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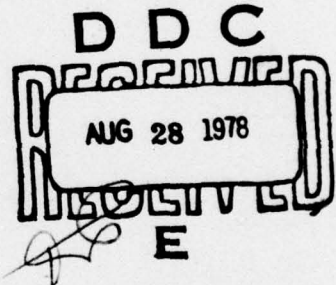
AN ATTENTIONAL APPROACH TO INDIVIDUAL

DIFFERENCES IN IMMEDIATE MEMORY

by

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June 1978

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) AN ATTENTIONAL APPROACH TO INDIVIDUAL DIFFERENCES IN IMMEDIATE MEMORY		5. TYPE OF REPORT & PERIOD COVERED Final Technical Report - 1 April 1977 — 31 May 1978
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Marcy Lansman		8. CONTRACT OR GRANT NUMBER(s) N00014-77-C-0225
9. PERFORMING ORGANIZATION NAME AND ADDRESS Department of Psychology, NI-25 University of Washington Seattle, Washington 98195		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 61153N RR 042-06, RR 042-06-01 NR 154-398
11. CONTROLLING OFFICE NAME AND ADDRESS Personnel Training Research Programs Office of Naval Research (Code 458) Arlington, Virginia 22217		12. REPORT DATE June 1978
		13. NUMBER OF PAGES 137
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) RR042 0601		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Psychology, attention, memory, individual differences, verbal ability

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The purpose of this research was to study individual differences in the ability to maintain a set of items in memory while performing a second task. It was hypothesized that attentional factors might determine a person's ability to combine memory maintenance with other tasks, and that these attentional factors might be related to verbal ability.

The results from Experiment 1 indicated that rehearsal and response to a probe stimulus compete for processing capacity, since reaction time

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to the probe varied with difficulty of rehearsal. Furthermore, reaction time to the probe during an easy version of the recall task predicted proportion of items correctly recalled on a hard version of the recall task. Neither recall nor probe reaction time was related to verbal ability.

In Experiment 2, verbal ability was found to be strongly related to reaction time on a simple sentence verification task, but only weakly related to measures of immediate memory. When sentence verification and recall were combined into a dual task, prediction of verbal ability was not improved.

Results from Experiments 2 and 3 indicated that a few items can be maintained in memory without interfering with a sentence verification task. It was concluded that a few items can be held in memory for a short period without requiring processing capacity. The number of items that can be maintained "effortlessly" is related to digit span, but not to verbal ability. Maintaining additional items did interfere with the sentence verification task, but amount of interference was not related to verbal ability.

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INTRODUCTION

Most measures of immediate memory tap memory capacity. They measure how many items an individual can hold in memory for a period of seconds. Recent theories of attention suggest that immediate memory has another important dimension: The amount of attention or effort necessary to maintain a load in immediate memory. This second dimension may actually be more important than the first. Very seldom in the course of every-day thinking are we asked to remember an unrelated list of items that challenges our well-known immediate memory span of "seven-plus-or-minus-two" items. Much more commonly we are asked to hold a small amount of material in memory while we take in or manipulate other information. Success in this second situation depends on the attentional demands of memory: If much effort is required to maintain the memory load, little effort is available to process other information. The purpose of this research is to examine individual differences in the attentional demands of immediate memory. The main question to be addressed is whether the attentional demands of immediate memory represent an important source of variation in verbal ability.

Background for the research lies in three rather disparate branches of cognitive psychology: memory, attention, and individual differences. Research from each of these three areas is reviewed in the introduction, which is organized as follows: First, the

general concept of attention is discussed. Evidence is cited to support the claim that maintaining material in immediate memory requires attention. Two theories of attention are described and within each theory, possible sources of individual differences are isolated. Finally, recent cognitive approaches to the study of individual differences are described, and a new approach is suggested which draws upon the concepts of attentional theory.

The Concept of Attention

The basic observation that must be dealt with by any theory of attention is that we are limited in the number of things we can do at one time. Obviously we cannot look in opposite directions simultaneously, or press two buttons with the same finger. Such peripheral limitations are said to result from <u>structural interference</u> (Kahneman, 1973). But besides structural interference, there is a more central limitation in the amount of information we can process at one time. This limitation lies behind the theoretical concept of attention.

Limitations in attention are the source of non-structural interference between tasks. If two tasks that do not compete for the same sensory or motor system interfere with one another, the tasks are said to require attention. Different theorists attribute attentional limitations to either a <u>limited capacity processor</u> or a central pool of <u>mental resources</u>. Their theories will be discussed in more

detail in a later section. Within all theories, however, the attentional demands of a task are gauged by the interference that results when the task is combined with other tasks. Thus, in the following section, instances of interference between memory maintenance and other tasks will be cited in order to support the assertion that memory maintenance requires attention. The terms effort, resources, and processing capacity will be used synonymously with attention although they are associated with different theories.

Attentional Demands of Immediate Memory

Three components of memory have often been differentiated: encoding, retention, and retrieval (Melton, 1963; Murdock, 1974). Retention, is of primary concern here. To what extent does retention of a memory load for a period of seconds require attention? Two types of studies indicating that retention requires attention will be reviewed: a) those in which recall is impaired by the insertion of a distractor task into the retention interval, and b) those in which performance on a secondary or distractor task is affected by variations in memory load.

Deliberate rehearsal may or may not be involved in maintaining a memory load. The terms memory maintenance and retention will be used here in order to avoid assumptions as to subject strategies. On the other hand, rehearsal will be used when it is assumed that the subject has adopted an active, conscious strategy to maintain

material in memory.

Effects of a distractor task on recall. Probably the most
dramatic demonstrations that retention does require processing capa-
city were the original memory-distractor experiments (Brown, 1958;
Peterson & Peterson, 1959), which showed that a memory load of as
few as three items is almost completely forgotten within 15 sec
if subjects perform a filler task in the retention interval. The
classic interpretation of the Brown-Peterson results is that short-
term memory decays when rehearsal is prevented. According to this
view, rehearsal is an all-or-none process, and the crucial function
of the distractor in this paradigm is to prevent rehearsal. This
point of view was clearly represented by Reitman (1971, 1974), who
first argued that her signal detection distractor task successfully
prevented rehearsal, but then found evidence that it did not.

A somewhat different interpretation of the memory-distractor
paradigm is suggested by attentional theory. It seems reasonable
to say that the function of the distractor task is to prevent the
subject from devoting processing capacity to the recall task.
According to this view, the question is not whether the distractor
task prevents rehearsal, but how much processing capacity is required
by the distractor and how much is left for memory maintenance.

Posner and Rossman (1965) were the first to directly vary the
demands of the distractor and observe the effects on recall.

Subjects were presented with six-digit sequences and required to transform one or more pairs of these digits according to various rules. The rate of forgetting of the initial pair increased with the amount of information reduction involved in the transformation of subsequent pairs. Posner and Rossman suggested that memory maintenance should not be considered an all-or-none process analogous to covert speech. Rather, memory maintenance should be seen as a process which uses whatever capacity or attention is available.

Brown (1958), Peterson and Peterson (1959), and Posner and Rossman (1965) all used verbal distractor tasks and found that memory deteriorated quickly over the retention interval. Reitman (1971, 1974) and Shiffrin (1973), on the other hand, used signal detection as the distractor task and found almost no forgetting. One might conclude from these studies alone that retention does not require attention, but competes with verbal distractor tasks for some specific verbal mechanism. In other words, structural interference, not attentional limitations, might be thought to account for the decrement. However, other experiments have shown that non-verbal distractor tasks can also cause forgetting. For example, Watkins, Watkins, Craik and Mazuryk (1973) found that a distractor task consisting of pressing keys in response to tones caused forgetting. However, verbal distractors do seem to interfere far more with memory maintenance than non-verbal distractors. There are at

least two possible explanations: a) verbal distractors require
more capacity than do non-verbal distractors or b) besides com-
peting for general processing capacity, verbal rehearsal and ver-
bal distractors compete for a specific verbal mechanism.

Effects of a memory load on other tasks. Crowder (1967) re-
lated the memory-distractor paradigm to other dual-task paradigms,
and measured not only recall but distractor performance as well.
Subjects were presented with five words, performed a distractor task
for 24 sec, then recalled the words. The distractor task involved press-
ing a key each time a light appeared. The task was serial, i.e., each
time a key was pressed a new light appeared. Three aspects of the
distractor task were varied: compatibility of the key-light relation-
ship, redundancy of the sequence of lights, and the subject's pre-
vious practice at keypressing. Both recall and rate of keypressing
showed that the two tasks interfered with one another: Keypressing
was slower when the subject was maintaining the memory load than in
a control condition, and more forgetting occurred when the key-light
relationship was incompatible than when it was compatible. This
study showed that the memory-distractor paradigm can be viewed as a
dual task in which there is a trade-off between performance on one
task component and the capacity demands of the other component.
Not only does recall suffer as a result of the distractor task, but
the distractor task may suffer as a result of the memory load.

Following Crowder (1967), a number of investigators studied

performance on various tasks as a function of the demands of a simultaneous memory load. For example, Stanners, Meunier, and Headley (1969) required subjects to turn off a buzzer during rehearsal of 6-8-item lists. Reaction time was much longer during rehearsal than in a no-rehearsal control condition. Shulman and Greenberg (1971) showed that ability to identify a tachistoscopically presented number decreased as memory load was increased from three to ten letters. Similarly, reaction time to indicate which of two lines was longer increased as a function of size of the memory load. In three separate experiments using tracking as a secondary task, Johnston, Greenberg, Fisher, and Martin (1970) showed that tracking performance decreased as a function of the demands of retention. These studies provide another line of evidence that memory maintenance competes with other tasks for attention. The interference could not have resulted from competition for some specific verbal mechanism since the tasks showing interference were non-verbal. A more general attentional limitation is necessary to account for the interference between retention of a verbal memory load and performance of a non-verbal task.

The issue of whether rehearsal and non-verbal distractor tasks actually do compete for processing capacity has recently been revived by Roediger, Knight, and Kantowitz (1977). They argued that in order to show that rehearsal and a distractor task actually compete for capacity, it is necessary to show that an increase in

the capacity demands of one results in a decrease in performance on
the other. It is not enough to show that either recall or distractor
performance is worse in a combined condition than in a single-task
control condition, since single- and dual-task situations are not di-
rectly comparable. Roediger et al. found that increasing the dif-
ficulty of a tapping task which functioned as a distractor did not
cause a decrease in recall. In spite of their own warning that one
cannot generalize from one distractor task to another, Roediger et
al. argued on the basis of these results that verbal rehearsal and
non-verbal distractor tasks do not draw on the same sources of
capacity. While this conclusion seems unwarranted, these results
and others suggest that it is easier to show that the difficulty
of a recall task affects performance on a secondary task than it is
to show that the difficulty of a distractor affects recall.

Memory and sentence verification. Baddeley and Hitch (Baddeley
& Hitch, 1974; Hitch & Baddeley, 1976), though not directly interested
in the processing demands of retention, did a series of studies that
are very relevant to the topic. They were interested in the ques-
tion of whether we use short-term memory during the course of simple
problem solving and hypothesized that if problem solving does require
short-term memory, then asking a subject to maintain a short-term
memory load during problem solving should prolong solution time.
Although Baddeley and Hitch used different terminology, the question

they were asking seems empirically indistinguishable from the question of whether memory maintenance and problem solving compete for processing capacity.

Baddeley and Hitch presented the subject with a list of letters. The subject then responded "True" or "False" to an item of the type:

<div align="center">

A precedes B.   AB

or   B is followed by A.   AB

</div>

After responding, the subject was asked to recall the letters. When the memory load consisted of one or two items, recall was virtually perfect and memory load had no effect on solution time. When the memory load was six items, its effect on solution time depended on the relative emphasis placed on the two components of the task in the instructions. If the tasks were given equal emphasis, then recall suffered substantially, but solution time was no longer than in a control condition. If recall was emphasized, then solution time was increased over the control condition and recall suffered only slightly. These results are certainly in line with the theory that there is a capacity trade-off between recall and distractor performance. However, subject reports and trial by trial analysis of the data raised doubts as to whether capacity was actually being shared between the two tasks. Subjects reported that in the recall-emphasis condition they quickly rehearsed the to-be-recalled items once, then solved the problem. In the equal-emphasis condition they

made no effort to rehearse the memory items. Subject introspection was supported by the data, which showed that solution time in the memory-emphasis condition was delayed a constant amount over all levels of complexity of the problem. If memory maintenance and problem solution had actually shared capacity, the effect of the memory load would be expected to be greater for more complex problem types. Furthermore, within each condition, shorter solution times were accompanied by higher recall, which is the opposite of what would be expected were there a trade-off between the two components.

Two aspects of the Baddeley and Hitch results are troubling to those who hope to find a simple relationship between memory maintenance and processing capacity. First, memory loads of up to two items did not interfere at all with distractor performance. Baddeley and Hitch (1974) concluded that there is a small "buffer" within working memory that is dedicated to storage and therefore does not interfere with other functions. Translating their ideas into attentional terminology, we might hypothesize that a small number of items can be held in memory for a period of a few seconds without requiring processing capacity.

Second, the extent to which a six-item memory load interfered with sentence verification depended on whether the instructions stressed the memory task. It may be, after all, that the relationship

between memory maintenance and processing capacity depends in a cru-
cial way on subject strategy--in particular, on whether the sub-
ject attempts to rehearse. If the subject attempts to rehearse, then
the presence or size of the memory load will affect distractor or
secondary performance significantly (Baddeley & Hitch, 1974, memory
stress condition; Shulman & Greenberg, 1971; Stanners et al., 1969).
However, if the subject does not attempt to rehearse the memory load,
then there may be little or no effect on the distractor (Baddeley &
Hitch, 1974, equal stress condition). Similarly, if the distractor
prevents or severely reduces rehearsal over a control condition, then
the effect on recall will be dramatic (Peterson & Peterson, 1959;
Posner & Rossman, 1965). But when the difficulty of the distractor
is varied without affecting the likelihood of rehearsal the effect
of distractor difficulty is less consistent (Crowder, 1967) and some-
times insignificant (Roediger et al., 1977).

Theories of Attention

In the last section, instances of interference between retention
and other tasks were cited to support the assertion that memory main-
tenance requires attention. However, the argument remains somewhat
vague unless it is put in the context of a specific theory of atten-
tion. The terms attention and processing capacity, though more and
more commonly used in cognitive psychology, vary in meaning from
one theory to another, and are actually quite poorly defined within

many theories. In this section, two contrasting theories of attention will be described briefly with particular emphasis on the concept of processing capacity.

The Limited Capacity Processor Model. Broadbent (1958) popularized the notion of man as an information channel. He and many other theorists have tried to identify attentional limitations with a particular stage in the flow of information from sensory input to motor output. Broadbent felt that the attentional "bottleneck" occurs before the stimulus is identified. According to his model, a filter, which operates mainly on the basis of physical characteristics, selects only one stimulus at a time to enter a limited capacity channel. A second signal cannot enter until processing of the first is finished.

Various experimental results since 1958 have made a strict interpretation of Broadbent's filter model untenable. For example, there is evidence that selection can be made on the basis of semantic characteristics of the stimulus, which suggests that identification can take place before selection (see Deutsch & Deutsch, 1963). But Broadbents's notion that the source of attentional limitations is a bottleneck somewhere in the flow of information has survived in many more recent models of attention. Representative of these models is the first model to be considered here, that advanced by Posner and Keele (Keele, 1973; Posner & Boies, 1971, Posner & Keele, 1970).

This model will be referred to as the <u>Limited Capacity Processor Model</u>.

Posner and Keele have argued that the bottleneck occurs beyond the identification or pattern recognition stage of information processing. Additional limitations arise because mental operations beyond this stage require a <u>limited capacity processor</u>. Operations that do not require the limited capacity processor, most notably long-term memory access, can occur automatically and in parallel without interfering with each other. Operations which do require the limited capacity processor, such as response selection and execution and many aspects of problem solving must be carried out serially and therefore do interfere with each other. According to this theory, rehearsal is one of the processes that require the limited capacity processor (Keele, 1973; Posner & Keele, 1970).

Recently the distinction between automatic processes, which do not require the limited capacity processor, and non-automatic processes, which do, has received support from the research of Schneider and Shiffrin (Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977). These researchers have identified two very distinct modes of recognition in visual search and memory scanning paradigms: a) automatic detection, which involves well-learned categories, is extremely rapid and can take place in parallel; and b) controlled search, which involves less well-learned categories, is much slower and proceeds

serially. Schneider and Shiffrin have developed a theory of attention which could easily be considered an extension and refinement of Posner and Keele's earlier ideas.

For the purposes of this paper, the most important features of the Limited Capacity Processor Model are: a) the dichotomy between automatic and control processes in which only the latter require the devotion of a limited capacity processor, and b) the assertion that all processes that involve the limited capacity processor must take place serially.

The Limited Resources Model. Rather than locate the attentional bottleneck at any particular point in the information processing system, Kahneman (1973) denied that there was a bottleneck. According to his model, which is closely related to ideas advanced earlier by Moray (1967), all mental processes draw from the same sources of processing capacity (also called resources, attention, or effort). This common pool of processing capacity is limited, although it increases somewhat as increasing demands are placed upon it. Thus, this model will be referred to as the Limited Resources Model. Within this model, interference can occur between any pair of tasks if the combined processing demands of the two tasks exceed the total processing capacity. Kahneman specifically notes that rehearsal requires processing capacity.

Norman and Bobrow (1975) advanced a theory of attention very similar to Kahneman's, but with some conceptual innovations. Norman and Bobrow, like Kahneman, asserted that all processes compete for resources, and that interference occurs when the demands of two tasks exceed the available resources. They introduced the concept of a performance-resource function, a function that describes how performance on a task varies as a function of the amount of resources devoted to that task. At various points on the performance-resource function, a process may be either <u>resource-limited</u> or <u>data-limited</u>. A process is resource-limited if an increase in resources will produce an increase in performance and data-limited if an increase in resources will have no effect on performance. Norman and Bobrow also introduced the concept of a <u>performance-operating characteristic</u> (POC), which describes the trade-off between performance on two tasks performed simultaneously.

The important features of the Limited Resources Model as compared to the Limited Capacity Processor Model are that a) there is no class of automatic processes that are free of processing capacity requirements, and b) it is theoretically possible for any two processes to take place in parallel as long as the processing demands of the two tasks do not exceed the available capacity.

Possible Sources of Individual Differences

The purpose of this paper is to study individual differences

in the attentional demands of memory maintenance. The critical
question is, "How do people differ in their ability to hold material
in memory while carrying out other mental processes?" Having
briefly summarized two theories of attention, it is now reasonable
to ask what the possible sources of individual differences are
within each theory. This discussion will provide a foundation for
the empirical study of the individual differences.

Sources within the Limited Capacity Processor Model. Accord-
ing to Posner and Keele, rehearsal requires the limited capacity
processor. Within this theoretical framework there appear to be at
least four possible sources of individual differences:

a) The simplest possible source, and perhaps the hardest to
confirm empirically, would be that in some individuals the limited
capacity processor is more efficient than in others. Efficiency,
in this sense, refers to the amount the processor could accomplish
in a given time period. Suppose, for example, that a person was
asked to hold five items in memory for 6 sec while simultaneously
performing a tracking task, and that the memory task was primary.
The limited capacity processor would have to switch between rehearsal
and tracking, since neither task is entirely automatic. A person
with a more efficient processor would be able to devote less time
to rehearsal and still recall the five items perfectly. This
would free more time for the tracking task and presumably lead to

better tracking performance.

Efficiency of the processor might be specific to rehearsal, or it might be a general characteristic applying to all non-automatic processes. If it were a general characteristic, we would expect measures of memory efficiency to be highly correlated with a wide variety of other measures of processing efficiency. If efficiency were specific to rehearsal, we would expect memory measures to be independent of processing measures that did not involve memory maintenance.

b) Individuals also might differ in the speed with which they switch attention (i.e., switch the limited capacity processor) between rehearsal and other processes. This would allow some people to combine rehearsal with other forms of processing more efficiently than others. Posner (Posner, Nissen & Klein, 1976) and others (LaBerge, 1973) have found that it does take time to switch attention from one sensory channel to another. Furthermore, Gopher and Kahneman (1971) have found that the ability to switch attention from one ear to another is related to the proficiency of military pilots. Poltrock (Note 3) found that Gopher and Kahneman's measure of attention switching was also related to verbal ability in the college population. Thus it does not seem implausible that the speed of switching between rehearsal and other processes could be an important source of individual differences in memory efficiency.

c) Individuals might differ in conscious rehearsal strategies. Use of a good rehearsal strategy, such as grouping items, might allow a person to devote less processing time to the maintenance of a given memory load. This would free more time for other processing demands.

d) Individuals might differ in strategies for allocating processing time to different tasks. Some allocation strategies might allow for more efficient use of processing time than others. For example, in the dual task described above, a good allocation strategy might be to rehearse the five items once before beginning the tracking task.

