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KNOWLEDGE AND PROCESSING SPEED AS DETERMINANTS OF ASSOCIATIVE LEARNING

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SUMMARY

This paper documents 5 experiments that examined the relationships between knowledge, processing speed, mnemonic strategies, and paired-associates learning success. Experiments were conducted as part of the Air Force's Learning Abilities Measurement Program. The major goals of the program are to devise new models of the nature and organization of human abilities with the long-term goal of applying those models to improve current selection and classification systems. In the studies documented in this report, approximately 2500 Air Force trainees were administered a variety of information processing tests, designed to tap specific processing skills, and a series of learning tests, designed to assess the efficiency of associative learning. The major findings were that (a) the most important determinant of learning success was general knowledge; (b) processing speed (specifically, speed of searching long-term memory) was also predictive of learning, particularly when study time on the learning task was short; (c) knowledge of mnemonic strategies was important in determining how much would be learned; and (d) in some cases, better retention on the learning task was accompanied by slower retrieval of items learned. One explanation for the results is that learning efficiency results from a well-organized memory. Methodology for individual differences investigations is discussed.

PREFACE

Development of this paper was supported by the Air Force Learning Abilities Measurement Program (LAMP), a multi-year program of basic research conducted at the Air Force Human Resources Laboratory (AFHRL) and sponsored by the Air Force Office of Scientific Research and AFHRL. The goals of the program are to specify the basic parameters of learning ability, to develop techniques for the assessment of individuals' knowledge and skill levels, and to explore the feasibility of a model-based system of psychological assessment. Support was provided by AFHRL and the Air Force Office of Scientific Research, through Universal Energy Systems, under Contract No. F41689-84-D-0002/58420360, Subcontract No. S-744-031-001, and Subcontract No. S-744-049-001. We thank Scott Chaiken, Dan Woltz, and William Alley of AFHRL for their comments on this paper. We also thank Major Hector Acosta and his crew at Lackland Air Force Base for their data collection efforts. We thank Janice Hereford, Frank Rilling, Rich Walker, and other members of the OAO corporation for their technical assistance on all phases of the study.

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KNOWLEDGE AND PROCESSING SPEED AS DETERMINANTS OF ASSOCIATIVE LEARNING

Recently, a number of studies in the experimental literature have employed individual differences (correlational) methods to identify hypothetical cognitive processing components. This union between what were once distinct disciplines has been expressed in two ways. In one, the validity of theory-based components, knowledge structures or processing mechanisms, is tested by correlating individuals' performances on sets of tasks presumed either to engage or not to engage the component. This approach, originally suggested by Underwood (1975), has been applied in areas such as memory (Underwood, Boruch, & Malmi, 1978), imagery (Kosslyn, Brunn, Cave, & Wallach, 1984; Poltrock & Agnoli, 1986), and reasoning (Sternberg, 1977).

Another approach, termed *cognitive correlates* analysis (Pellegrino & Glaser, 1979), investigates the degree to which basic processing components identified in the experimental literature, such as lexical access speed, short-term memory scanning rate, and so forth, account for individual differences in broad ability categories such as verbal ability (Hunt, 1978), spatial ability (Cooper, 1982), and reading (Daneman & Carpenter, 1980; Jackson & McClelland, 1979). Reliable empirical linkages have been identified in these studies, suggesting that well-established individual-differences categories may ultimately be understood in terms of the underlying elementary components that give rise to them. As an example, a number of studies have reported a small but consistent relationship between verbal ability, as indicated by one's performance on a battery of vocabulary and reading comprehension tests, and the speed with which information can be retrieved from long-term memory (Hunt, Lunneborg, & Lewis, 1975; Jackson & McClelland, 1979). Explanations for this relationship have typically focussed on the cumulative advantage provided by efficient operations over a lifetime of learning (Perfetti & Lesgold, 1977). Yet, thus far, learning per se has not been the target of this kind of analysis.

