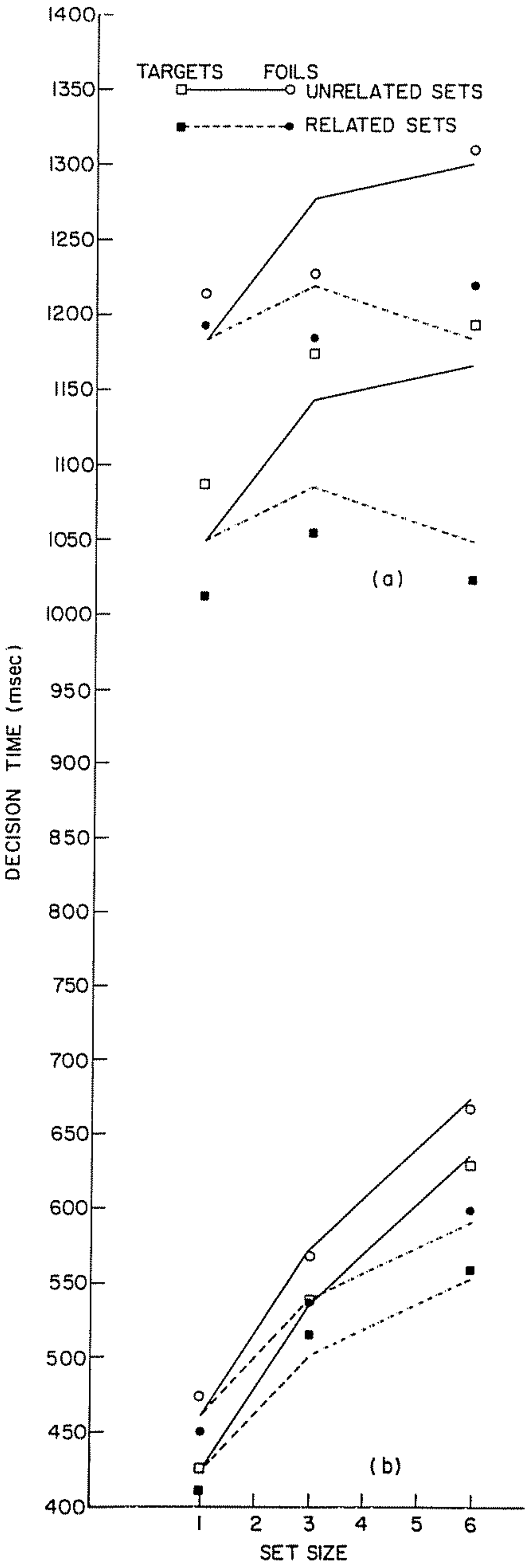
TARGETS
FOILS
UNRELATED SETS
RELATED SETS
(a)
(b)
DECISION TIME (msec)
1400
1350
1300
1250
1200
1150
1100
1050
1000
950
900
850
800
750
700
650
600
550
500
450
400
1
2
3
4
5
6
SET SIZE

Fig 5

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Notes

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[2] Please address all correspondence concerning this article to the first author, William P. Jones, Microelectronics and Computer Technology Corporation, P.O. Box 200195, Austin, Texas 78720.

[3] Test probes in the fact-retrieval paradigm range from complete sentences to word pairs (see Anderson, 1976, 1983) and the essential task facing subjects is one of associative recognition, i.e., subjects must decide whether the elements referenced in a test probe have been connected together through the activities of the learning phase.

[4] Note, however, that the activation a test item sends to a connecting pathway may be diminished by other experimental factors such as the frequency of the item's usage in other memory sets of the experiment. Some of these factors can be represented via the scheme in Figure 1 as links emanating from the item node.

[5] The notion of indirect pathways is essentially a familiar notion of mediational chaining applied here to explain relatedness effects in a speeded retrieval task.

[6] The division of single-word sets between the related and unrelated conditions is arbitrary.

[7] Some portion of a "preactivated" node's pre-trial activation will be divided amongst associated object nodes. Nevertheless, the preactivated node (i.e., a precued node in the precueing task or a set node in a Sternberg task) will be comparatively more active at the onset of a trial.

[8] The actual generation of a response is production-driven. The inspection of a connecting pathway is thus accomplished through the selection of conditionals to a production generating a response.

[9] The assumption of exponential distributions is being made solely for the sake of analytic tractability.

[10] Alternatively, the activation from several connecting pathways could sum together in order to reach a threshold even though none of these pathways by itself reaches a threshold. Under certain assumptions (e.g., the exponential distribution of activation levels for connecting pathways) the model performs identically in either case.

[11] The maximum number of parameters that can be estimated using the program STEPIT is 20 and this number would have been exceeded had a parameter F been separatedly estimated for each experimental task.

[12] Nevertheless, we did not collapse across the blocking factor in our modeling efforts. Included in the chi-square statistic measuring the model's fit, therefore, is a test of the model's implicit assumption that the blocking manipulation is of minimal consequence as a determiner of decision time patterns.

[13] Note, however, that the interpretation of parameter P in relation to the set nodes of a Sternberg task is not entirely clear. If set nodes are manufactured for the presumably novel object-word combinations in Experiments 1 and 2, why should we expect these set nodes to have any pre-experimental fan? (Even when this parameter was separately estimated for the Sternberg tasks, the value produced of 1.450 was appreciably above zero and resulted in no appreciable improvement in the model's fit). On the other hand, as has been observed before (Anderson, 1976, chapter 8), the typical estimate of from two to three for the pre-experimental fan of established concepts in semantic memory (e.g., the person and object words of Experiments 1 and 2) seems entirely too low. One way of explaining these anomalies (see Anderson, 1976, pgs 292-293) is to assert that all experimental concepts correspond to newly formed nodes. Associated estimates of pre-experimental fan then essentially represent a

general loss factor related to the attempt to reach these concepts from the physical representation of the test probe. Although a discussion of this and other candidate explanations is beyond the scope of this paper, it seems evident that any assumed direct correspondence between concepts and nodes in memory is at best only a useful simplification.