Sources within the Limited Resources Model. According to the attentional theories of Kahneman and of Norman and Bobrow, rehearsal and all other forms of information processing require processing capacity. However, rehearsal and other processes can occur simultaneously without interference as long as total processing demands do not exceed processing capacity. Within these theories, there appear to be at least five potential sources of individual variation:

a) One individual might have more total processing capacity than another. This would increase the likelihood that rehearsal could be combined with other processes without interference. If differences in total capacity were the principal source of variation in measures of memory efficiency, then one would expect these

measures to be highly correlated with a wide variety of other cog-
nitive measures, especially those involving several components.

b) Individuals might differ in the performance-resource func-
tion relating recall to the resources devoted to retention. For
example, the rate of increase in recall as a function of resources
might be faster for one person than another. In other words, one
person's rehearsal processes might make more efficient use of re-
sources than another's. Unfortunately, we cannot directly observe
performance-resource functions, since we have no direct measure of
resources. Norman and Bobrow (1975) suggested that we study the
relationship between performance and resources by setting up a dual
task in which performance on two tasks can be measured as the resource
allocation between them is varied. The result would be a POC relat-
ing performance on the two tasks. If the POC functions for two
individuals differed, we might conclude that the individuals differed
in either total capacity or in their performance-resource functions
for one or both of the two tasks. Unfortunately, it would be impos-
sible to distinguish between these two possibilities on the basis
of one experiment. This point is illustrated mathematically in the
Appendix A.

c) According to Kahneman's theory, but not Norman and Bobrow's,
individuals might differ in the extent to which processing capacity
increases with increasing demands. It is very difficult to conceive

of an empirical test of this possibility just as it is very difficult to conceive of a test of the original assertion that capacity does increase with the demand placed on the system. A possible prediction is that individual differences would appear on difficult tasks or on dual tasks which were absent on simple or single tasks. Unfortunately, this prediction is by no means unique to this theory.

d) As in the Limited Capacity Processor Model, individuals might differ in conscious rehearsal strategies. One strategy might make more efficient use of resources than another.

e) Individuals might differ in strategies for allocating resources between two tasks.

Previous Approaches to the Study of Individual Differences

Rarely have individual differences been studied within the framework provided by theories of attention. Yet attentional concepts may provide a new approach to questions left unanswered by previous studies of individual differences. In particular, an attentional approach could help provide a link between conventional psychometric measures of verbal ability and theory-based measures provided by cognitive psychology.

Psychometricians have devised various measures of verbal skills which reveal large and reliable individual differences, which are highly intercorrelated, and which seem to predict school and job performance quite well. These include tests of vocabulary, reading

comprehension, analogies, and verbal reasoning. Ability to do well
on these various tests has often been lumped under the term <u>verbal
ability</u>. Hunt (Hunt, Frost, & Lunneborg, 1973; Hunt, Lunneborg, &
Lewis, 1975; Hunt, 1978), and more recently several other congitive
psychologists (Hogaboam & Pellegrino, 1978; Jackson & McClelland,
in press; Perfetti & Lesgold, 1977) have attempted to explain, in terms of
recent models of cognition, exactly how individuals of high and low
verbal ability differ. Psychometricians seem to have identified an
important source of variation in intellectual functioning; it has
been the aim of these cognitive psychologists to analyze this
variation in terms of simpler processes that make up our models of
cognition.

Most models of cognition specify the stages of information pro-
cessing which intervene between sensory input and motor response.
Insofar as these models provide a complete analysis of cognitive pro-
cessing, it should be possible to explain variation in psychometric
test scores in terms of the stages specified by the models. In
some cases the analysis might describe processes that actually take
place during the test. Suppose, for example, that we wanted to
describe the difference between people who scored high and low on
a psychometric test of reading comprehension in terms of a particular
model of reading. In this case we would hope to show that high- and
low-scoring individuals differed in some stage of processing

required by the actual reading test. In other cases the analysis might describe processes involved in acquiring the knowledge required to take the test. For example, we would expect to explain the difference between people who score high and low on a vocabulary test not so much in terms of the processes involved in taking the test as in terms of the processes involved in acquiring the vocabulary.

In an effort to relate verbal ability to models of cognitive processing, many theory-based measures of cognitive processes have been developed. The vast majority of these measures fall into two categories: reaction-time measures and recall measures. Reaction-time tasks have been designed to measure the speed of various cognitive processes, while recall tasks measure various parameters of the memory system.

Reaction time and verbal ability. Most reaction-time measures used to study individual differences involve a choice between two possible responses. The main concern is the relationship between verbal ability and the processes involved in choosing the correct response in reaction-time tasks. However, we might first ask whether the sensory and motor processes that are components of any two-choice reaction time task are related to verbal ability. A task which measures these components but does not seem to involve complex cognitive processes is a highly compatible two-choice reaction-time task in which the subject is required to press a key on the left if

a stimulus appears on the left side of a screen and a key on the right if the stimulus appears on the right. Within a broad subject population, there may be a low correlation between reaction time on this task and verbal ability (Lunneborg, 1977), but in the college population the correlation seems to be near zero (Lunneborg, 1977).

Reaction-time tasks that are related to verbal ability in the college population generally involve two processes: encoding of verbal stimuli and comparison of these stimuli. One example is the name-identity condition of Posner's letter-matching task (Posner & Mitchell, 1967). Here the subject is asked to respond as to whether two letters not identical in shape have the same name. The correlation between reaction time and verbal ability is between .3 and .4 in the college population (Jackson & McClelland, in press; Lansman, Note 2). A second example is the sentence-verification task used by Clark & Chase (1972). Here the subject sees a sentence (e.g. PLUS ABOVE STAR) and a picture (e.g., $^+_*$), and must respond as to whether the sentence is a true description of the picture. Again there is a moderate correlation between reaction time and verbal ability (Lansman, Note 2). Although the two tasks are quite different, in both cases verbal stimuli must be encoded and a comparison made, and in both cases a moderate correlation with verbal ability has been found.

Reaction times based on comparisons which do not involve encoding

verbal stimuli show lower, usually insignificant correlations with
verbal ability. For example, correlations between verbal ability
and reaction time in the physical-identity condition of the Posner
letter-matching task, where the comparison can be made on the basis
of shape alone, are lower than in the name-identity condition (Jackson
& McClelland, in press; Lansman, Note 2). Reaction time to compare
non-verbal symbols or dot patterns is uncorrelated with verbal
ability (Jackson & McClelland, in press).

Are reaction times which involve encoding, but not comparison,
of verbal stimuli correlated with verbal ability? Jackson and Mc-
Clelland (in press) found that minimum exposure time necessary
for a subject to correctly name a letter was not correlated with
verbal ability. But since the measure in this task is a threshold
measure, not reaction time, the study is not, strictly speaking, com-
parable to the others cited here. In an effort to isolate the encod-
ing stage of processing, Hunt (e.g., 1978) has looked at the differ-
ence between name-identity and physical-identity reaction times in
the Posner letter-matching task. If we can assume that the two
tasks are identical except that the name-identity condition requires
encoding the names of the letters and the physical-identity condition
does not, then the difference should reflect encoding speed. The
difference is indeed moderately correlated with verbal ability. Thus
there is evidence that encoding speed is related to verbal ability.

Recall measures and verbal ability. Cognitive psychologists have also studied individual differences in various measures of memory capacity. The most common measure of memory capacity is digit span. Digit span has long been a part of various intelligence tests, and is known to be moderately correlated with other tests of intelligence. The average correlation of digit span with other sections of the WAIS is .43 (Matarazzo, 1972). However, Matarazzo pointed out in his discussion of the digit span subtest of the WAIS that digit span is more useful in discriminating the grossly retarded from the normal population than in distinguishing between normal individuals of different levels of intelligence. Other studies have substantiated this assertion, showing that within the college population digit span is not highly correlated with measures of verbal intelligence (Jackson & McClelland, in press; Underwood, Boruch, & Malmi, Note 4).

Martin (1978) found that digit span was related to measures of memory for order information but not to any of a number of theoretical measures of short-term memory capacity. Is short-term memory capacity related to verbal ability? No study has found a strong relationship between the two although in some cases high- and low-verbal ability subjects have been found to differ somewhat on measures of short-term memory capacity. Perfetti and Lesgold (197) reviewed a number of studies relating short-term memory and verbal

comprehension and concluded that where there was a relationship, it was based on encoding differences, not differences in short-term memory capacity. Crowder (1976) concluded that short-term memory capacity is virtually constant across variations in age, intelligence, and mnemonic ability.

It does not make sense to talk about individual differences in long-term memory capacity, since according to most models long-term memory capacity is unlimited. But many traditional memory tasks, such as free recall, and paired-associate learning, measure ability to store and retrieve items from long-term memory. Underwood et al. (Note 4) have done an extensive study in which they related perfor-. mance on a great variety of these memory tasks to verbal ability. In no case was the correlation above .31, and the majority of correlations were below .20. Thus these measures, which reflect long-term memory storage and retrieval, are only weakly related to verbal ability.

It has been hypothesized that memory for order information is more strongly related to verbal ability than memory for item information (Hunt et al., 1973; Perfetti & Lesgold, 1977), but the data are by no means clearcut. For example, in a study of release from proactive inhibition in short-term memory, Hunt et al. (1973) found that scoring recall for order as well as item information resulted in a bigger difference between high and low verbal-ability subjects. But in a

later study using a similar short-term memory paradigm, (Hunt
et al., 1975) they found that errors in order information were no
more highly related to verbal ability than errors in item information.
Thus this issue is unresolved.

To summarize, reaction-time measures involving encoding and com-
parison are related to verbal ability, but the relationship is not
strong. Many types of recall measures, including those stressing
recall for order, are also weakly related to verbal ability. Al-
though some progress has been made toward analyzing psychometric
measures in terms of cognitive processes, the picture is not com-
plete. Measures of speed and memory capacity account for a relative-
ly small proportion of the variance in verbal ability. The hypo-
thesis underlying the research proposed here is that important dif-
ferences arise in the combination of simple processes, which are not
evident when these processes are studied alone. An attentional
analysis of performance on dual tasks may account for variation in
verbal ability which now remains unexplained.

An Attentional Approach to Individual Differences

Stage theories of information processing describe the sequence
of processes that takes place when a single stimulus is presented
and a single response made. In fact, though, we seldom make a sin-
gle response to a single stimulus. Stimuli arrive in quick succession,

so that while the first stimulus is being processed, the second one
arrives, and often output from processing the first and second sti-
muli must be stored while the third and fourth are processed, and so
on. Language comprehension is a perfect example of a real life situa-
tion where stimuli arrive in quick succession, several types of pro-
cessing must go on simultaneously, and the results of processing the
initial stimuli often must be held in memory and used in processing
later stimuli. It could easily be that parameters of the separate
processes involved in a complex task like language comprehension
cannot account for differences in ability to combine the processes
successfully. Factors which arise only in the combination of several
simple processes may be crucial in the analysis of verbal ability.
Of particular importance may be the ability to hold verbal material
in memory while new stimuli are being encoded and processed.

The attentional theories described earlier provide a means
for explaining why neither speed nor memory capacity measures may
be sufficient to account for individual differences in complex
verbal tasks. First consider the problem viewed from the framework
of the Limited Resources Model: I have argued that the ability
to hold material in memory while processing other information might
be related to either total processing capacity or to the performance-
resource functions of the two task components. But the speed meas-
ures associated with many simple processes may be, in Norman and

Bobrow's terminology, data-limited. That is to say, although speed
is a characteristic that varies across individuals, within an in-
dividual increasing the resources allocated to a simple speeded task
may not increase the speed on that task. Similarly, memory capacity
measures may be data-limited. Beyond a certain minimum resource al-
location, increasing the resources allocated to a memory task such
as digit span may not cause an increase in performance. If this
were the case, then neither speed nor memory capacity measures
would give any indication of total processing capacity or of the
relevant performance-resource functions.

Consider, for example, the performance-resource functions illus-
trated in Figures 1a and 1b. Each function shows recall as function
of processing capacity devoted to memory maintenance for two
hypothetical subjects. In Figure 1a, both subjects, S_1 and S_2, have
identically shaped performance-resource functions, but S_1 has more
total capacity than S_2. Total capacity for S_1 is T_1 and for S_2 is
T_2. When asked to do the recall task alone, both subjects devote
their total capacity to the task. S_1 performs at P_1 on the curve,
S_2 at P_2, and both obtain a recall score of N items. However, if
these subjects were asked to perform a secondary task simultaneously
with the recall task, S_1 would be more successful, since S_2 must
devote total capacity to maintaining a memory load of N items, but
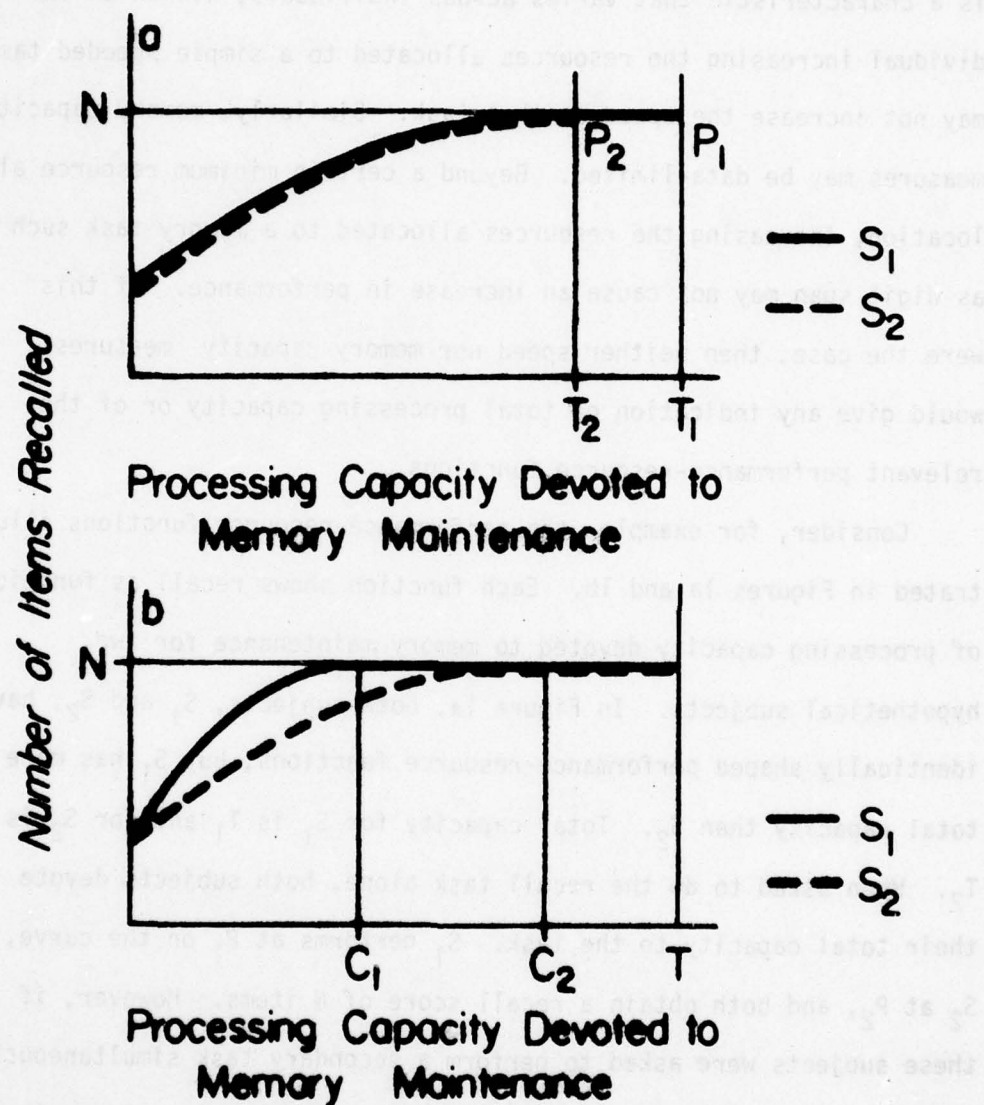
Figure 1. Performance-resource functions relating recall and capacity devoted to memory maintenance for two hypothetical subjects. a. The two subjects have identical performance-resource functions but differ in total processing capacity. b. The subjects have the same total processing capacity but different performance-resource functions.

S_1 can maintain N items with capacity to spare for the other task.

In Figure lb both subjects have the same total capacity, T, but the shapes of their respective performance-resource functions differ. For S_1 recall increases faster as a function of resources devoted to the task than for S_2. Their performance is equal when each is devoting total capacity to the recall tasks. (Each recalls N items.) But if they were asked to combine recall with a secondary task, S_1 would do better. S_1 could maintain N items in memory by devoting only C_1 capacity to the task, whereas S_2 would have to devote C_2 capacity to the task. Thus S_1 would have more spare capacity to devote to the secondary task than S_2. Performance in a dual task might reveal differences between these two individuals that were not evident from performance on the single recall task. These differences might prove important in the complex combinations of processes required by psychometric tests.

Within the Limited Capacity Processor Model, efficiency of the limited capacity processor but not total processing capacity is a possible source of individual differences. To understand how efficiency of the limited capacity processor might be important to performance on dual- but not single-task measures within this theory, consider Figure 2. Figure 2 is identical to Figure lb except that the variable represented by the abcissa is "Time the Limited Capacity Processor is Devoted to Memory Maintenance" instead of "Processing

Number of Items Recalled

N

— S₁
--- S₂

T

Time the Limited Capacity Processor Is Devoted to Memory Maintenance
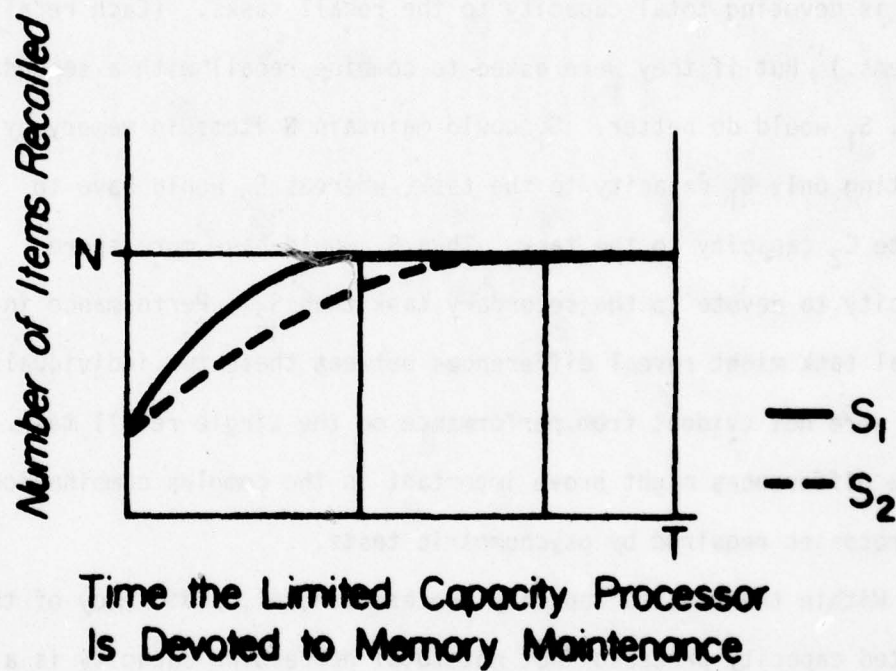
Figure 2. Functions relating recall to time the limited capacity processor is devoted to memory maintenance for two hypothetical subjects.