The purpose of the present study is to examine the processing components of associative learning by means of an individual differences analysis. An individual differences analysis can serve two purposes. First, consonant with the Underwood (1975) proposal, the analysis can be used to test specific theoretical claims emanating from commonly assumed models of associative learning. In this study we test implications of the relation-construction principle in associative learning models. Second, a cognitive correlates analysis can serve to determine the underlying constituents of associative learning. At least as far back as Thurstone (1938), associative memory has been recognized as a broad, distinct individual-differences category (the Ma factor). A goal for the analysis therefore is to determine whether differences in associative memory are predictable from differences on more elementary, or more tractable information processing measures.

Associative Learning and Relation-Construction

In this study, we test hypotheses derived from currently popular associative learning models, which are based on what we refer to as the *relation-construction* principle. According to these models, the strength of a bond between a pair of items (which governs the success of retrieval of that pair) is determined by the *quantity* and the *quality* of the relations constructed between the items during study. If items are simply presented contiguously, or rehearsed together, memory for those items will not increase unless, in addition, a relation between the items is constructed (Bradley & Glenberg, 1983). Models based on relation-construction include those based on depth-of-processing. We prefer relation-construction because, as pointed out by Anderson and Reder (1979), depth-of-processing is probably best interpreted as referring to the number of relations (or synonymously, *elaborations*) a learner constructs.[1]

It is useful to consider the means by which learners construct relations. Consider a typical trial, in which a learner is given a pair to memorize, such as *bottle-window*. Constructing a relation involves retrieving stored memory facts relating to bottles or windows and finding a plausible proposition that connects them. For example, the learner might retrieve facts about bottles, such as "a bottle is made of glass," "a bottle can be used in drinking," or "a bottle can be thrown." Window facts might include "a window can be looked through," "a window is made of glass," or "a window can be broken by something thrown through it." One connecting proposition, of an episodic nature, might be "a bottle was thrown through a window"; another, of a semantic nature, might be that "windows and bottles are made of glass."

According to Anderson (1983, 1985) the reason relations (or elaborations) like these improve memory is that they represent redundant, alternative connections between the two concepts. If the learner, who had encoded both relations, is asked to retrieve the associate to *bottle*, he or she could get to window by either the "thrown-through" path or the "glass" path. Even if the learner was unable to retrieve either path at test time, he or she could think about bottles, think about the fact that they are made of glass, then thereby be reminded of the "glass" path.

A number of task-effect and individual-differences implications follow from the relation-construction principle. First, because relations between two paired-associate terms are constructed by drawing on previously stored facts, the breadth of factual knowledge an individual brings to the learning situation might be expected at least partly to determine paired-associate learning success. A learner with a rich network of facts stored in long-term memory, will be able to retrieve numerous diverse facts relating to each term. The more facts retrieved, the more likely that the learner will be able to construct a relation between terms; further, with a richer knowledge base, a relation constructed will more likely be a distinctive relation, which will also contribute to memorability. A learner with an impoverished knowledge base, on the other hand, will be less likely to retrieve facts during study that will be useful for creating linking relations. Any relations constructed are likely to be poorer in quality, that is, less distinctive, than those constructed from a richer knowledge base.

Given this rationale, it is somewhat surprising that the empirical picture regarding the relationship between breadth of knowledge and associative learning success is mixed, at best. There are some studies that have found a reliable correlation between scores on a vocabulary test, which can be taken as an indicator of breadth of knowledge, and paired-associates learning success (Thurstone, 1938; Kyllonen & Tirre, 1988). Other studies (Underwood et al., 1978) have failed to find such a relationship. It may be that characteristics of the paired-associates learning task, such as study time, recall versus recognition tests, and the like, are responsible for the inconsistency. To explore this idea, we vary a number of features of the learning task in the study to be reported.

A second implication following from the relation-construction principle is that more study time should lead to better memory, due to the fact that more study time enables the construction of more (and better) relations between items. Numerous studies have found a relationship between study time and learning success (Paivio, 1979). The individual differences corollary is that processing speed, that is, the speed with which facts can be retrieved and relations constructed, should predict learning success, because fast-processing learners have the equivalent of more study time. To our knowledge, this hypothesis has not received direct support in the literature, at least partly due to difficulties in operationalizing processing speed. But there are hints that this relationship holds.