Capacity Devoted to Memory Maintenance." S_1 and S_2 achieve identical performance when the limited capacity processor is entirely devoted to the recall task during its duration, T. But if a secondary task were added, S_1 could do better, since S_1 can maintain N items in memory with a smaller expenditure of limited capacity processing time. Thus a primary-secondary task combination would reveal differences between these two subjects which are not evident from performance on the primary recall task alone.

Within either of the two attentional theories, attention switching is a possible source of individual differences in dual or complex task performance. Yet differences in ability to switch attention or in speed of switching would not be reflected in single-task measures. Similarly, strategies for combining rehearsal with a second task would not influence measures of either task alone. Only multiple-task combinations would tap these possible sources of variation.

Thus, attentional theories suggest why single-task measures previously used by cognitive psychologists may fail to account for individual differences on complex tasks. These measures were attempts to isolate various parameters of information processing. But even if it were possible to measure the parameters of each stage of information processing, such measures might fail to account for individual differences that appear in the performance of complex tasks. Complex tasks require that several processes take place simultaneously

or in quick succession. And individual differences may arise in the
combination of various processes that are absent when these pro-
cesses take place in isolation. Theories of attention help explain
exactly why this may be the case.

Proposed Research

Complex verbal tasks often involve holding a load in memory
while encoding and manipulating other verbal input. Theories of
attention postulate that memory maintenance and other processes com-
pete for limited processing capacity. Success on complex verbal
tasks may depend on the processing demands of memory maintenance.
Since capacity is interchangeable between memory maintenance and
other processes, when more capacity is required by maintenance, less
is available for other processes. Subjects who can maintain a mem-
ory load with more capacity to spare for other processes should do
better on complex verbal tasks. The research reported here represents
an initial effort to investigate these ideas.

Measurement is the first problem to be handled by such a research
effort. Can we develop reliable measures that reflect the processing
demands of memory maintenance? How are these measures related to
measures of memory capacity? Do such measures lend validity to the
idea that an individual's processing capacity is interchangeable be-
tween memory maintenance and other processes? These questions were
dealt with in Experiment 1.

I have argued that there are several possible sources of varia-
tion in performance on dual tasks which are irrelevant to single-task
performance, and that these sources of variation may be related to
verbal ability. Is performance on the two components of a dual task
highly correlated with performance on their single-task counter-
parts? Or does a time-sharing factor arise that affects dual-task
but not single-task measures? If there is such a time-sharing
factor, does it affect correlations with verbal ability? These
questions were addressed in Experiment 2, in which dual- and single-
task measures were compared to one another and to general verbal-
ability measures.

If the processing demands of memory maintenance are related to
verbal ability, then ability groups should differ in efficiency
with which they can combine memory maintenance and other tasks. In
this case, the function relating memory load to performance on a
second task should be different for different ability groups. This
hypothesis was tested in Experiment 3.

Verbal ability is a concept which has emerged from psychometric
analysis of test scores. It has been found to be the most accurate
predictor of school and job performance available. We need to know
whether to continue to look for the theoretical roots of verbal
ability in the parameters of simple psychological processes, or to
look for these roots in the way people combine simple processes.

The research reported here may suggest which is the more promising approach to take.

OVERVIEW OF THE EXPERIMENTS

In the first experiment, a memory task was combined with a secondary task chosen to interfere as little as possible with re- hearsal processes. Thus performance on the secondary task could be considered a measure of the spare capacity associated with rehearsal. This experiment involved easy and hard versions of a continuous paired-associate memory task. Spare capacity associated with re- hearsal was measured by reaction time to a visual probe. The main purpose of the experiment was to study the relationship between spare capacity and recall. It was predicted that spare capacity associated with easy recall would be positively correlated with proportion correct on hard recall.

In the second experiment, a memory task was combined with a distractor task designed to demand a large proportion of subjects' total processing capacity and thus prevent voluntary rehearsal. Recall in this experiment measured subjects' ability to maintain a memory load while performing a second, capacity-demanding task. Performance on the distractor task was also measured. The purpose of the experiment was to find out whether performance measures based on this dual task predicted performance on two complex criterion measures better than performance on each of the components of the dual task measured separately.

The third experiment employed the same task combination as the

second, except that in this case the memory task was the primary
task. Subjects were instructed to devote as much effort to the
memory task as was necessary to attain almost perfect recall, and
to devote their remaining effort to the distractor task. Memory
load was varied from zero to five items, and distractor task perform-
ance was studied as a function of memory load. Subjects were high-
and low-verbal ability college students. The purpose of the experi-
ment was to find out whether the function relating distractor perform-
ance to memory load was different for high- and low-ability subjects.

EXPERIMENT 1

In this experiment, spare capacity associated with the rehearsal phase of a simple recall task was measured. This recall task was the continuous paired-associate, or "keeping track," task used by Atkinson and Shiffrin (1968). Reaction time (RT) to a visual signal presented during the retention interval was used as a measure of spare capacity associated with rehearsal. Digit span was also measured, and a psychometric measure of verbal ability was available for all subjects.

The spare capacity measure was assumed to reflect the processing demands of rehearsal. If these demands are relatively low, then the subject should respond quickly to the visual probe; if they are high, responses should be slower. The spare capacity measure may also reflect total capacity, since a person with more total capacity should have more capacity to spare during rehearsal.

The main purpose of the experiment was to find out whether spare capacity associated with an easy version of the recall task would predict performance on a harder version of the task. Such a result would validate the notion, drawn from attentional theories, that central processing capacity is interchangeable between two widely different tasks--rehearsal and simple RT. The interchangeability of processing capacity has been demonstrated in group studies where there is a trade-off between performance on two simultaneous tasks.

But it has yet to be shown on an individual basis that capacity available during an easy version of a task is a predictor of performance on a harder version.

Correlations between spare capacity and general verbal ability were also obtained. If spare capacity reflects the efficiency of rehearsal strategies specific to this recall task, then correlations with verbal ability should be low. But if spare capacity reflects total capacity, these correlations should be high.

The study was also designed to re-examine the question of whether verbal rehearsal and a simple non-verbal task compete for processing capacity. For this reason, RT to the visual probe was measured during both easy and hard versions of the recall task. RT should be longer during the hard recall task than during the easy one if both tasks actually compete for capacity.

Method

Subjects

Twenty-four male and 24 female freshmen at the University of Washington served as subjects in this experiment. They were selected on the basis of verbal ability.

Washington State high school students who plan to apply for admission to the University of Washington take the Washington Pre-College test in their junior year. Scores on the English Usage, Spelling, Reading Comprehension, and Vocabulary Subtests of this

examination are combined to yield a Verbal Composite score for each subject. The distribution of Verbal Composite scores in the freshmen class at the University of Washington was divided into approximate sixths. Four men and four women from each sixth were recruited as subjects in this experiment.

Subjects were paid $8.00 for participation in two 1½-hour sessions. Bonus points were awarded on the basis of performance in the experimental tasks, and each subject also received a bonus payment based on points earned.

Apparatus

The presentation of stimuli and recording of responses were under the control of a Data General Corporation NOVA 800 computer. Stimuli were presented on independently controlled Tektronix 602 cathode ray tube oscilloscopes. Subjects responded on a set of eight custom-designed telegraph-style response keys.

One to four subjects were run simultaneously but asynchronously in separate, partially soundproofed booths. Each was seated in front of a 10 cm by 13 cm oscilloscope screen with eight fingers resting on the eight response keys.

Tasks

Primary task. The primary task in this experiment was the continuous paired-associate recall task. Stimuli for the easy version of the task were A and B. Stimuli for the difficult version were

A, B, C, D, E, F, and G. Responses for both versions were the digits 1 through 8. Each block consisted of 48 trials, and was preceded by eight practice trials.

A typical sequence of events for the easy version is illustrated in Table 1. The subject initiated the block by pressing a key. Then each of the stimulus items appeared for 3 sec paired with a randomly chosen digit (e.g. "A = 3"). After this initial presentation of letter-digit pairs, the trials began. Each trial consisted of a question involving one of the stimulus items (e.g. "A = ?"), and a new pair involving that same stimulus item (e.g. "A = 4"). On each trial, the stimulus item to be queried was chosen randomly from the entire set.

The correct response to a question was the number with which the stimulus item had last been paired. A subject responded to the question by pressing one of eight numbered keys. After the response, a feedback message ("Right" or "Wrong") appeared on the screen. If a subject failed to respond for 10 sec, the message, "Too slow", appeared on the screen and an error was recorded. The feedback message lasted for 1 sec, then a new pair appeared, in which the stimulus just queried was paired with a new response. This new response was randomly chosen from the digits 1 to 8 with the restriction that it could not be the same as the digit last paired with that stimulus item. The new pair was presented for 3 sec and was followed immediately by the question for the next trial.

The term lag is used to indicate the number of stimulus pairs intervening between presentation of a stimulus item in a pair and

Table 1

Sequence of Events in Experiment 1

Event	Display	Duration
Sequential presentation of initial pairs.	A = 7 B = 3	3 sec 3 sec
Query. The correct answer is 3.	B = ?	Subject-paced
Letter just queried is paired with a new number.	B = 4	3 sec
(Visual probe: On 3/4 of the trials in the probe condition, asterisks appear 500, 1000, or 1500 msec after the presentation of the new pair. The subject presses any key as quickly as possible.	(****) B = 4	(If subject fails to respond to probe within 1.5 sec, the probe disappears.)
Query. The correct answer is 7.	A = ?	Subject-paced
Letter just queried is paired with a new number.	A = 5	3 sec

Presentation of a question involving that itme. Thus if the same stimulus item occurred on two consecutive trials, the second trial would be said to have occurred at lag 0. If one trial intervened between two presentations of the same stimulus, the second trial occurred at lag 1, and so on. Atkinson and Shiffrin (1968) showed that performance is much better at lag 0 than at any other lag. Since it was desirable in this experiment for the task to be of equal difficulty for every subject, the order of presentation of of stimuli was the same for all subjects. However, response items were randomized separately for each subject.

At the end of each block of trials, a message appeared telling each subject the percentage of digits recalled correctly.

Secondary Task. The secondary task required the subject to press any key as quickly as possible in response to a probe stimulus. The probe stimulus consisted of four asterisks which appeared im-mediately above a letter-number pair. Probes occurred on 36 of the 48 trials in the probe condition. They always occurred during the presentation of a new pair, never during a question. No probes oc-curred during the initial presentation of pairs in a block. An equal number of probes occurred at 500, 1000, and 1500 msec following the onset of a new letter-number pair. The order of probe and no-probe trials was random, as was the order of probe intervals.

Subjects responded to the probe stimulus by pressing any key as quickly as possible. As soon as a key was pressed, the stimulus disappeared. The probe stimulus disappeared after 1500 msec if the subject failed to respond. Subjects were given no feedback on secondary RTs until the experiment was over.

The primary and secondary tasks were entirely independent, i.e., neither the occurrence of, nor the response to, a secondary probe affected the sequence or timing of events in the primary task.

Digit span. Digit span was measured at the beginning of either the first or second day of the experiment. (For some subjects it was measured on both days, but only the first day's data was considered in the correlational analysis.) There were two blocks of trials. Each block consisted of 14 trials, two trials each on digit strings 4-10 items long. Two four-digit strings were presented first, then two five-digit strings, and so on up to two ten-item strings. There was a short break between blocks. On each day there were also five practice trials preceding the recorded trials, one trial each on digit strings 4-8 items long.

At the beginning of each trial a message was displayed on the screen indicating how many digits would be presented during that trial and instructing the subject to press a key to begin the trial. After a key was pressed, a warning signal appeared. One sec after time onset of the warning signal, the digits were displayed one at a time

for 750 msec each. Each digit was chosen randomly from the digits 1-8 with the restriction that no two consecutive digits could be the same. When all the digits had been presented, a message instructed the subject to recall the appropriate number of digits. The subject responded by pressing the keys corresponding to the digits that had been presented. When the correct number of keys had been pressed, a feedback message informed the subject how many items had been recalled in the correct position. Bonus points were based on the subject's average digit span (computed as described in the results section) over the two blocks on that day.

Procedure

Subjects were tested on two days. On both days there was one block of trials in each of the five conditions listed below.

RT Control. In this condition, subjects were instructed to ignore the letters and numbers and respond only to the probe stimuli. Letter-number pairs and questions appeared exactly as described under "Primary task," but questions remained on the screen for only 1 sec. Points in this condition were based on mean RT to probe stimuli.

Easy Recall-No Probe. In this condition, the subject was required to keep track of two stimulus items, A and B. No secondary probes appeared. Points in this condition were based on percentage of response items correctly recalled.

Easy Recall with Probe. Here the easy version of the paired-associate task was combined with the secondary RT task. Subjects were instructed that the recall task was more important than the RT task. Points in this condition were based on percent recall and mean RT to probe, with twice as many points possible for recall.

Hard Recall-No Probe. Here the subject was required to keep track of seven stimulus items, the letters A through G. No secondary probes appeared. Points were based on percentage of response items correctly recalled.

Hard Recall with Probe. In this condition, the hard version of the paired-associate task was combined with the secondary RT task. Points were based on percentage of items correctly recalled and mean RT to probes, with twice as many points possible for recall.

Since the main purpose of this experiment was to study individual differences, it was necessary that measures taken on all individuals be comparable. Therefore the order of conditions was not counter-balanced between subjects. The order of conditions was identical for all subjects and is shown in Table 2.

Results and Discussion

Group Results

The effect of probe condition on recall. Ideally, if probe RT is to be a pure measure of the processing demands of the recall task, then the presence of the probe should not affect performance on

Table 2

Order of Conditions in Experiment 1

Position

	1	2	3	4	5
Day 1	RT Control	Easy Recall No Probe	Easy Recall with Probe	Hard Recall No Probe	Hard Recall with Probe
Day 2	RT Control	Easy Recall with Probe	Easy Recall No Probe	Hard Recall with Probe	Hard Recall No Probe

the recall task. Figure 3 shows mean proportion of items correctly recalled as a function of probe condition and task difficulty. Results are summed over the two days of the experiment. An analysis of variance in which the three factors were probe condition, difficulty of the recall task, and subjects revealed that the effect of probe condition was significant, F (1,47) = 30.3, MS_e = .003, $p < .01$, as were the effect of difficulty, F (1,47) = 703.7, MS_e = .011, $p < .01$, and the interaction, F (1,47) = 6.4, MS_e = .002, $p < .05$. The analysis of easy and hard recall separately revealed that recall was significantly poorer in the probe condition than in the no-probe condition for both easy recall, F (1, 47) = 14.7, MS_e = .001, $p < .01$, and hard recall, F (1, 47) = 24.0, MS_e = .003, $p < .01$. Thus although subjects were instructed that recalling the letter-number pairs was more important than responding to the probes, the probes did interfere somewhat with recall.

Interpretation of these and all other experimental results must be qualified by the fact that the experiment could not be completely counterbalanced. For all subjects, the no-probe condition preceded the probe condition on the first day and followed it on the second day. However, analyses of variance of the two days separately showed that on both days (i.e., for both orders) the effects of probe condition and difficulty were significant. A complete table of means is given in Appendix B.
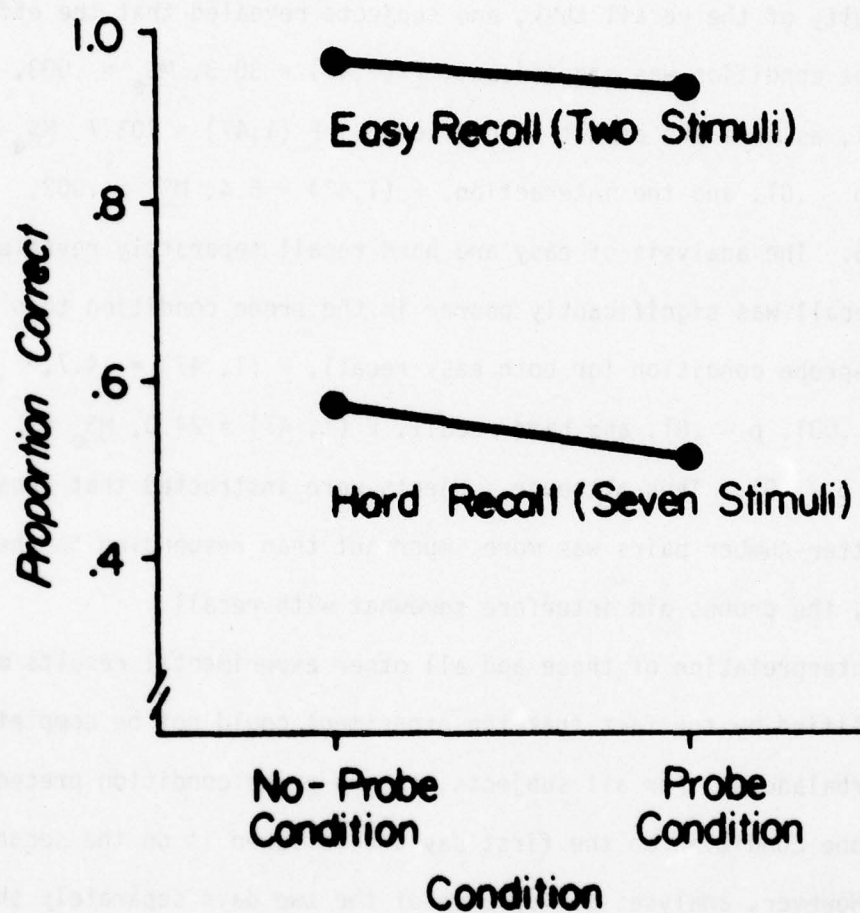
Figure 3. Proportion of items correctly recalled as a function of difficulty and probe condition, Experiment 1.

Effects of recall condition on probe RT. Roediger et al. (1977)
argued that in order to show that rehearsal and a second task compete
for resources, one would have to show that either a) performance on
the second task varied as a function of difficulty of rehearsal, or
b) recall varied as a function of the difficulty of the second task.
Roediger et al. failed to find result (b). In this Experiment, (a)
can be tested: We can ask whether RT to the probe varied as a func-
tion of the difficulty of the recall task. Mean probe RT was com-
puted for each probe condition, omitting ignored probes. (Less than
1% of probes were ignored.) Figure 4 shows mean probe RT as a
function of recall condition. Results were again summed over days.
An analysis of variance in which the two factors were recall con-
dition and subjects showed that the effect of recall condition on
probe RT was significant, F (2, 94) = 124.6, $\underline{MS}_e$ = 5694, p < .01.
Planned orthogonal comparisons showed that: a) probe RT was shorter
in the control condition than in the easy and hard recall conditions
combined, $\underline{t}$ (94) = 15.59, p < .01; and b) probe RT was shorter in
the easy recall condition than in the hard recall condition, $\underline{t}$ (94) =
2.18, p < .05.

Note that on both days the three recall conditions were pre-
sented in the same order (control first, easy recall second, and
hard recall third). Therefore order and recall condition were con-
founded. However, it seems quite certain that condition (nor order)
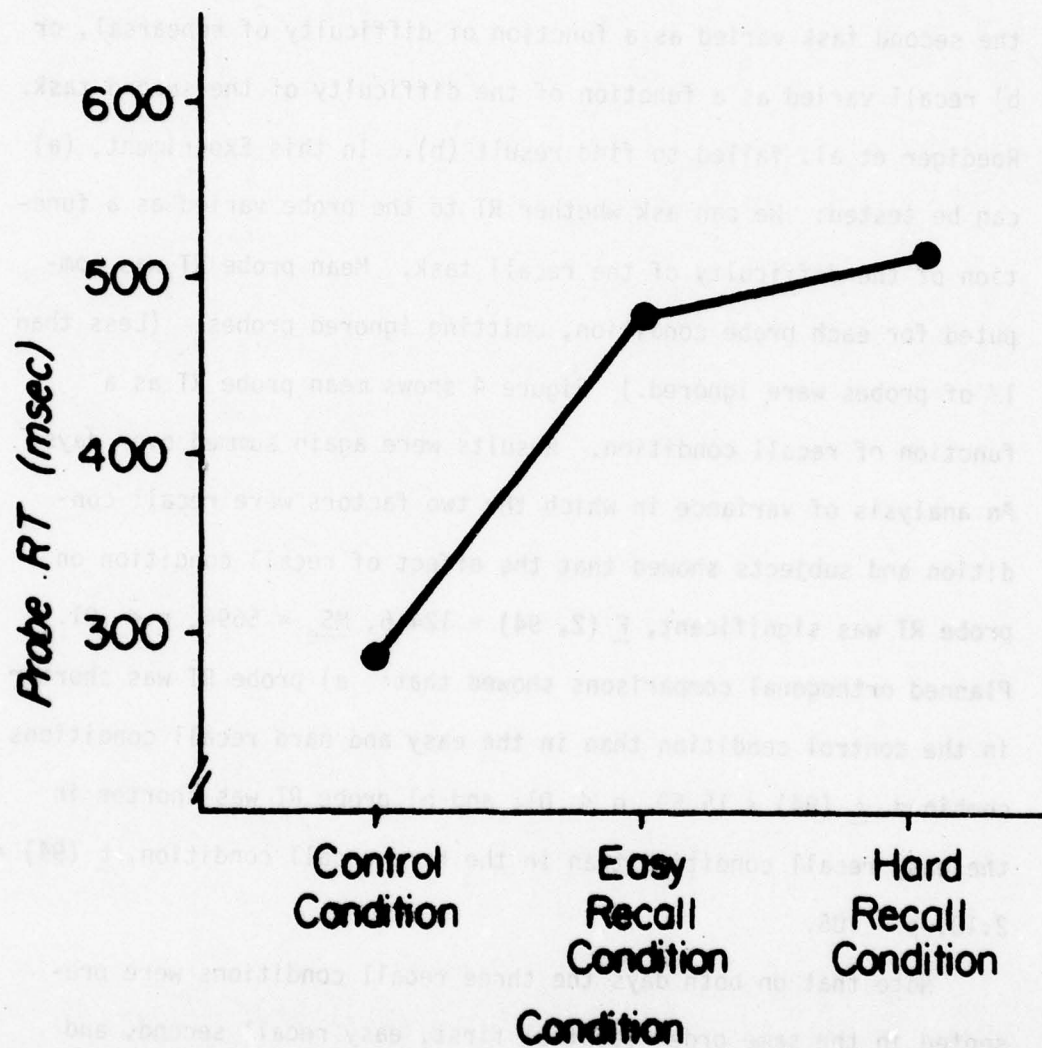
Figure 4. Mean probe RT as a function of recall condition, Experiment 1.

was responsible for the effects of probe RT, since practice effects would be expected to work in the opposite direction. A complete table of means is shown in Appendix C.

These results, then, meet the requirements put forth by Roediger et al. for demonstrating that rehearsal and response to the probe compete for processing capacity. An increase in the difficulty of the recall task caused an increase in probe RT. The fact that recall was poorer in the probe condition strengthens the argument that the two tasks compete for capacity.

These results support the validity of probe RT as an appropriate measure of the processing demands of rehearsal.

Individual differences

Nine measures were included in the correlational analysis. Mean RT to the probe was computed in each of three conditions: RT Control, Easy Recall with Probe, and Hard Recall with probe. Mean RT in the control condition was subtracted from mean RT in each of the recall conditions to obtain measures of how much each recall task interfered with response to the probe. These interference measures will be abbreviated EDLAY and HDLAY. The patterns of correlations were quite similar for recall scores in the probe and no-probe conditions. For this reason, recall measures for the easy and hard conditions were summed over probe conditions. These measures represent the proportion of correct recall responses. Data from both days of the experimental task were combined in computing

these seven measures.

Digit span was computed as follows: Raw span on a particular block was the largest number of digits the subject recalled correctly in order on both trials. For every subsequent digit string recalled correctly, .5 was added to the raw span. Thus if a subject recalled both 6-digit strings, one 7-digit string, and one 8-digit string, digit span for that block was 6 + .5 + .5, or 7.0. The digit span measure was the mean of the scores on the two blocks.

The ninth measure was WPC Verbal Composite, which has been described previously.

Reliabilities of the probe RT and recall measures were computed by correlating Day 1 and Day 2 scores. The Spearman-Brown formula was used to estimate from these correlations the reliability of Day 1 and Day 2 data combined. In the case of digit span, 29 subjects performed the digit span task on both days of the experiment. Reliability of the digit span measure was the correlation between Day 1 and Day 2 scores for these 29 subjects. Reliabilities, mean scores, and minimum and maximum scores on all measures are presented in Table 3.

The complete correlation matrix is shown in Table 4. Note that simple RT is correlated with neither Verbal Composite, digit span, nor either of the recall measures. Digit span is weakly correlated with Verbal Composite, as has been found previously in the college

Table 3

Reliabilities, Mean, Minimum, and Maximum

Scores and Standard Deviations - Experiment 1

	Reliability	Mean Score	Minimum Score	Maximum Score	Standard Deviation
1. Probe RT, Control Condition (msec)	.76	288	230	395	36
2. Probe RT, Easy Recall Condition (msec)	.91	480	288	828	117
3. Probe RT, Hard Recall Condition (msec)	.93	513	270	920	133
4. Probe Delay, Easy Recall Condition - EDLAY (msec)	.88	192	26	476	103
5. Probe Delay, Hard Recall Condition - HDLAY (msec)	.90	225	19	639	125
6. Proportion Correct Easy Recall	.85	.945	.760	1.000	.055
7. Proportion Correct Hard Recall	.86	.539	.328	.807	.130
8. Digit Span	.83	6.43	4.00	8.75	1.05
9. Verbal Composite WPC	.85	55	37	68	8.23

Table 4

Correlation Matrix - Experiment 1[a]

	1	2	3	4	5	6	7	8
1. Probe RT, Control Condition								
2. Probe RT, Easy Recall Condition	.52							
3. Probe RT, Hard Recall Condition	.36	.76						
4. Probe Delay Easy Recall Condition-EDLAY	.25	.96	.73					
5. Probe Delay Hard Recall Condition-HDLAY	.09	.66	.96	.71				
6. Proportion Correct Easy Recall	-.08	-.41	-.09	-.43	-.08			
7. Proportion Correct Hard Recall	-.04	-.38	.05	-.42	.07	.61		
8. Digit Span	-.03	-.06	-.09	-.06	-.08	.11	.28	
9. Verbal Composite WPC	-.01	.01	-.02	.01	-.02	.28	.17	.33

a Correlations of .27 and .35 are significant at the .05 and .01 levels
   with 48 subjects.

population. Finally, the recall measures are only marginally related to either digit span or Verbal Composite.

The measure of primary interest is EDLAY, the difference between RT to the probe during easy recall and control RT. Exactly what does this difference measure? RT to a probe stimulus has often been claimed to be a measure of spare capacity, which reflects the processing demands of a primary task (Kerr, 1973). Indeed, in this experiment probe RT has been shown to be sensitive to the difficulty of the recall task. However, different attentional theories have different explanations of the attentional mechanisms involved.

Within the Posner-Keele theoretical framework, the limited capacity processor is required to execute the response to the probe. If the response is slowed more by one primary task than another, then that primary task places greater demands on the limited capacity processor. Similarly, if the probe response is slowed more in one subject than another, then in that subject the primary task places greater demands on the limited capacity processor. Thus within this theory, EDLAY is an indirect measure of the demands rehearsal places on the limited capacity processor.

From Kahneman's point of view, however, both rehearsal and response to the probe are drawing upon the same pool of capacity. At the group level, if response to the probe is slowed more by one

primary task than another, the first task must require more capacity. However, here the interpretation of individual differences is more complicated. If we are to stay within the "pool of capacity" analogy of Kahneman's theory, we must allow for the possibility that one individual can have more "total capacity" than another. In this case, EDLAY could reflect either the processing demands of rehearsal or the individual's total capacity.

If there are individual differences in total capacity, then we would expect them to influence performance on all complex tasks where various component processes compete for attention. Thus total capacity would surely be represented in Verbal Composite, the general measure of verbal ability. However, Verbal Composite is uncorrelated with EDLAY. So it seems more likely that EDLAY is a specific measure of the processing demands of rehearsal in this recall task.

Now consider the correlation between EDLAY and easy recall ($r =$ -.43, corrected for attenuation, -.50). This correlation means that subjects with higher recall scores had shorter probe delays, i.e., higher recall was associated with more spare capacity during rehearsal. Insofar as the spare capacity measure reflects the processing demands of rehearsal, the correlation between EDLAY and easy recall means that subjects who recall more items expended less processing capacity on rehearsal.

This negative correlation disconfirms the notion that subjects

recall more by expending more effort on rehearsal. The opposite was true: High scorers seemed to expend less effort on rehearsal. I suggest that some subjects achieve higher recall scores at a smaller expense of processing capacity by using more efficient rehearsal strategies.

The recall score used to compute this correlation was summed over probe and no-probe conditions. We can also look at recall in these conditions separately. The correlations between EDLAY and recall in the probe and no-probe conditions respectively were -.49 and -.28. Since EDLAY is significantly negatively correlated with recall in both conditions, one cannot argue that the correlation is an artifactual result of the fact that subjects who responded faster to the probe had more time to rehearse.

Furthermore, the correlation provides no evidence that subjects differed in their inter-task biases. If there were a trade-off between subjects (i.e., if some subjects emphasized the recall task and others emphasized the probe task), then there would tend to be a positive correlation (negative relationship) between the two tasks.

Turning now to HDLAY, we see that the positive relationship between recall and spare capacity does not generalize to the hard recall task. HDLAY is not correlated with hard recall. I cannot explain this result except to suppose that the notion of "spare capacity" is not useful when subjects are faced with such a difficult

task. Perhaps subjects devoted their total capacity to rehearsal
during the hard task. Then RT to the probe would not be a measure
of spare capacity, but of some other individual characteristic.

The most important correlation in this experiment is the correla-
tion between EDLAY and hard recall ($\underline{r}$ = -.42; corrected for attenua-
tion, -.49). Those subjects who had shorter probe delays (i.e.,
more spare capacity) during   the easy recall task, recalled more
items in the hard recall task. Insofar as the spare capacity measure
reflects the processing demands of rehearsal, this correlation means
that subjects who could perform the easy recall task with a smaller
expenditure of processing capacity did better on the hard recall
task. I suggest that rehearsal strategy may mediate this relation-
ship: Subjects who adopted efficient rehearsal strategies had more
spare capacity during rehearsal on the easy task and also recalled
more items in the hard task.

One further question of interest is whether a time-sharing factor
arose in the combination of recall and RT tasks which was independ-
ent of performance on control tasks. There is evidence for such a
time-sharing factor in the high correlation between RT to the probe
in the easy and hard recall conditions ($\underline{r}$ = .76). This correlation
is higher than the correlation of either measure with control RT.
In fact, when variation associated with all three single-task meas-
ures (control RT, proportion correct on easy recall, and proportion

correct on hard recall) is partialled out, the correlation between
RT to the probe during easy and hard recall increases to .83. The
two probe RT measures share a large amount of variation which is un-
related to single-task performance and thus seems to reflect a time-
sharing factor unique to dual-task performance. This time-sharing
factor is obviously not associated with verbal ability, since neither
RT measure is correlated with the verbal ability. However, it may
prove to be associated with performance on other tasks where vigil-
ance is involved. The ability to interrupt ongoing processing to
respond to a signal seems to be an important component of performance
in many areas ranging from parenting to piloting.

EXPERIMENT 2

In the introduction I argued that single-task measures may be insensitive to attentional factors that are important in determining performance on complex tasks. Dual tasks may be necessary to tap these attentional or time-sharing factors. In Experiment 2, dual-task measures of RT and recall were compared to single-task measures as predictors of performance on criterion measures of verbal ability. In the dual task, subjects first saw five digits, then performed a serial RT task involving sentence verification, and finally recalled the digits. Dual-task measures were ordered recall of the digits and sentence-verification RT. Single-task measures were digit span and sentence-verification RT in a control condition.

In the dual task, recall of the digits was the secondary task. The primary sentence-verification task was designed to discourage deliberate rehearsal. Thus the recall measure assessed the subject's ability to hold a memory load without rehearsal.

Sentence verification was chosen as the distractor task for several reasons: First, in order to predict performance on complex verbal criterion tasks, it was desirable to have a distractor task known to involve verbal processes. All models of sentence verification incorporate manipulation of propositional representations (Clark & Chase, 1972; Carpenter & Just, 1975). Second, studies in

our lab have shown that sentence-verification RT is moderately cor-
related with verbal ability (Lansman, Note 2; MacLeod, Hunt, & Mathews,
in press). Third, pilot subjects in the dual task reported that
serially presented sentence-verification items completely prevented
deliberate rehearsal.

There were two dual-task conditions in this experiment. In the
first condition, all subjects responded to six sentence-verification
items between presetnation and recall of the digits. In this con-
dition the retention interval for the digits was determined by the
subject's RTs to the sentence-verification items. Thus a positive
relationship between the RT measure and the recall measure could be
interpreted as an artifact of the retention interval. For this reason,
a second condition was added in which all subjects responded to sen-
tence-verification items for six seconds. Here faster RTs would not
influence the retention interval. However, subjects with faster RTs
would make more responses during the retention interval, which could
lead to an artifactual negative relationship between RT and recall.
Although each condition alone involved problems of interpretation,
consistent results across the two conditions would eliminate the
possibility that artifacts were responsible. In fact, the patterns
of correlations resulting from the two conditions were almost identi-
cal.

As stated before, the purpose of the experiment was to compare

dual- and single-task measures as predictors of criterion measures involving complex verbal processes. The first criterion measure was the WPC Verbal Composite score. It was used as a typical psychometric measure of verbal ability. The second criterion task required solution of three-term series probelms of the type:

A ABOVE B

B ABOVE C

TOP?

This task was chosen because subjects must store some representation of the first premise while encoding and perhaps transforming the second. The task seems to involve linguistic processes similar to those required by the sentence-verification task with the additional requirement of maintaining a memory load. Although furious debate has raged over how people solve three-term series problems (Clark, 1969; Huttenlocher, 1968), all models seem to agree that a) representation of one or both premises must be transformed in order to integrate the two, and b) representation of the first premise must be stored while the second premise is processed.

Method

Subjects

Twenty male and 20 female freshmen at the University of Washington served as subjects. They constituted a stratified sample of verbal ability in the freshmen class and were selected and

recruited exactly as in Experiment 1. No subject participated in both experiments. Subjects were paid $10.00 for completing four 1-hour sessions, and also received a bonus based on points accumulated during the experimental tasks.

Apparatus

Presentation of stimuli and recording of responses were under control of a Data General Corporation NOVA 820 computer. Stimuli were presented on independently controlled Tektronix 604 cathode ray tube oscilloscopes. Subjects responded on eight push-button style keys.

Subjects were run in groups of one to six. Each subject was seated in a dimly lit soundproof booth. The 10 cm by 13 cm screen was at eye level. The keyboard was constructed so that the subjects could rest eight fingers on the keys throughout the experiment.

Tasks

Digit span. Digit span was measured exactly as in Experiment 1 except that there were two blocks of trials on each of two days.

Three-term series problems. Below is another sample problem from the three-term series task:

<div align="center">

A ABOVE B

C BELOW B

BOTTOM?

</div>

Each subject completed four blocks of 16 problems each. The three

terms in each problem were always A, B, and C. In half the problems the question was "Top?", and in the other half it was "Bottom?" In each block there were four trials involving each of the possible pairs of relations: above-above, below-below, above-below, and below-above. The same 16 problems were used in each of the four blocks, but they appeared in a different random order in each block. There were eight practice trials.

At the beginning of each block the subject initiated the trials by pressing a key. Immediately after a key was pressed, the first problem appeared. The subject answered by pressing one of three keys labelled A, B, and C. Following a response, feedback ("Right" or "Wrong") was displayed for 1.5 sec. Immediately after the offset of the feedback message, the next problem appeared. The two premises and the question for each problem appeared simultaneously.

Bonus points were based on mean RT across blocks, but no points could be earned if the subject made more than 10% errors.

Sentence verification - Control Condition. Each trial in this task consisted of six items of the form:

STAR ABOVE *
            +

or   PLUS BELOW +
                        *

The subject was instructed to decide whether the sentence was a true description of the picture and to respond by pressing a key with the right index finger if it was true or the left index finger if it

was false.

There were eight possible sentence-picture items formed by the factorial combination of PLUS and STAR, ABOVE and BELOW, and $^+_*$ and $^*_+$. The six items presented during a trial were chosen by random selection without replacement from these eight possible items. (There were no negative items such as "PLUS NOT ABOVE.")

There were five practice trials, then four blocks of 16 trials each with short breaks between blocks. A trial consisted of the serial presentation of six items. The subject pressed a key to initiate each trial. A warning signal then appeared, followed in 1 sec by the first item. Almost immediately (50 msec) after the subject responded to the first item, the second item appeared. This continued until six items had been presented. After responding to the sixth item, the subject received feedback on performance for the whole trial. Feedback consisted of number of errors and mean RT.

Bonus points were based on mean RT over the four blocks, but no points were possible if the subject made more than 5% errors. This system was used to discourage subjects from increasing speed at the expense of accuracy.

Dual task - Six-Item Condition. This task was very similar to the last except that at the beginning of each trial, five digits were presented, and at the end the subject was required to recall the digits. On each of two days there were two blocks of 16 trials each.

On both days there were also five practice trials.

The subject pressed a key to initiate each trial. After a 1-sec warning signal, five digits were displayed, one at a time, for 750 msec each. The digits were randomly chosen from the set 1-8 without replacement. Immediately after the fifth digit, the first sentence-verification item appeared. The six sentence-verification items were identical to those in the control condition described above. As soon as the subject had responded to the sixth sentence-verification item, the word "Recall" appeared on the screen. At that point the subject attempted to recall the five digits that had been presented, by pressing the appropriately numbered keys in the correct order.

At the end of each trial a message was displayed informing the subject of a) the number of errors made on the sentence-verification items, b) mean RT on the sentence-verification items, c) number of digits recalled in the correct position, and d) bonus points earned on that trial.

The system for awarding points was designed so that subjects would consider the sentence-verification task primary and recall secondary. For each subject, a critical RT was determined. This critical RT was equal to the mean RT for that block of trials in the Control Condition on which the subject responded fastest (usually the last of the four blocks). No points were awarded for any

trial on which an error was made or on which the mean RT was greater than the critical RT on the sentence-verification task. If there were no errors, and if the mean RT was less than the critical RT, the subject received five points plus one point for each digit recalled in the correct position.

Dual task - Six-Second Condition. This condition was identical to the Six-Item Condition except that instead of responding to six sentence-verification items, the subject responded to serially presented sentence-verification items for exactly 6 sec before recalling the digits. The sequence of events in a trial was as follows: Five digits were presented as before. The sentence-verification items were presented, each one immediately following the response to the last until 6 sec had elapsed. After 6 sec, the word "Stop appeared, then "Recall." The subject was instructed not to complete a response after the stop signal, but to begin recall of the digits immediately when the screen said "Recall." Feedback and bonus point system were the same as in the Six-Item Condition.

On each of two days, subjects completed two blocks, 16 trials each, of this task.

Procedure

All subjects did the five tasks in the same order. Each subject was tested for one hour on each of four days as follows:

Day 1: Digit span - 2 blocks

Three-term series problems - 4 blocks

Day 2: Digit span - 2 blocks

Sentence verification - Control Condition - 4 blocks

Day 3: Dual task - Six-Item Condition - 2 blocks

Dual task - Six-Second Condition - 2 blocks

Day 4: Dual task - Six-Second Condition - 2 blocks

Dual task - Six-Item Condition - 2 blocks

Results and Discussion

Summary Data

Table 5 gives the mean, minimum, and maximum scores, standard deviations and reliabilities for each measure in Experiment 2. Table 6 shows the complete correlation matrix.

Digit span. The score for each block of digit-span trials was computed as in Experiment 1. The final digit-span measure was the mean of these four block scores. Reliability was estimated by correlating scores for Day 1 and Day 2 and correcting for length using the Spearman-Brown Formula.