[1] Throughout this paper we use the terms relations and elaborations interchangeably.

Scores on tests of verbal fluency, which require subjects, for example, to generate four-letter words beginning with S and ending with D, or to generate multiple associations to a stimulus word, have been shown to predict success in paired-associates learning (Greeno, 1965; Thurstone, 1938).

There is a problem with interpreting this simple correlation as unequivocal support for the hypothesis that processing speed predicts learning success. The problem is that scores on a fluency test may reflect a variety of cognitive skills besides semantic processing speed. Fluency test scores could at least partly reflect breadth of knowledge, or they could reflect a non-semantic processing speed component. Most generally, the problem is one of discriminant validity; the finding that fluency correlates with learning success does not directly implicate any particular component of processing speed. In the present study we examine a variety of processing speed measures, from simple reaction and decision time, to memory search for semantic relations. Examination of a full range of processing speed indicators enables more precise identification of the processing component responsible for learning success.

A third implication to be drawn from the relation construction principle is that, in addition to the benefits of redundancy, there might be a processing cost. It is well documented (Anderson, 1983) that the more associates to a concept one studies, the longer it takes to verify any one of those associates as being related to the concept, a phenomenon known as the *fan effect*. The fan effect might be expected to apply to *relations constructed* as well as to *relations studied*. That is, the more relations constructed while studying a pair, the longer it would take to retrieve any of those relations at test time. Then we would predict that, first, longer study time would lead to slower retrieval, because more relations would be constructed. Second, those individuals who construct more relations per unit study time (i.e., those who are most accurate on the retrieval test, fast processors, or high-knowledge subjects) would retrieve associates relatively slowly. Further, individual differences might even be expected to interact with study time: Fast subjects should be particularly slow in retrieving associates following long study time.

Anderson (1985) has argued that fan should result in slowed retrieval time only when it is created by relations *studied*, and even then, only when those relations are independent of (or "irrelevant to") each other (e.g., bottle is arbitrarily associated with glass, chair, dog). In contrast, relations *constructed* tend to reinforce each other, and therefore should not interfere with each other. In fact, there is evidence for a negative fan effect: When associates are reinforcing (e.g., causally linked), memory is better the more associates there are (Myers, O'Brien, Balota, & Toyofuku, 1984). This might suggest that constructed relations, which could typically be assumed to reinforce each other, should even produce a result opposite to our prediction. But to our knowledge, there are no data that directly pertain to our predictions of a fan effect due to variation in relations constructed.

In sum, we propose that the relation-construction principle can be used to generate predictions regarding individual differences in associative learning. If learning is a process of constructing relations, then retention will depend on both (a) the extent and quality of the semantic material (i.e., knowledge) available to be used in constructing linking relations, and (b) the rate at which material used in constructing relations can be accessed (i.e., processing speed). However, there may also be a liability associated with proficiency in constructing relations: increased retrieval interference with more study time. This liability might be partially compensated for with greater information processing speed.

EXPERIMENT 1

The purpose of the first experiment was to determine the effects of study time, and subject knowledge and processing speed, on associative learning proficiency. To measure learning proficiency we employed a study-test procedure in which subjects studied a block of ten word-pairs, then were given a 5-alternative-choice test on those pairs. The test required subjects to select not the actual response term they had studied but rather, a synonym to that response term. The intention was to elicit a more active, recall-like retrieval process. To further encourage recall-like processing, we suggested to subjects during the instructions that the best strategy for selecting a response was first to attempt to recall the response term, and only then to search among the five alternatives in the multiple-choice test for a synonym to that response term. Study time varied by block, from .5 to 8 s per pair.

Subject knowledge was indicated by performance on a vocabulary test. Subject processing speed was indicated by performance on a series of tests (simple reaction, choice reaction, physical-, name-, and meaning-identity judgment) that required subjects to make increasingly complex decisions about word stimuli. These tests have frequently been administered in studies of individual differences in reading comprehension ability (Hunt et al., 1975; Jackson & McClelland, 1979; Perfetti, 1985). As a group, they are designed to enable the identification of independent processing components: simple reaction (a combination of perceptual encoding and motor response), decision (or response selection), comparison, long-term-memory (LTM) access, and LTM search (see Figure 1).