Sentence verification and recall. In all conditions, the sentence-verification RT measure was the mean of all correct trials. Percent errors was also computed for all conditions. The recall measure for both dual-task conditions was the mean number of items recalled in the correct position. Reliability for RT, error, and

Table 5

Reliabilities, Mean, Minimum, and Maximum Scores and Standard Deviations for All Measures-Experiment 2

	Reliability	Mean Score	Minimum Score	Maximum Score	Standard Deviation
Single-Task Measures					
Digit Span	.88	6.76	5.25	9.00	.89
Sentence-Verification RT (msec)	.99	1195	850	1619	216
Sentence-Verification Errors (%)	.82	4.4	1.3	13.6	2.6
Dual-Task Measures					
Six-Item Condition					
Digit Recall	.96	3.01	1.56	4.94	.90
Sentence-Verification RT (msec)	.99	966	695	1379	172
Sentence-Verification Errors (%)	.57	3.9	1.0	7.8	2.0
Six-Second Condition					
Digit Recall	.95	2.90	1.27	5.00	.91
Sentence-Verification RT (msec)	.99	918	678	1280	146
Sentence-Verification Errors (%)	.71	4.5	.8	13.3	3.2
Three-Term Series					
RT (msec)	.96	5441	2930	10003	1622
Errors (%)	.76	8.4	0	28.1	6.4
WPC Verbal Composite	.85	55	32	70	8.6

Table 6

Correlation Matrix - Experiment 2[a]

	1	2	3	4	5	6	7	8	9	10	11
1. Digit Span											
2. Sentence-Verification RT, Control Condition	-.10										
3. Sentence-Verification Errors, Control Condition	-.36	-.03									
4. Digit Recall, Six-Item Condition	.61	-.08	-.35								
5. Sentence-Verification RT, Six-Item Condition	-.14	.95	.06	-.12							
6. Sentence-Verification Errors, Six-Item Condition	-.15	-.05	.67	-.20	.04						
7. Digit Recall, Six-Second Condition	.57	.00	-.31	.92	-.05	-.25					
8. Sentence-Verification RT, Six-Second Condition	-.14	.94	.07	-.14	.98	.02	-.09				
9. Sentence-Verification Errors, Six-Second Condition	-.26	-.07	.64	-.17	-.01	.83	-.21	-.04			
10. Three-Term Series RT	-.14	.72	-.09	-.15	.73	.00	-.02	.72	-.13		
11. Three-Term Series Errors	-.28	.18	.39	-.27	.20	.32	-.24	.24	.15	.25	
12. WPC Verbal Composite	.22	-.58	-.23	.16	-.61	-.16	.20	-.62	-.20	-.37	-.22

a Correlations of .30 and .39 are significant at the .05 and .01 levels with 40 subjects.

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recall measures was estimated by correlating the mean for blocks 1 and 3 with the mean for blocks 2 and 4 and correcting for length using the Spearman-Brown Formula.

  <u>Three-term series problems</u>. Mean RT for correct items and percent errors were computed over the four blocks of three-term series problems. Reliability of three-term series measures was again estimated by correlating the mean of blocks 1 and 3 with the mean of blocks 2 and 4 and correcting for length.

Comparison of the two Dual-task Conditions

  Two dual-task conditions, one in which <u>number</u> of distractor responses was held constant, and one in which distractor task <u>interval</u> was held constant, were included in this experiment in order to disambiguate the relationship between retention interval and RT on the distractor task. Order of the two conditions was balanced within subjects so that the conditions could be compared. As shown in Table 5, mean RT, recall, and percent errors in the two conditions were very similar. More importantly a) the correlation between recall measures in the two conditions was very high ($\underline{r}$ = .92), as was the correlation between RT measures ($\underline{r}$ = .98); b) the correlation between recall and RT in the Six-Item Condition ($\underline{r}$ = -.12) was almost identical to the correlation between RT and recall in the Six-Second Condition ($\underline{r}$ = -.09); and c) correlations between experimental measures and criterion measures were very similar for the two conditions.

Since results for the two conditions were so similar, the Six-Second

Condition will not be discussed further. All conclusions based on

the Six-Item Condition can be generalized to the Six-Second Condition.

Three-Term Series Results

In designing this study, I assumed that since three-term series

problems are more complex than sentence-verification problems, three-

term series measures (both RT and errors) would be more highly cor-

related with the WPC Verbal Composite than sentence-verification

measures. This was not the case. Sentence-verification RT was more

highly correlated with Verbal Composite (r = -.58) than three-term

series RT (r = -.37). (Neither error measure was significantly cor-

related with Verbal Composite.) Furthermore, the two RT measures

were very highly correlated with each other (r = .72). Apparently

I was correct in arguing that the two tasks involve similar processes,

but incorrect in assuming that the added complexity of the three-term

series problems made them more similar to conventional measures of

verbal ability. For this reason, the three-term series measures were

not used as criterion measures.

Prediction of WPC Verbal Composite

Figure 5 compares single-task measures and dual-task measures

as predictors of WPC Verbal Composite The striking conclusion is

that the two types of measures are close to identical in their ability

to predict the criterion. It is not surprising that correlations
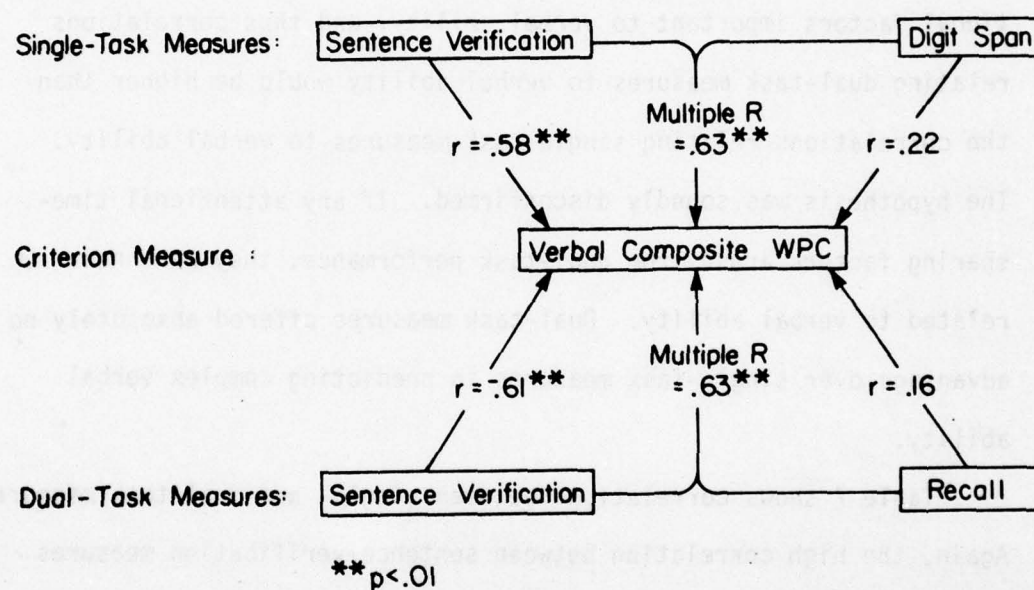
Figure 5. Comparison of single-task and dual-task measures as predictors of WPC Verbal Composite, Experiment 2.

relating the criterion to single- and dual-task sentence-verification
measures are similar, since subjects were instructed not to let re-
call of the digits interfere with sentence verification. But it
is surprising that correlations relating the criterion to digit
span on the one hand and dual-task recall on the other were so
similar. I hypothesized that dual-task measures would reflect atten-
tional factors important to verbal ability, and thus correlations
relating dual-task measures to verbal ability would be higher than
the correlations relating single-task measures to verbal ability.
The hypothesis was soundly disconfirmed. If any attentional time-
sharing factors arose from dual-task performance, they were not
related to verbal ability. Dual-task measures offered absolutely no
advantage over single-task measures in predicting complex verbal
ability.

Table 7 shows correlations between single- and dual-task measures.
Again, the high correlation between sentence-verification measures
was expected. The correlation of .61 between digit span and recall
in the dual-task condition is more interesting. The distractor
task did cause considerable forgetting. Mean digit span was 6.76,
while mean recall after the distractor was only 3.01. Yet recall
after the distractor interval was still highly related to digit span.
Apparently individual differences in immediate recall and in recall
after a distractor arise from similar sources. And these sources

Table 7

Correlations Between Single-Task

and Dual Task Measures - Experiment 2

Single-Task Measure	Dual-Task Measure	Correlation
Sentence-Verification RT	Sentence-Verification RT	.95
(Reliability = .99)	(Reliability = .99)	
Digit Span	Digit Recall	.61
(Reliability = .88)	(Reliability = .96)	

are not important in determining performance on this measure of verbal ability.

Evidence Concerning a Trade-Off Between Distractor and Recall

In the introduction, many studies were cited which showed that memory maintenance competes with other mental processes for attention. Was there any evidence for a trade-off between recall and distractor performance in Experiment 2? There might have been a trade-off over subjects such that some subjects took very seriously the instructions to consider the RT task primary, while others tried to rehearse at the expense of the RT task. Such a trade-off would presumably lead to a more negative relationship (higher correlation) between dual-task measures of RT and recall than between single-test measures of RT and recall. The correlations between RT and recall in the single- and dual-task conditions were -.10 and -.12 respectively. Obviously there was no trade-off over subjects.

There also might have been a trade-off within the individual such that a subject would "try extra hard" (or expend more processing capacity) on the distractor task during some trials, causing more forgetting on those trials. In this case, there would tend to be a negative relationship (positive correlation) between RT and recall in the dual-task across trials for the same subject. The correlation between mean RT and recall across trials was computed for each subject on Days 1 and 2 separately. Mean correlations were .04 and .00

respectively. Again, no trade-off is suggested.

Although the distractor task caused forgetting, all correlational evidence suggests that performance on the recall and distractor components of the dual task were quite independent: a) The relationship between dual-task measures of RT and recall was very similar to the relationship between single-task measures of RT and recall. b) The correlation between corresponding single- and dual-task measures was high. c) The relationship between dual-task measures and the criterion was almost identical to the relationship between single-task measures and the criterion. d) There was no trade-off between the two dual-task components within subjects. This raises doubts as to whether the two components of the dual task actually shared resources during this task. Perhaps the distractor was so effective that no processing capacity at all was allotted to memory maintenance.

Sentence-verification RT as a Predictor of Verbal Ability

The correlation between sentence-verification RT and WPC Verbal Composite was -.58 in the Control Condition, -.61 in the dual-task condition. These correlations are very high considering how diverse the two types of measures are. Sentence verification involves knowledge of only four words, "star," "plus," "above," and "below," and a relatively simple comparison process. The Verbal Composite score, on the other hand, reflects a much broader knowledge base (e.g., the

Vocabulary Subtest) and more complex processes (e.g., the Reading

Comprehension Subtest). Correlations between sentence-verification

RT (Control Condition) and the Vocabulary and Reading Comprehension

Subtests were -.55 and -.41 respectively, based on the 33 subjects

for whom these subtests scores were available.

Table 8 compares this study with other studies of verbal ability

and sentence verification. Differences in sentence-verification

paradigms are noted in the "Study and Paradigm" column. All other

studies used both affirmative and negative sentences, but Table 8

is based on data from affirmative trials only. Subjects in all the

studies were drawn from very similar college populations. In all

of the studies there was a negative correlation between sentence-

verification RT and WPC Verbal Composite.

What specific processes are responsible for the correlation be-

tween sentence-verification RT and the verbal ability measure? We

can be quite certain that simple motor speed does not contribute to

the correlation. For 33 of the 40 subjects, RT on a highly compat-

ible two-choice RT task was available from a later experiment. (In

the two-choice task, subjects were to press the left-hand key if a

stimulus appeared on the left and the right-hand key if the stimulus

appeared on the right.) Table 9 shows correlations between psycho-

metric test scores, two-choice RT, and sentence-verification RT. The

correlation between sentence-verification RT the two-choice

Table 8

Comparison of Four Studies of Sentence Verification and Verbal Ability

Study and Paradigm		Correlation Between Sentence-Verification RT and WPC Verbal Composite	Mean Sentence-Verification RT for Affirmative Trials	Number of Trials	Number of Subjects	Mean WPC Verbal Composite	Range, WPC Verbal Composite
Experiment 2. Sentence and picture presented simultaneously. Items presented serially.		-.58	1195	384	40	55	32-70
Experiment 2. Block 1 only.		-.50	1348	96	40	55	32-70
Lansman (Note 2). Sentence and picture presented simultaneously. Discrete trials.		-.32	1911	80	25	51	35-71
Reading study, in preparation. Picture presented for 1 sec, then sentence. RT to sentence is recorded.		-.44	1838	64	91	55	37-74
MacLeod et al. (in press). Sentence presented first, then picture. RT to both recorded.	Sentence RT	-.24	1661	64	48	54	37-70
	Picture RT	-.56	893	64	48	54	37-70

Table 9

Correlations: Sentence-Verification RT, Two-Choice RT, and

Psychometric Measures, Experiment 2

	Sentence- Verification RT	Two-Choice RT	Vocabulary
Two-Choice RT	.50**		
Vocabulary, WPC	-.55**	.11	
Reading Comprehension, WPC	-.41*	.05	.65**
Verbal Composite, WPC	-.58**	-.02	-----

Controlling for Two Choice RT

	Sentence- Verification RT
Vocabulary, WPC	-.72**
Reading Comprehention, WPC	-.54**
Verbal Composite, WPC	-.73**

**p < .01

RT is .50, but the correlation between two-choice RT and WPC Verbal Composite is only -.02. Holding two-choice RT constant increases the correlation between sentence-verification RT and Verbal Composite from .58 to .73. The variability associated with the non-verbal two-choice task decreased rather than increased the correlation between sentence-verification RT and verbal ability.

We can also conclude that reading speed is not the main factor producing the correlation. MacLeod et al. (in press) presented the sentence first, then the picture in a sentence-verification task. When finished reading the sentence, the subject pressed a key, causing the sentence to disappear. Then the picture was presented and the subject made a true-false response. As shown in Table 8 RT to decide whether sentence and picture matched ("Picture RT") was highly correlated with Verbal Composite (r = -.56) even though this RT did not include time to read the sentence.

Only further research can determine which of the remaining processes--encoding, comparison, decision, or perhaps some factor not included in present models--are responsible for the correlation between sentence verification and verbal ability measures. The correlation itself is an important finding since it shows that a considerable proportion of the variation in a knowledge-based test of verbal ability is associated with a measure that has almost no knowledge requirements.

EXPERIMENT 3

In Experiment 2, subjects were instructed not to let recall of the digits interfere with the distractor task. Under these conditions, the two components of the dual task, recall and sentence verification, were quite independent of one another. The pattern of correlations based on the two dual-task measures was very similar to the pattern of correlations based on corresponding single-task measures. No individual differences in time-sharing efficiency arise from the combination of the two tasks, at least none that were related to performance of the criterion task.

A possible explanation for these results is that when deliberate rehearsal is prevented, there is little interchange of capacity between memory maintenance and the distractor. This explanation is consistent with Baddeley and Hitch's (1974) suggestion that recall from immediate memory has two components. A few items are stored in a buffer that does not interfere with other kinds of mental operations--in attentional terminology, a storage system that does not require processing capacity. Additional items can be maintained by using rehearsal, which <u>does</u> interfere with other mental operations. According to this theory, items recalled in the dual-task condition of Experiment 2 were recalled from the effort-free buffer. Recall and RT were independent of each other because they did not compete for resources. The two tasks interacted only

in the sense that the presence of the primary distractor task pre-
vented rehearsal.

To study the processing demands of immediate memory, a dual
task involving rehearsal may be necessary. Therefore, in Experi-
ment 3 recall was made the primary task and the distractor was
secondary. The paradigm was similar to the Six-Second Condition of
Experiment 2. Subjects were presented with a set of digits, then
performed a sentence-verification distractor task for 6 sec, and
finally recalled the digits. Perfect recall of the digits was
stressed. Whereas in Experiment 2 subjects were instructed not
to let recall of the digits interfere with sentence verification,
here subjects were instructed not to let sentence verification
cause them to forget the digits.

In this experiment, memory load was varied from 0 to 5 items.
If Baddeley and Hitch's theory is correct, a small memory load should
not interfere with performance on the sentence-verification task.
Subjects should be able to maintain at least one or two items
in memory without attention-demanding rehearsal. However, at
some point as memory load is increased from 0 to 5 items, rehearsal
should begin to interfere with the sentence-verification task, and
sentence-verification RTs should increase. One purpose of this
experiment was to study relationship between distractor perfor-
mance and memory load.
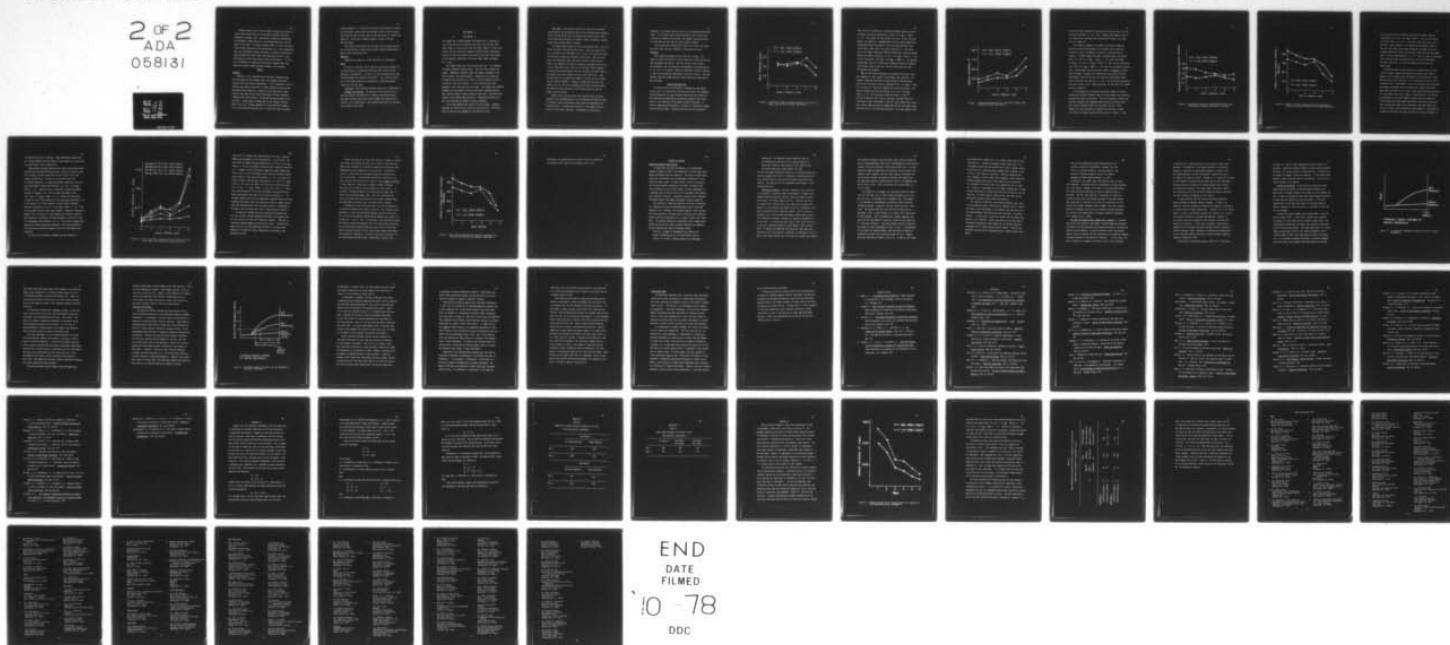
Another purpose was to find out whether subjects who differ in verbal ability also differ in the function relating distractor performance to memory load. Two groups of subjects, representing the extremes of verbal ability in the college population, participated in the study. If these two groups differ in any of the attentional factors discussed in the introduction (e.g., total processing capacity, performance-resource functions, or speed of switching between rehearsal and other tasks) then they should differ in the efficiency with which they combine recall and distractor. In this case, differences in sentence-verification RT between high- and low-ability groups should increase as memory load increases.

Method

Subjects

Subjects in this experiment were selected to represent high and low verbal-ability students within the sophomore and junior classes at the University of Washington. As in Experiments 1 and 2, selection was made on the basis of Verbal Composite scores on the Washington Pre-College Test. Subjects in the high-ability group scored in the upper sixth of the distribution for their entering freshmen class, while those in the low-ability group scored in the low third. (The original intention was to use subjects from the lower sixth, but it proved impossible to find sufficient students in this classification who were still in school and would volunteer

as paid subjects.) In relation to the entire distribution of scores

for high school students who took the WPC, scores of the low group

fell below the mean and the scores of the high group fell within the

upper 10%. There were 12 female subjects in each of the two

ability groups.

Each subject participated for one hour a day on eight days and

was paid $24.00 plus a bonus based on points earned through perfor-

mance in the experimental task.

Apparatus

Apparatus was identical to that described for Experiment 2.

Tasks

On the first two days, digit span was measured and subjects re-

ceived practice on a sentence-verification task similar to that

described in Experiment 2. On Days 3-8, they performed a dual task

involving memory and sentence verification. This task was similar

to the Six-Second Condition of Experiment 2, except that memory

load was varied over days.

Digit span. Digit span was measured exactly as in Experiment 2.

Sentence verification. The purpose of this task was to pro-

vide the subjects with practice on sentence verification before

they began the dual task involving both memory and sentence veri-

fication. As in Experiment 2, each stimulus consisted of a sentence

and a picture of the form:

STAR ABOVE. $\begin{matrix} * \\ + \end{matrix}$

or   PLUS BELOW. $\begin{matrix} + \\ * \end{matrix}$

The subject was to decide whether the sentence was a true description of the picture and respond by pressing a key with the right index finger if it was true or the left index finger if it was false. Stimuli for each trial were randomly selected without replacement from the 16-item set containing two each of the eight items formed by the factorial combination of PLUS and STAR, ABOVE and BELOW, and $\begin{matrix} + \\ * \end{matrix}$ and $\begin{matrix} * \\ + \end{matrix}$.

The subject began each trial by pressing a key. This keypress initiated a 500-msec warning signal. Then the first stimulus appeared. Immediately (50 msec) after the subject responded to the first stimulus, the second appeared. Response to the second was followed by the third and so on until 6 sec had elapsed since presentation of the first stimulus. At this time the word "Stop" appeared on the screen and the trial ended. The subject then received feedback as to the number of errors and correct responses she had made, and the number of points earned on that trial. No points were awarded if the subject made any errors. Otherwise the points for each trial equalled the number of correct responses.

Trials were grouped into blocks of 16 trials each. Subjects completed two blocks on Day 1 and four blocks on Day 2. The first block on each day was preceded by five practice trials.

Dual task. This task was identical to that described above except that at the beginning of each trial 0-5 digits were presented and at the end of the trial the subject was asked to recall them. Since trials were blocked as to number of digits presented, subjects always knew how many digits to expect.

The subject again began each trial by pressing a key. This key-press initiated a 500-msec warning signal. After the warning signal, the digits were presented one at a time. Each digit was shown for 500 msec followed by a 250-msec blank period. After the last digit (or immediately after the warning signal if there were no digits) the sentence-verification items were presented serially for 6 sec as described above. After 6 sec, the word "Stop" appeared. If digits had been presented, this was followed by the word "Recall." The subject was given unlimited time to recall the digits. When she had typed in the appropriate number of digits, the trial ended and she received feedback. Feedback informed the subject of the number of errors and correct sentence-verification responses made, the number of digits recalled in the correct position, and the number of points earned.

Subjects were instructed that recalling the digits was more important than responding quickly to the sentence-verification items. To reinforce these instructions, bonus points were awarded on the following basis: No points were possible if the subject did not recall all the digits correctly. Furthermore, no points were

possible if the subject made any errors on the sentence-verification items. If all digits were recalled correctly, and if there were no errors on sentence verification, the subject received one point for each digit and one point for each correct response.

Trials were again grouped into blocks of 16 trials, and there were four blocks per day, preceded by five practice trials.

Procedure

Each subject performed this dual task for six days. The number of digits presented to a given subject on a given day was the same throughout the session. Over the six days, each subject was assigned to the six conditions corresponding to presentation of 0, 1, 2, 3, 4, or 5 digits. Order of conditions for the 12 subjects in each ability group was determined by two Latin squares. Thus two subjects from each group received a given condition on each day of the experiment.

Results and Discussion

In scoring recall of the digits, a response was considered correct only if it occurred in the correct position in the sequence. The mean proportion of items correctly recalled by each subject in each condition was obtained by dividing the subject's mean recall score in that condition by the number of digits presented. In Figure 6, mean proportion correct is plotted as a function of memory load and ability group. Although proportion correct was greater
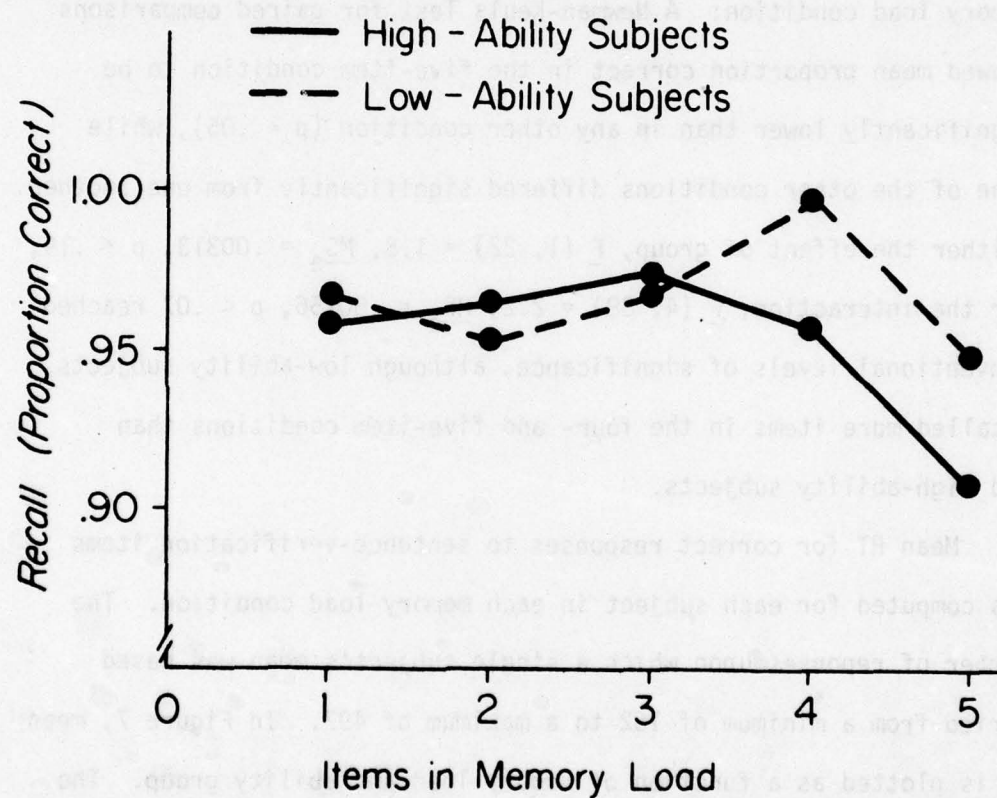
Figure 6. Proportion of items correctly recalled as a function of memory load and ability group, Experiment 3.

than .90 in all conditions, a mixed design ANOVA showed the effect
of memory load to be significant, $\underline{F}$ (4,88) = 5.2, $\underline{MS}_e$ = .00156
p < .01. This effect was due primarily to recall in the five-item
memory load condition: A Newman-Keuls Test for paired comparisons
showed mean proportion correct in the five-item condition to be
significantly lower than in any other condition (p < .05), while
none of the other conditions differed significantly from one another.
Neither the effect of group, $\underline{F}$ (1, 22) = 1.8, $\underline{MS}_e$ = .00313, p < .19,
nor the interaction, $\underline{F}$ (4, 88) = 2.2, $\underline{MS}_e$ = .00156, p < .07 reached
conventional levels of significance, although low-ability subjects
recalled more items in the four- and five-item conditions than
did high-ability subjects.

Mean RT for correct responses to sentence-verification items
was computed for each subject in each memory-load condition. The
number of reponses upon which a single subject's mean was based
varied from a minimum of 162 to a maximum of 497. In Figure 7, mean
RT is plotted as a function of memory load and ability group. The
effect of memory load was significant, $\underline{F}$ (5, 110) = 6.5, $\underline{MS}_e$ =
16477, p < .01, but the effect of ability group, $\underline{F}$ (1,22) < 1,
and the interaction, $\underline{F}$(5, 110) < 1, were not. Data were then col-
lapsed over groups, and Dunnett's Test for paired comparisons involv-
ing a control mean was used to compare mean RTs for each memory-load
condition to RT in the zero-load condition. Only under memory loads
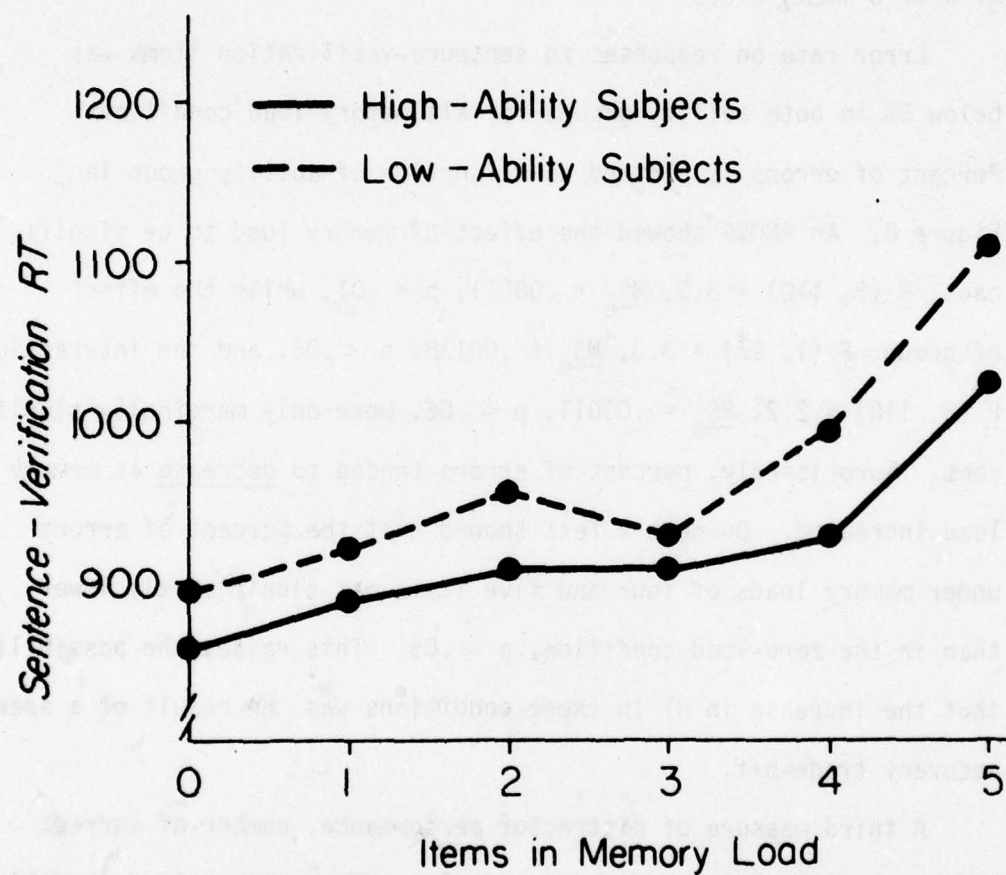
Figure 7. Sentence-verification RT as a function of memory load
and ability group, Experiment 3.

of four and five items was RT significantly increased over RT in the zero-load condition, p < .05. Thus it appears that memory loads of 1-3 items did not interfere with sentence-verification, but loads of 4 or 5 items did.

Error rate on responses to sentence-verification items was below 5% in both ability groups for all memory load conditions. Percent of errors is plotted as a function of ability group in Figure 8. An ANOVA showed the effect of memory load to be significant, F (5, 110) = 3.5, MS_e = .00011, p < .01, while the effect of group, F (1, 22) = 3.3, MS_e = .00138, p < .08, and the interaction, F (5, 110) = 2.2, MS_e = .00011, p < .06, were only marginally significant. Surprisingly, *percent of errors* tended to <u>decrease</u> as memory load increased. Dunnett's Test showed that the percent of errors under memory loads of four and five items was significantly lower than in the zero-load condition, p < .05. This raises the possibility that the increase in RT in these conditions was the result of a speed-accuracy trade-off.

A third measure of distractor performance, number of correct sentence-verification responses made in a given memory-load condition, assessed both speed and accuracy. Since the distractor interval was constant, subjects who responded faster and more accurately made more correct responses within the distractor interval. Mean number of correct responses per subject per condition is shown as a function of memory load and ability group in Figure 9. Just
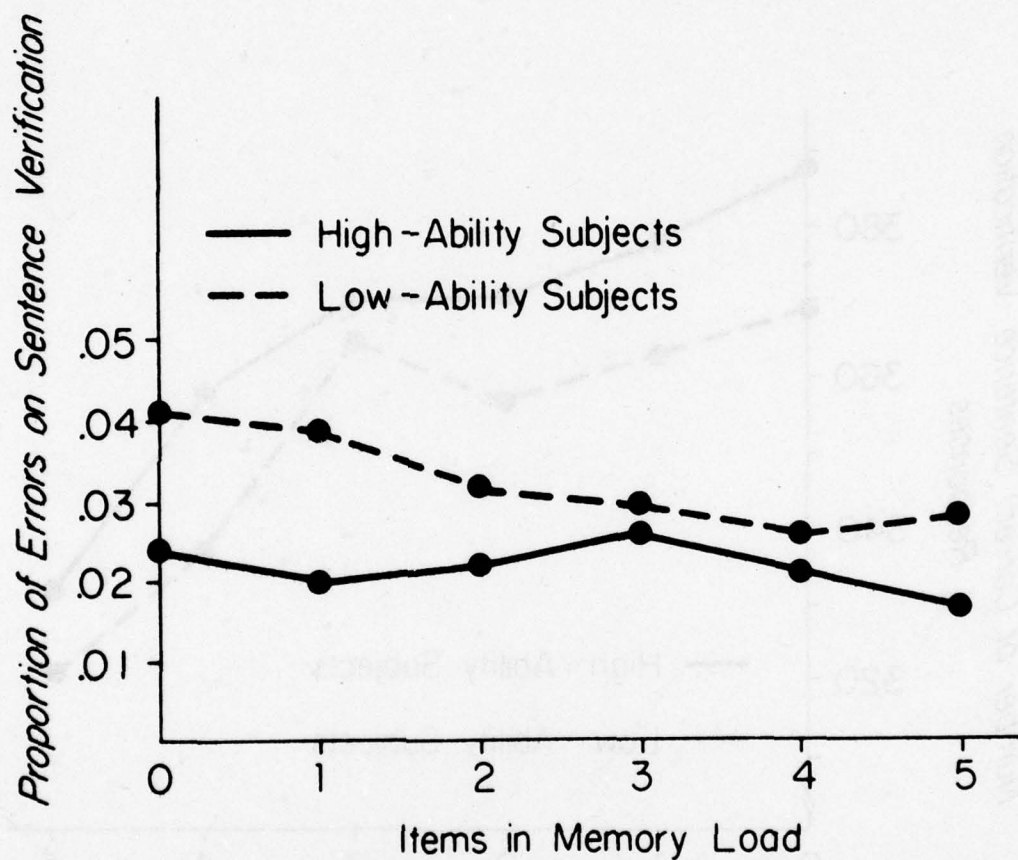
Figure 8. Proportion of errors on sentence-verification items as a function of memory load and ability group.
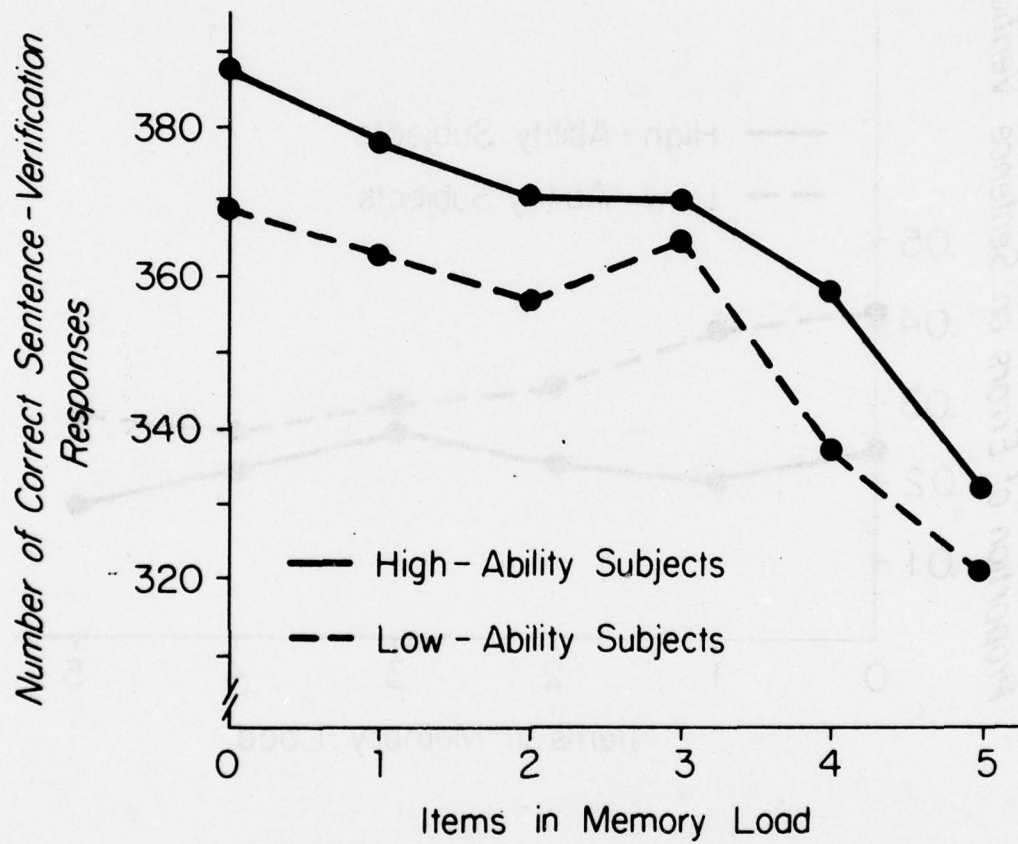
Figure 9. Number of correct sentence-verification responses as a function of memory load and ability group, Experiment 3.

as in the case of the RT measure, the effect of memory load was significant, $\underline{F}$ (5, 110) = 5.2, $\underline{MS}_e$ = 1654, p < .01, but the effect of ability group, F (1, 22) < 1, and the interaction, $\underline{F}$ (5, 110) < 1, were not. Again, Dunnett's Test showed that only memory loads of four and five items significantly decreased the number of correct responses made within the 6-sec distractor interval below the number made in the zero-load condition, p < .05. Thus even when the decreased error rate was taken into consideration, distractor performance was worse under four- and five-item memory loads than with no memory load.

Although we must be very cautious in accepting the null hypothesis, the data suggest that maintaining three or less items in memory did not interfere with performance on the distractor. Maintaining four or five items did. It is interesting to note in this connection that in Experiment 2, when the distractor task was primary and subjects presumably did not deliberately rehearse the digits, mean recall was 3.08 out of 5 items. Both experiments are consistent with the theory that a small number of items (three in this particular paradigm) can be held in memory without requiring attention. From the many short-term memory experiments involving a distractor task, we know that items in this effortless store must decay very quickly if they are not maintained through rehearsal. Therefore our estimate of the number of items the store can hold would depend on

the length of the recall interval. These experiments suggest that for college students the mean number of items remaining in the effortless store after 6 sec is about three.

Many subjects reported rehearsing the digits once quickly before beginning the sentence-verification task. Insofar as subjects used this strategy, we would expect the first RT of each trial to be longer than other RTs. In Figure 10, first and "other" RTs are plotted separately. A mixed design ANOVA showed that first RTs were significantly longer than other RTs, F (1, 22) = 14.2, $\underline{MS}_e$ = 74031, p < .01. There was also a significant interaction between position of response (i.e., first or other) and memory load, F (5, 110) = 17.6, $\underline{MS}_e$ = 14789, p < .01. Neither the main effect of group nor any of the interactions with group were significant. As in the analysis of all RTs together, the main effect of memory load was significant, F (5, 110) = 10.9, $\underline{MS}_e$ = 49676, p < .01. (Here first and other RTs were given equal weight.) Orthogonal comparisons between first and other RTs in each memory-load condition revealed that there was a significant difference between the two only in the five-item memory-load condition, p < .01. These results suggest that subjects did indeed concentrate rehearsal of the digits before the first sentence-verification response in the five-item memory-load condition.