Experiment 1 also served as the baseline against which various manipulations in Experiments 2-5 could be examined. Those experiments differed from Experiment 1 by only one change.

Method

Subjects

Subjects were 400 Air Force enlistees selected randomly on their sixth day of Basic Military Training. Four subjects' data were not analyzed because these data deviated radically from the other data. The sample was 88% male, 81% Caucasian; 99% were high school graduates, and 27% had at least some college. The mean Armed Forces Qualification Test (AFQT; OASD/MRA&L, 1982) percentile score for the subjects was 64.4, with standard deviation of 17.0. It is appropriate to interpret these percentile scores with respect to the population of American youths, because the AFQT has been calibrated on a national probability sample of 16- to 23-year-olds.

Testing Stations

The testing facility consisted of 30 testing stations in a large room. Each station was a TERAK 8510a microcomputer system with disk drives for test item and response data storage, a standard keyboard for response entry, and a medium-resolution (320 x 240) black-and-white video monitor for timed presentation. Millisecond timing for stimulus presentation and response latency recording was achieved with an algorithm developed by Armstrong (1984). All test materials, including items, response scoring and recording procedures, and feedback presentation procedure, were written in PLATS, a high-level task authoring system (Walker, 1985). Data compilation at the end of a session was accomplished by a network system tying the 30 TERAKs to a PDP 11/34 minicomputer for transfer from the floppy disks to standard magnetic reel-to-reel tape.

Experimental Tasks

Subjects were administered 7 cognitive tasks and a paired-associates learning task. The cognitive tasks were designed to reflect various processing components involved in recognizing the meaning of a word. All cognitive tasks were presented in the same format; a target stimulus appeared above