To find out if the effect of memory load was confined to
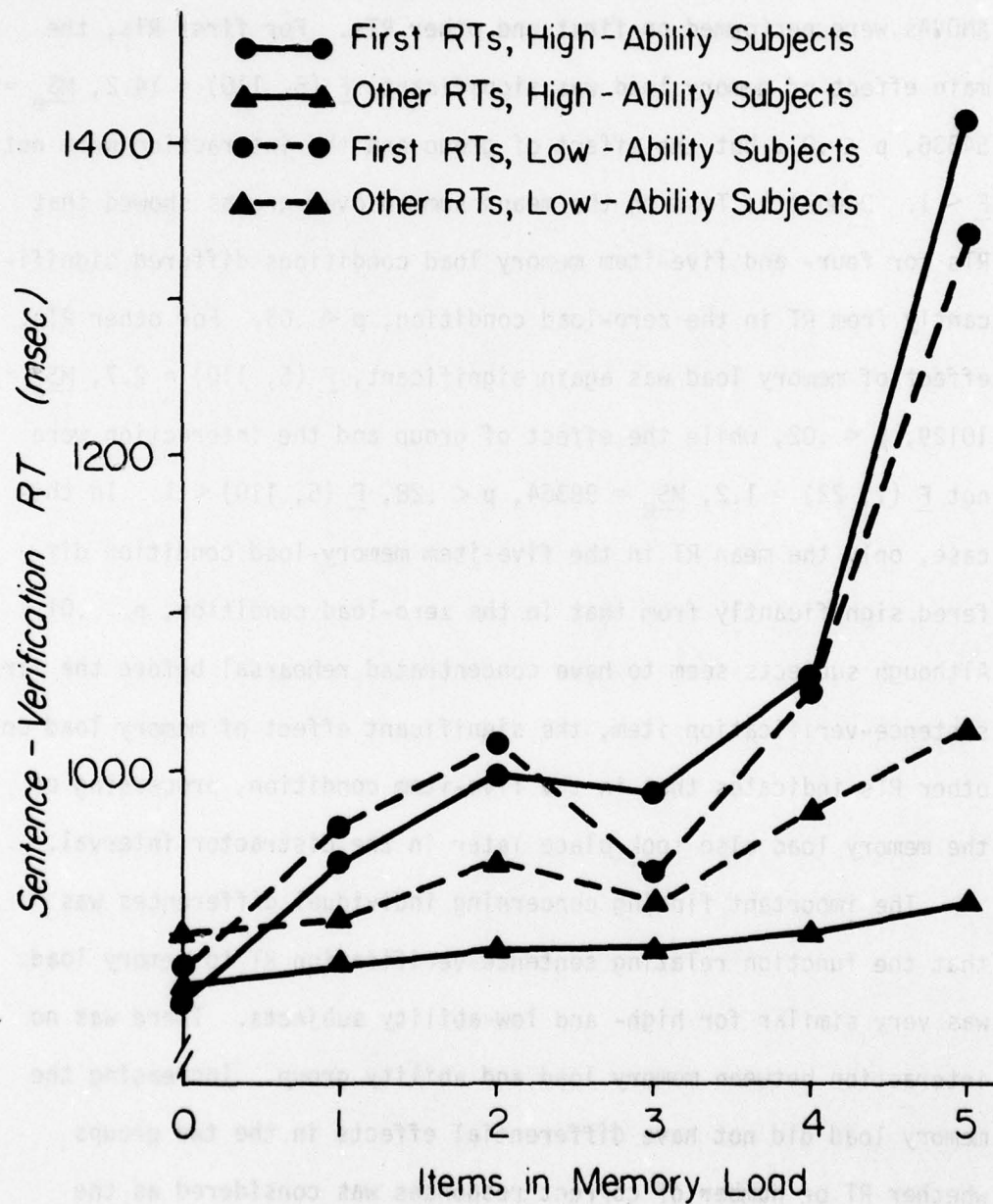
Figure 10. "First" and "other" sentence-verification RTs as a function of memory load and ability group, Experiment 3.

first RTs, or if memory load affected other RTs as well, separate ANOVAs were performed on first and other RTs. For first RTs, the main effect of memory load was significant, F (5, 110) = 14.2, MS_e = 54336, $p < .01$, but the effect of group and the interaction were not, $F < 1$. Dunnett's Test on the means summed over groups showed that RTs for four- and five-item memory load conditions differed significantly from RT in the zero-load condition, $p < .05$. For other RTs, effect of memory load was again significant, F (5, 110) = 2.7, MS_e = 10129, $p < .02$, while the effect of group and the interaction were not F (1, 22) = 1.2, MS_e = 98364, $p < .28$, F (5, 110) < 1. In this case, only the mean RT in the five-item memory-load condition differed significantly from that in the zero-load condition, p .01. Although subjects seem to have concentrated rehearsal before the first sentence-verification item, the significant effect of memory load on other RTs indicates that in the five-item condition, processing of the memory load also took place later in the distractor interval.

The important finding concerning individual differences was that the function relating sentence-verification RT to memory load was very similar for high- and low-ability subjects. There was no interaction between memory load and ability group. Increasing the memory load did not have differential effects in the two groups whether RT or number of correct responses was considered as the dependent variable.

Neither the analysis of RT nor the analysis of number of correct items takes into account the fact that in the four- and five-item memory-load conditions the low-ability subjects recalled more items. Performance on both components of the dual task is reflected in Figure 11, which shows the performance-operating characteristics for the two groups. The performance-operating characteristic relates sentence-verification RT to number of items actually recalled in each condition, rather than to number of digits presented. The shapes of the POCs for the two groups are quite similar. If anything, differences between the groups decrease rather than increase with increasing memory load. Thus this experiment provides no evidence that high verbal-ability subjects combine these two tasks more efficiently than low verbal-ability subjects.

An unexpected result from Experiment 3 was that sentence-verification RT showed no main effect of ability. This contrasts with Experiment 2, where the correlation between sentence-verification RT in the Control Condition and WPC Verbal Composite was highly significant ($r = -.58$, $p < .01$) In Experiment 3, the high-ability group had shorter sentence-verification RTs in all memory-load conditions, but the differences between groups were small and not significant. Several possible reasons for this inconsistency between experiments are considered in Appendix D. No really convincing explanation for the inconsistency has been found. Differences in practice and
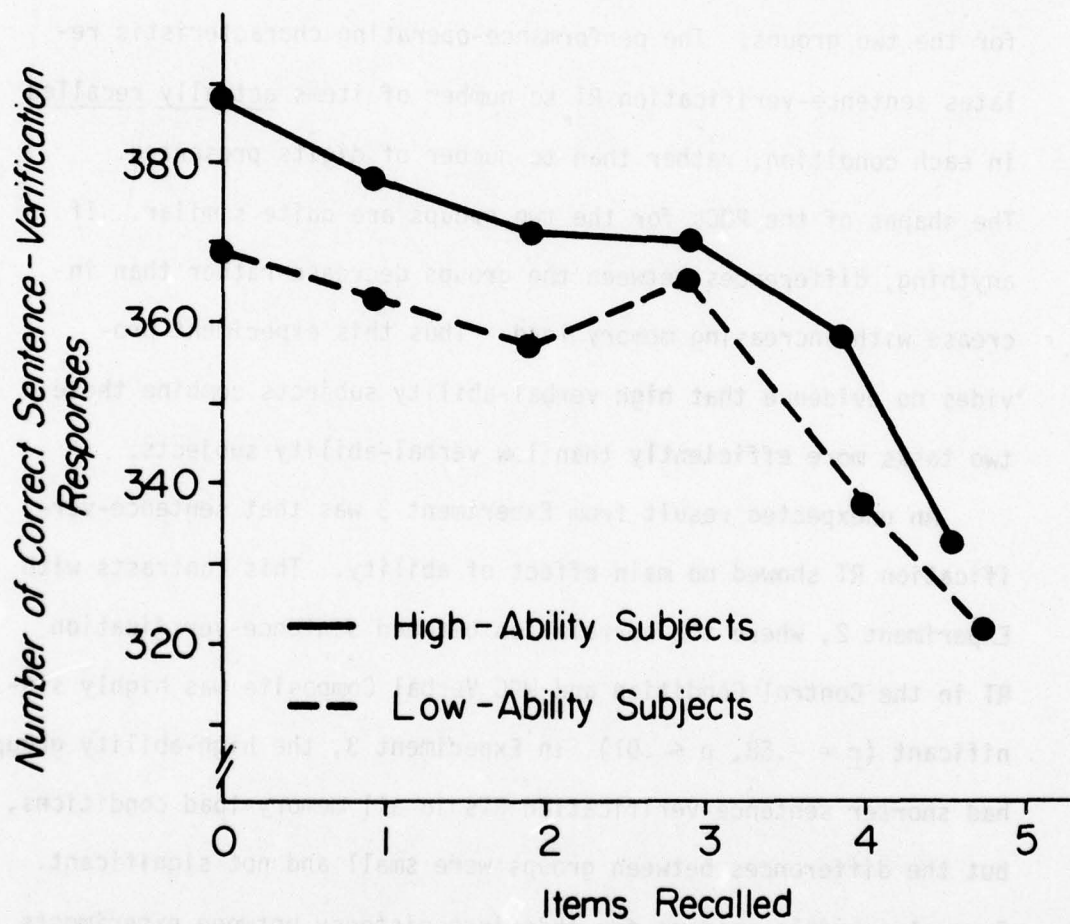
Figure 11. POCs relating sentence-verification RT and recall for
high and low verbal-ability subjects, Experiment 3.

differences in subject populations may be partially responsible,
but sampling error seems to have played a part as well.

GENERAL DISCUSSION

Memory Maintenance and Attention

To understand individual differences in the attentional demands of memory, we must first understand in exactly what sense memory maintenance requires attention. Two types of studies have shown that interference results when memory maintenance is combined with other tasks: a) those studies in which a distractor task inserted between presentation and recall of memory items caused forgetting, and b) those studies in which performance on a secondary task varied with the size of the memory load subjects were required to maintain. Attentional theorists have concluded from these studies that memory maintenance requires attention.

This position is shared by theorists who think of attention as a resource that can be distributed among several concurrent processes (e.g., Kahneman, 1973; Norman & Bobrow, 1975), and theorists who postulate a limited capacity processor which performs various functions successively (e.g., Posner & Boies, 1971; Keele, 1973). The contrast between the attentional view of memory maintenance and the earlier verbal learning conception of rehearsal was well-expressed by Posner and Rossman (1965):

There are a number of advantages [in] replacing the
notion of rehearsal as an all-or-none process with a
view of S as having a limited capacity for information

> processing. The rehearsal process requires a part of
> this capacity and can coexist to a greater degree with
> tasks which require a small amount of this capacity than
> with those requiring a larger amount. (p. 504)

The view that memory maintenance makes use of available processing
capacity suggests that there is a monotonic, non-decreasing func-
tion relating recall to the processing capacity devoted to main-
tenance. This function will be considered in more detail in the
following sections.

Effortless retention. How much information can be recalled
if no capacity is devoted to memory maintenance? If memory main-
tenance requires processing capacity, does zero capacity lead to
zero recall? The answer seems to be "No." There are two lines
of evidence which indicate that a few items can be maintained in
memory for a few seconds even though little or no attention is de-
voted to them during the retention interval. The first line of
evidence lies in classic short-term memory studies where three to
five items were presented, followed by a maximally demanding dis-
tractor task. In no case did recall drop to zero within the first
10 sec (e.g., Peterson & Peterson, 1959; Murdock, 1961; Hellyer,
1962). No matter how demanding the distractor, some items were
retained for this short period. Similarly, in Experiment 2 of this
paper, even though subjects were instructed to consider the sentence-

verification distractor task the primary task, and even though the
pay-off system demanded a high level of performance on the distractor,
subjects recalled an average of three items after 6 sec. The argu-
ment could always be made that the distractor did not require the
subject's total capacity, and that spare capacity associated with
the distractor allowed the subject to maintain the memory load.
But then there should be some distractor which is so demanding that
recall drops to zero. Such a distractor has not been found, as
far as I know.

The second line of evidence for relatively effortless reten-
tion of a few items lies in studies where the memory task is pri-
mary but fails to interfere with a secondary task. One example
is an experiment by Wattenbarger and Pachella (1972) using the
Sternberg paradigm. Target set size was varied from one to five
items. Two seconds after the last item of the target set was
presented, either a probe stimulus or a stimulus for a two-choice
RT task appeared. Until the moment this stimulus appeared, sub-
jects did not know whether it would be a probe for the target set
or a two-choice stimulus. They were therefore forced to maintain
the target set until presentation of the stimulus. If maintenance
of the target set required effort, then two-choice RT would be
expected to increase with increasing target set size. However,
there was absolutely no effect of set size. As many as five items

were maintained in memory for 2 sec without interfering with the
two-choice RT. Shulman and Greenberg (1971) found that a 1-4
item memory load failed to interfere with either a pattern recog-
nition task or a timed perceptual judgment task, although a load
of five or more items did interfere. Similarly, Baddeley and
Hitch (Baddeley & Hitch, 1974; Hitch & Baddeley, 1976) found that
holding a memory load of one or two items did not increase RT
to a sentence-verification item, but a memory load of six items
did. Finally, in Experiment 3 of this paper, maintaining 1-3 items
did not significantly interfere with the 6-sec distractor, but 4-5
items did. All these results indicate that a few items can be
maintained in memory without requiring attention.

The concept of effortless short-term maintenance has a place
in the attentional model of Shiffrin and Schneider (1977). Within
this model, short-term memory is considered to be that collection
of long-term memory nodes which have been activated. Activation
normally dies down within a matter of seconds, but the subject may
maintain it by rehearsal. Within this model, to say that there is
"effortless maintenance" simply means that activation continues
spontaneously for a short period before it decays. Shiffrin and
Schneider have explicitly incorporated such a feature within their
model:

Thus an item removed from controlled processing still
requires a period of time before it becomes lost from
STS (i.e., becomes inactive). This persistence in the
absence of attention might be called the automatic
component of short-time maintenance. (p. 169)

According to this model, then, zero capacity does not imply
zero retention. Activation persists spontaneously without attention
for a few seconds. However, if an item is to be maintained beyond
this short period of effortless activation, attention must be
available. The fact that attention is necessary to sustain act-
ivation for more than a few seconds accounts for the many studies
which show that a) retention varies with the difficulty of a dis-
tractor task (Posner & Rossman, 1965; Crowder, 1967) and b) perfor-
mance on a secondary task during the retention interval decreases
as the size of the memory load is increased (Shulman & Greenberg,
1971; Stanners et al., 1969).

The role of attention when subjects don't rehearse. A question
that arises with respect to this model is whether memory maintenance
can benefit from the availability of processing capacity even when the
subjects do not rehearse. A study by Wickens, Israel, and Donchin
(Note 5) clearly indicates that the availability of processing capacity
can boost retention in the absence of rehearsal. In this study, sub-
jects listened to a sequence of auditory signals while performing

a tracking task. Evoked potentials to the auditory signals were
measured. The magnitude of the evoked potential to an auditory
stimulus is sensitive to the previous sequence of stimuli. Thus
the evoked potential provides physiological evidence for a sort
of "memory" for previous stimuli. Wickens et al. showed that the span
of this "memory" decreased when the difficulty of the simultaneous
tracking task was increased, even though subjects had no reason
to rehearse the sequence. This study offers impressive evidence
that retention varies with available processing capacity even when
conscious rehearsal strategies are not involved.

It seems possible that the function relating retention to
capacity depends on whether subjects rehearse. If there is no
rehearsal, then the increase of retention with capacity is relative-
ly slow and hard to detect behaviorally. (Wickens et al. were able to
detect it using a physiological measure, but Roediger et al. failed
using simple retention as the dependent measure.) However, if
the subject consciously rehearses, then retention increases more
sharply with capacity. In this case, increases in the capacity
demands of the distractor task have a greater effect on retention
(Posner & Rossman, 1965). Retention is affected most dramatically
by the distractor when the distractor entirely prevents rehearsal
(Peterson & Peterson, 1959).

A hypothetical performance-resource function is illustrated

in Figure 12. There is some retention even when no capacity is
available. Retention increases gradually as more capacity becomes
available. At a certain point C, enough capacity is available for
the subject to engage in conscious rehearsal. If the subject does
rehearse, recall increases rapidly with capacity. If not, the in-
crease continues to be gradual.

Sharing or switching? So far nothing has been said about
whether processing capacity is shared between rehearsal and a
second task, or whether subjects switch back and forth between the
two. An implicit analogy has often been drawn between maintaining
a memory load and holding up a physical weight. It has been
assumed that in both cases there must be a constant output of
"effort" (physical in one case, mental in the other) or the load
will be "dropped."

Consider two recent studies, one by Egeth (Note 1) and the
other by Logan (1978). In both cases, subjects were required
to perform a RT task either with or without a memory load. The
investigators assumed that the memory load required a continuous
output of processing capacity. They then argued that if a certain
stage of processing in the RT task required attention, then a
variable known to affect that stage should interact with memory
load. If a variable increased the amount of attention demanded
by a given stage, then a memory load should magnify the effect.
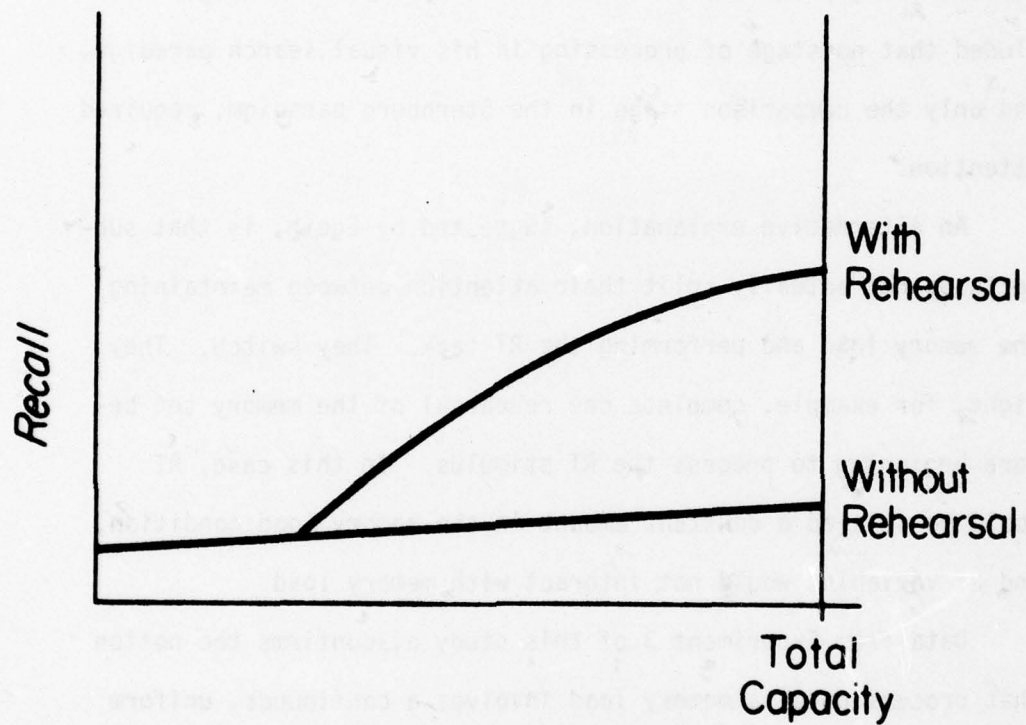
Figure 12. A hypothetical performance-resource function for memory maintenance.

The rather surprising results were that although in all conditions memory load increased RT, no variable (except target set size in the Sternberg paradigm) interacted with memory load. Logan concluded that <u>no</u> stage of processing in his visual search paradigm, and only the comparison stage in the Sternberg paradigm, required attention.

An alternative explanation, suggested by Egeth, is that subjects do not actually split their attention between maintaining the memory load and performing the RT task. They switch. They might, for example, complete one rehearsal of the memory set before beginning to process the RT stimulus. In this case, RT would be delayed a constant amount in the memory load condition, and RT variables would not interact with memory load.

Data from Experiment 3 of this study disconfirms the notion that processing of a memory load involves a continuous, uniform output of processing capacity. In the five-item memory-load condition, subjects concentrated processing of the memory items before beginning the distractor task, as indicated by the fact that memory load had a much larger effect on first than other RTs. Hitch and Baddeley (1976) drew a similar conclusion with respect to their task: When memory was stressed, subjects rehearsed the memory load before responding to the sentence.

The analogy between holding a memory load and supporting a

physical weight seems to be misleading in at least two ways: First, it may be possible to maintain a small memory load for a few seconds with no effort at all. Second, a quick rehearsal of a memory load at the beginning of the retention interval may serve to "consolidate" the items sufficiently so that little capacity is required to maintain them for the rest of the interval.

Individual Differences

What does the research reported here and elsewhere tell us about individual differences in the attentional demands of memory maintenance? In Experiment 1 the spare capacity associated with rehearsal of paired-associate items was measured. Spare capacity associated with an easy version of the recall task predicted proportion of items correctly recalled on a harder version. It was hypothesized that efficiency of rehearsal strategies mediated this relationship: Subjects who used efficient rehearsal strategies had more spare capacity during rehearsal on the easy task, and also recalled more items on the hard task. Figure 13 illustrates hypothetical performance-resource functions for two subjects in Experiment 1. Subject 1, who uses a more efficient rehearsal strategy, can recall two pairs (i.e., do the easy task perfectly) with more capacity to spare than Subject 2. Subject 1 also recalls more items on the hard recall task when both subjects are devoting total capacity to rehearsal during the retention interval.
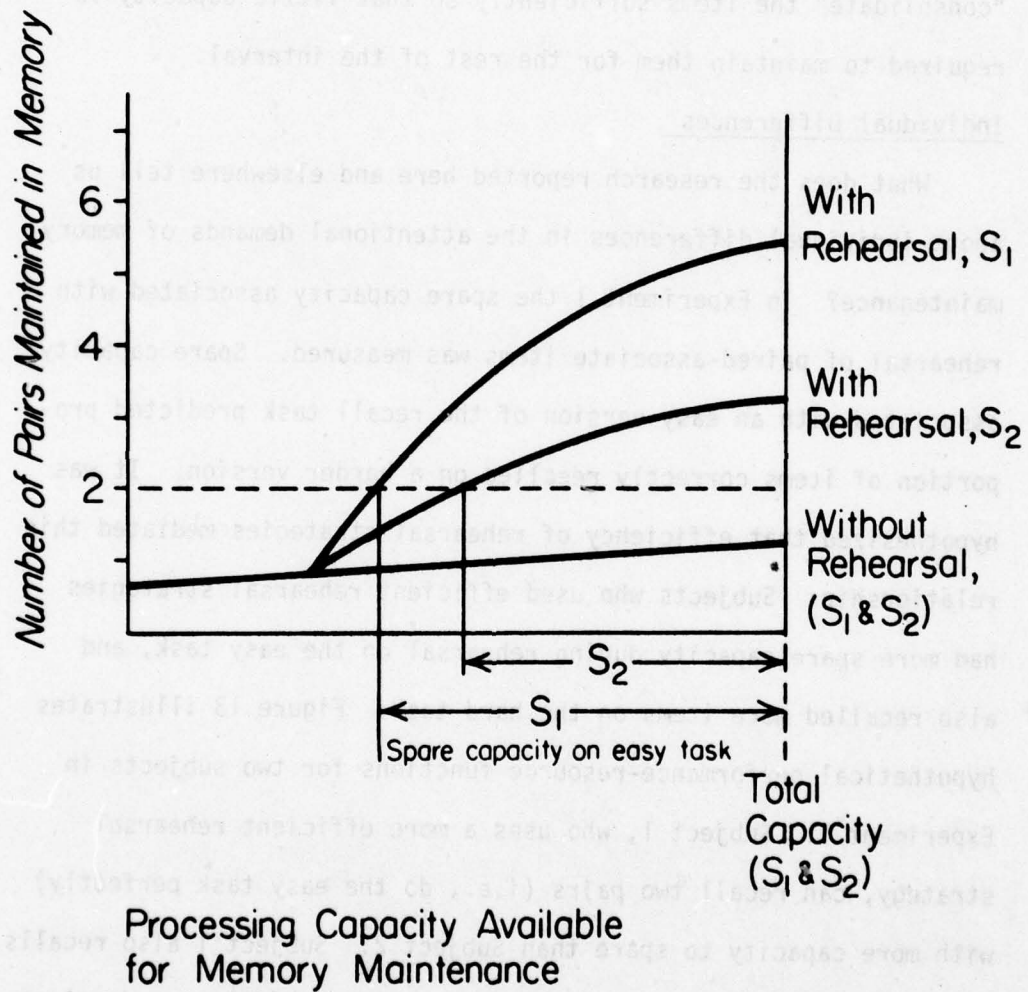
Figure 13. Performance-resource functions for two hypothetical
subjects in Experiment 1.

In Experiment 1, neither recall nor spare capacity was correlated
with general verbal ability, which suggests that efficiency of
rehearsal is not related to verbal ability.

In Experiment 2, subjects' ability to maintain five digits
in memory during an attention-demanding distractor task was measured.
The distractor task was designed so that little or no processing
capacity would be available for maintaining the digits. Recall
in this task was compared to recall in a standard digit span para-
digm. Although the distractor caused considerable forgetting,
it had little effect on relative performance of individuals on
the recall measure. Recall in the dual task was highly correlated
with digit span. The correlation between recall in the dual task
and digit span suggests the possibility that digit span is related
to the number of items subjects can maintain effortlessly.

Several recently published studies provide evidence that
individual differences in digit span are unrelated to rehearsal
or other mnemonic strategies. Lyon (1977), for example, found
that individual differences in digit span were unaffected by speed
of presentation or by grouping of items. Mnemonic strategies would
presumably be affected by both of these variables. Cohen and
Sandberg (1977) showed that intelligence was more strongly related
to probed recall of the final three items of a 9-item list than to
the first or middle three, though recall of earlier items would

be expected to be more affected by rehearsal. Huttenlocher and Burke (1976) argued that changes in digit span with age are probably not related to changes in rehearsal strategy.

More and more evidence suggests that individual differences in digit span are related not to attention-demanding rehearsal but to some characteristic of the original memory trace which determines its durability. Huttenlocher and Burke (1976) pointed out that digit span is longer for items that are more quickly identified. They suggested that children's digit spans may increase as children become able to identify stimuli more quickly. It seems unlikely that speed of identification is an important determinant of digit span in adults, since increasing the rate of presentation does not affect relative performance (Lyon, 1977). But it does seem possible that encoding of items results in a stronger, more durable trace in some individuals. In terms of the activation model discussed earlier, activation of long-term memory nodes is stronger and therefore lasts longer in these individuals.

According to the interpretation proposed here, the locus of individual differences in Experiment 2 is different from that in Experiment 1. In Experiment 1, differences in efficiency of a particular rehearsal strategy were of primary importance. Rehearsal efficiency was unrelated to either digit span or general verbal ability. In Experiment 2, differences in the number of

items that could be maintained without attention were important. This "effortless maintenance" was related to digit span, but not to general verbal ability.

Both rehearsal efficiency and effortless maintenance were factors in Experiment 3, where the primary task was recall, and the secondary task was the sentence-verification distractor. In Experiment 3, memory load was varied from 0 to 5 items and the function relating sentence-verification RT to memory load was compared for high and low verbal-ability subjects. In this paradigm, memory loads requiring no attention should not interfere with the sentence-verification task. Memory loads requiring attention should cause an increase in sentence-verification RT. Results summed over groups showed that memory loads of 1-3 items did not interfere with sentence verification, but that loads of four or five items caused an increase in sentence-verification RT. However, there did not appear to be differences between the two ability groups in either a) the number of items that could be maintained without interfering with the distractor, or b) the amount of interference caused by four- and five-item loads. These results are consistent with those of Experiment 1 and 2 in suggesting that neither effortless maintenance, nor rehearsal efficiency is related to general verbal ability.

A Concluding Note

The hypothesis underlying this research was that attentional factors which affect the ability to combine memory maintenance with other processes are important sources of variation in general verbal ability. The results of the experiments did not support the hypothesis. Individual differences in the ability to combine memory maintenance and other tasks were not related to verbal ability. Dual-task combinations of recall and other simple in-formation-processing tasks did not predict performance on complex measures of verbal ability any better than single-task measures.

It is impossible to foretell whether this finding will gener-alize to other task combinations. Will we be able to say, as a general rule, that performance on combinations of simple tasks predicts performance on complex tasks no better than performance on simple tasks alone? This would be an extremely interesting discovery, for it would mean that variation does <u>not</u> arise in the combination of simple processes which is important in the perform-ance of complex tasks. It would suggest that such concepts as "total processing capacity" and "time-sharing efficiency" are not important in explaining individual differences on complex tasks. Rather, the parameters of simple tasks, performed alone, accounts for differences in complex performance. However, much more research, employing a wide variety of task combinations, is necessary before

such a generalization can be drawn.

It should be pointed out that within the college population, no measure of immediate memory--neither traditional span measures, continuous paired-associate measures, nor any of the attentional measures used in the present research--has been found to be highly correlated with verbal ability. Perhaps failure, in this research, to find task combinations which improved prediction of verbal ability was a result of the decision to study immediate memory measures. Other task combinations may provide an entirely different pattern of results.

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Appendix A

Suppose that two individuals performed a dual task under vary-
ing conditions of resource allocation, and for each individual
a separate POC was derived. Suppose also that the two POCs dif-
fered in some way. Under what circumstances could we conclude
that the two individuals had different performance-resource func-
tions (PRFs) on one or the other of the two tasks? Let us assume,
for the sake of simplicity, that for each individual, performance
on each task was a function of the resources devoted to that task,
and that the sum of the resources devoted to the two tasks in all
task combinations was a constant equal to that individual's total
resources. Let P_1 and P_2 represent performance on the two tasks,
L represent total resources, and r represent resources devoted to
the first task. Then the PRFs for the two tasks could be repre-
sented by the equations:

$$P_1 = f(r)$$
$$P_2 = g(L - r)$$

Assuming that the inverse of the function $f(r)$ (represented as f'
(r)) is a single valued function, we could represent the POC func-
tion by the equation:

$$P_2 = g(L - f'(P_1))$$

It is evident that if the two individuals had different POCs, the
only possible sources of the difference would be a) the PRF

represented by f; b) the PRF represented by g; c) L, total resources; or d) some combination of these three factors. Could we determine from the two individuals' POCs which of these was the source of the difference? The answer seems to be "No." There is no simple rule by which one could determine whether f, g, or L was the source of the difference between two POCs.

Take the relatively simple case where both PRFs are linear with zero intercepts:

$$P_1 = ar$$
$$P_2 = b(L - r)$$
$$P_2 = bL - bP_1/a$$

In this case,

a) A difference in either PRF (i.e. a difference in either a or b) would result in non-parallel POCs.

b) A difference in L, total capacity, would result in parallel POCs.

<u>but</u>

c) A difference in both PRFs could also result in parallel POC; e.g.,

$$P_1 = r \qquad\qquad P_1 = r/2$$
$$P_2 = 2(L - r) \qquad\qquad P_2 = L - r$$
$$P_2 = 2L - 2P_1 \qquad\qquad P_2 = L - 2P_1$$

and

c) A difference in both PRFs <u>and</u> L could result in identical

POCs; e.g., let L equal 3 in the first equation above and let L equal 6 in the second equation above, and the resulting POC for each would be:

$$P_2 = 6 - P_1$$

So in this case, non-parallel POCs would always imply a difference on one or both PRFs. But we could not determine from parallel POCs whether the source of the difference was L or the PRFs, and we could not conclude from identical POCs that the PRFs and L were identical.

Furthermore, if we allowed non-linear PRFs, then non-parallel POCs would not imply a difference in PRFs. Non-parallel POC's could result from differences in L alone; e.g.

$$P_1 = r$$
$$P_2 = (L - r)^2$$
$$P_2 = L^2 - 2LP_1 + P_1^2$$

For these PRFs, a difference in L would result in non-parallel POCs.

These simple examples suggest that determining the source of the difference in two POCs might well be impossible.

Appendix B

Table B1

Proportion of Items Correctly Recalled on Each Day

in Each Condition, Experiment 1

	Easy Recall	
	No Probe Condition	Probe Condition
Day 1	.929	.905
Day 2	.988	.957

	Hard Recall	
	No Probe Condition	Probe Condition
Day 1	.491	.462
Day 2	.643	.559

Appendix C
Table C1
Mean Probe RT (msec) on Each Day in Each

robe Condition, Experiment 1.

	RT Control	Easy Recall with Probe	Hard Recall with Probe
Day 1	294	538	551
Day 2	281	421	475

Appendix D

Results from Experiments 2 and 3 were inconsistent in that in Experiment 2 there was a significant correlation of -.58 between sentence-verification RT and WPC Verbal Composite whereas in Experiment 3 high and low verbal-ability groups did not differ significantly in sentence-verification RT. There are at least three possible explanations for this apparent inconsistency. The first possible explanation is that all subjects in Experiment 3 were women, whereas in Experiment 2 there were equal numbers of men and women. However, in Experiment 2 the correlation between sentence-verification RT and Verbal Composite was almost identical for females alone as for all subjects combined (r = -.57 and r = -.58 respectively) so this possibility was rejected.

The second possibility was that differences related to verbal ability decrease with practice. Including practice in the control condition and all dual task-conditions, there were 30 blocks of trials spread over eight days in Experiment 3, but only 12 blocks over three days in Experiment 2. To test the hypothesis that differences related to verbal ability decrease with practice, per-formance of the high- and low-ability subjects on the six practice blocks of Experiment 3 was examined. Figure D1 shows the two functions. Although the difference between the mean RTs of the two groups decreased from 137 msec to 47 msec over practice, neither
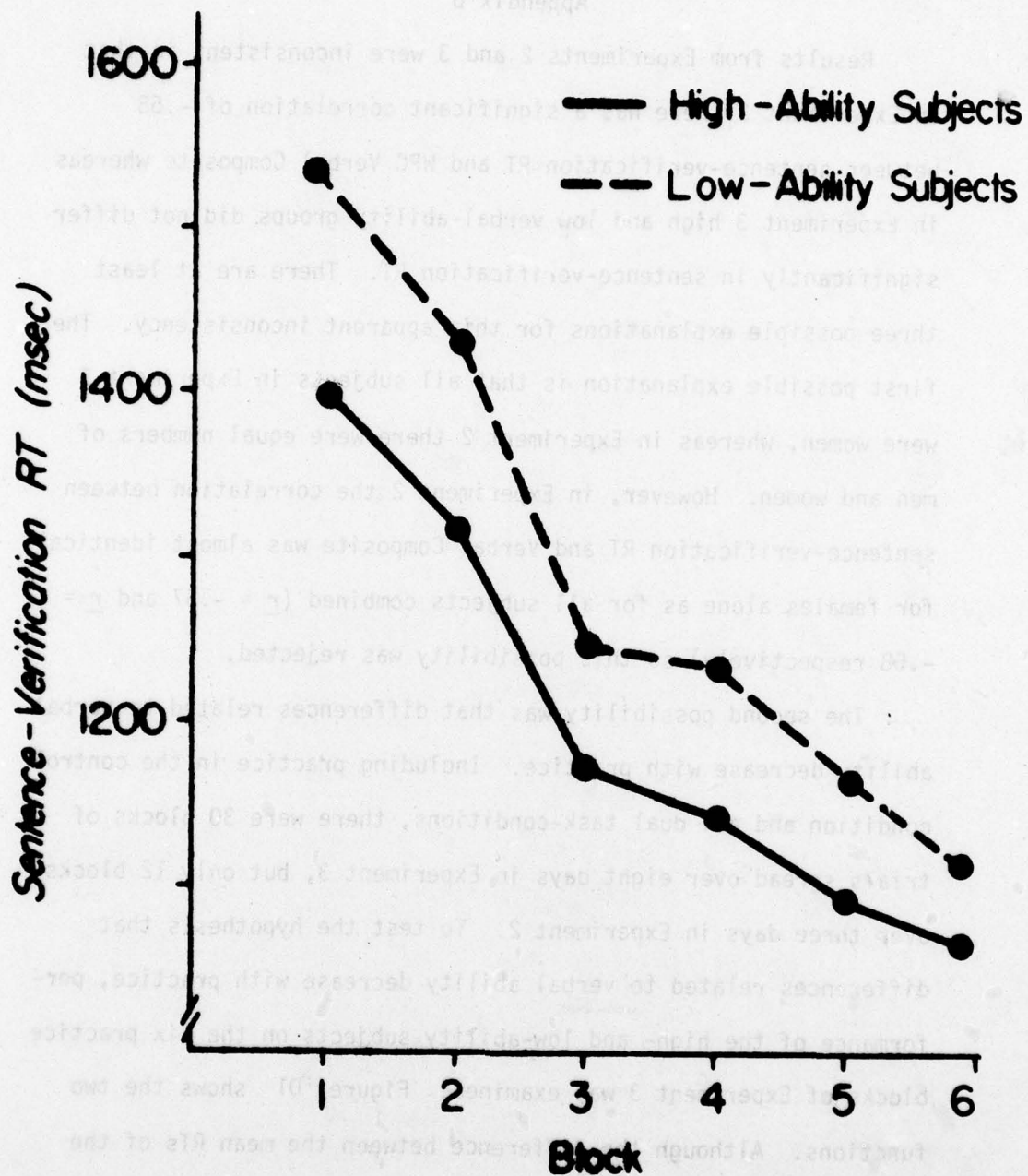
Figure D1. Sentence-verification RT during practice as a function of block and ability group, Experiment 3.

the main effect of ability nor the interaction between ability and practice was significant, F (1, 22) = 1.4, MS_e = 201037, p < .24; F (5, 110) = 1.4, MS_e = 4283, p < .23. There is no indication that the large amount of practice in Experiment 3 washed out effects of verbal ability. There were no significant differences between groups even on the initial six practice blocks.

Performance of high- and low-ability subjects on the first two blocks of sentence-verification trials were compared for Experiments 2 and 3. (The paradigms were only slightly different: In Experiment 2 subjects responded to six items per trial, while in Experiment 3 they responded for 6 sec.) For this comparison, those subjects were selected from Experiment 2 whose WPC Verbal Composite scores fell within the high and low categories used in Experiment 3. Table D1 shows mean sentence-verification RT for each group in each experiment. It is evident from the table that even during the first two blocks, the difference between verbal ability groups was much greater in Experiment 2.

The final possibility is related to the fact that subjects in Experiment 2 were freshmen, while those in Experiment 3 were sophomores and juniors. It is difficult to recruit "low-ability" sophomores and juniors, presumably because many low-ability students drop out of college during the first year. Possibly those who do survive the first year are not really "low-ability" students, i.e.,

Table D1

Mean Sentence-Verification RT (Control Condition) for High and Low
Verbal-Ability Subjects in Experiments 2 and 3

	N	Mean WPC Verbal Composite	Mean Sentence-Verification RT	Difference Between High- and Low-Ability Subjects on Sentence-Verification RT
Experiment 2				
Low-Ability Subjects	14	46	1413	282
High-Ability Subjects	8	66	1131	($\underline{t}$ = 2.77, p .05)
Experiment 3				
Low-Ability Subjects	12	47	1484	126
High-Ability Subjects	12	67	1358	($\underline{t}$ = 1.35, p .10)

their test scores do not reflect their present verbal ability.
To check out this possibility the Nelson-Denny Vocabulary Test
was administered to all subjects in Experiment 3 to find out whether
the scores on this test were correlated with the WPC Verbal Com-
posite scores, which had been obtained 2-4 years before. The cor-
relation was .93 within the high group, but only .48 within the
low group. The difference between these correlations is sig-
nificant, z = 2.41, p < .05. Thus WPC scores were less represent-
ative of the present ability of the low verbal subjects than high
verbal subjects. However, there was a large and significant dif-
ference between scores of high- and low-ability subjects on the
Nelson-Denny Test, t (22) = 5.46, p < .01 with almost no overlap
in the two distributions, so WPC scores are not completely invalid
for the low-ability subjects.

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