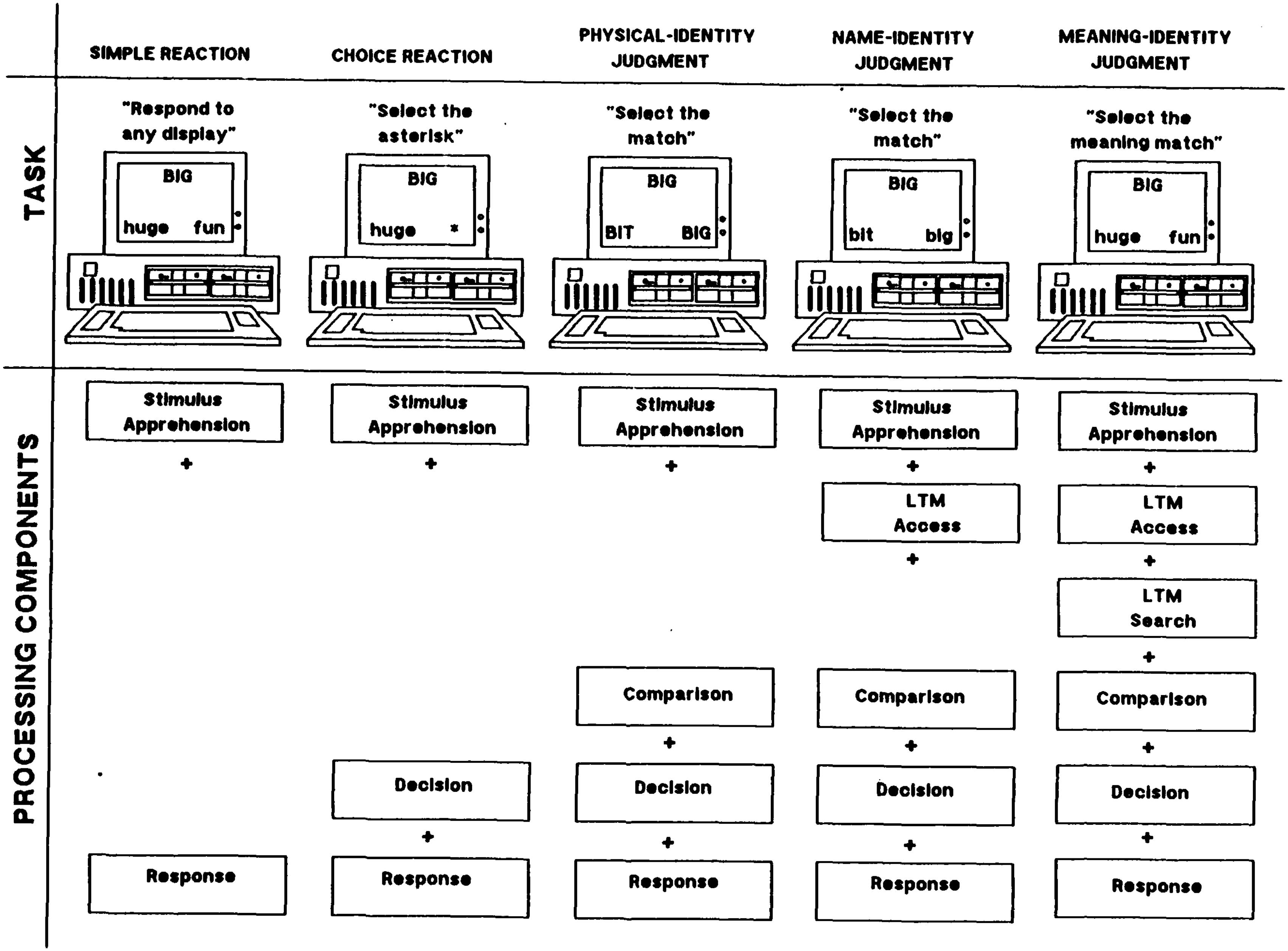

Figure 1. **Processing stages associated with the five information processing tasks administered in Experiments 1 - 5. Going from left-to-right, each task inserts an additional processing component beyond those required for the task to the immediate left. The top row presents task instructions.**

two alternative probe stimuli, forming a triangular pattern of stimuli. The subject's task was to select the probe stimulus that matched the target stimulus along the dimension specified by individual task instructions, then to press a key on the keyboard (either the L or D key) beneath the selected probe. This format was designed to minimize response time variance due to having to remember an arbitrary decision rule such as "left hand means true." Within a task, subjects all received the same items, but in different randomized orders. The position of the correct alternative (left versus right) was balanced within a block. A description of each task follows.

Simple Reaction (RT). Subjects were presented a stimulus pattern selected randomly from among the stimuli used on the other cognitive tasks. For the first 25 trials, subjects were instructed to press the L key with their right hand as soon as they perceived any stimulus on the display screen. For the next 25 trials, subjects were instructed to press the D key with their left hand as a response. This sequence was repeated for a total of 100 items. Accuracy and latency feedback was presented for 1 s immediately after the response, followed by a randomly varying intertrial interval (0.5 - 2.5 s). This task was presumed to measure SIMPLE REACTION.

Choice Reaction (CRT). Subjects were presented a triangular stimulus pattern selected randomly from among the stimuli used on the other tasks except that an asterisk was substituted for one of the two alternatives on the lower row. The subjects' task was to press the key on the keyboard below the asterisk (either L or D). Subjects were presented two blocks of 50 items in succession, with a 1-min break between blocks. Latency and accuracy feedback was presented for 1 s immediately following subject's response, and this was followed by a 1-s intertrial interval in which an asterisk was displayed, centered on the screen for .5 s, then replaced by a blank screen for .5 s. The next item was then immediately presented.[2] This task was the basis for estimating DECISION.

Physical-Identity Judgment (PI). Stimuli consisted of three words in the triangular format. The subjects' task was to select the alternative that physically matched the target. Targets and alternatives were always the same case (uppercase or lowercase), but case varied randomly from trial to trial, totaling half uppercase and half lowercase trials. Subjects were presented two blocks of 50 items each (see footnote 1). Feedback and intertrial interval were identical to the choice reaction time task. This task was the basis for estimating COMPARISON TIME.

Name-Identity Judgment (NI). This task was similar to the Physical Identity task except that both alternatives were opposite case from the target. The subjects' task was to select the alternative that was the same word as the target. This task was the basis for estimating long-term memory (LTM) ACCESS TIME.

Category-Identity Judgment. This task was similar to the Name and Physical Identity tasks except that subjects were to select the alternative word that was an instance of the category of which the target word was an instance. The distractor alternative was from an unrelated category, selected at random from among a list of category members. Categories and instances were taken from Battig and Montague (1969). Subjects were presented a total of 102 trials in two blocks of 51 items (see

[2]For experiments 1 and 5, in four of the cognitive tasks (choice reaction; physical-, name-, and category-identify), the next item was presented immediately following feedback (i.e., no intertrial interval). This was a mistake caused by a glitch in the computer program that controlled item administration. Also, in those two experiments some of the reaction time tasks were presented as a continous 100-item block, whereas in Experiments 2-4 the block was divided into two parts, with summary feedback given at the end of the first part. To assess the effect of these differences, we compared reaction time data from Experiments 2-4 with those from Experiments 1 and 5. Somewhat surprisingly, we found neither magnitude nor correlational differences.

footnote 1). Although we collected data on this task, those data were not analyzed for any of the studies to be reported here.

Meaning-Identity Judgment (K). This task was similar to Physical-, Name-, and Category-Identity Judgment except that the subject was to select the alternative word most similar in meaning to the target (in all cases, pairs could be considered synonyms according to a standard thesaurus). Words were taken from a variety of sources: non-operational versions of the ASVAB Word Knowledge Test (OASD/MRA&L, 1982), the vocabulary test from the ETS kit of cognitive reference tests (French, Ekstrom, & Price, 1963), and a vocabulary test from Marshalek (1981). Subjects were presented one block of 52 items followed immediately by a second block of 53 items. This task was presumed to measure KNOWLEDGE.

Easy Meaning-Identity Judgment (MI). This task was identical in all respects to Meaning-Identity Judgment, except that all word stimuli were selected to be at or above the 93rd percentile of correctness, based on a pilot study with subjects drawn from the same population as that assumed for this study. This task was the basis for estimating LTM-SEARCH TIME.

Paired-Associates Learning Task. This task consisted of blocks of paired associates, administered in a study-test format. A block consisted of a presentation phase, in which 10 paired associates were presented for study at a constant rate (0.5-, 1-, 2-, 4-, or 8-s study per pair), followed by a test phase consisting of multiple-choice questions for each paired associate. The 20 blocks of word pairs (4 at each of the 5 presentation rates) were constant for all subjects (Block 1 was a set of 10 specific pairs). But presentation rate was randomly assigned to word-pair blocks by a Latin Square, separately for each subject. This design guaranteed that (a) within subjects, each presentation rate was assigned to four different blocks; and (b) across subjects, each presentation rate was assigned to each study block an approximately equal number of times. Word pairs within a block were presented in a random order, separately for each subject.

Test questions were 5-alternative multiple-choice questions for each pair, in which the target was the stimulus term and 1 of the 5 alternatives was a synonym of the corresponding response term of the pair. Distractors were synonyms of response terms that appeared within a study block. Thus, for each block, any synonym appeared four times during the test phase, once as a correct alternative and three times as an incorrect distractor. Order of test items was random.

Words used as paired associates were those whose meaning was known by at least 95% of the sample (as determined in the pilot study). The synonyms, used as both correct and distractor response alternatives, were determined in the pilot study to be such that 92% of the pilot sample correctly identified them as synonyms of the target when presented in regular multiple-choice vocabulary test format. Therefore, only a small percentage of the variance in accuracy on this learning task could be attributed to differences in knowledge of the words used or of synonyms of those words.

After each test block, a summary of performance, indicating proportion correct, was given as feedback.

Procedure

Subjects were tested in groups of 27-30, with each subject seated at a randomly assigned testing station. The session began with oral instructions, presented through headphones, specifying the general nature of the tasks and the types of responses required. Subjects were told that their responses would be kept confidential according to the provisions of the Privacy Act. Subjects were asked through multiple-choice questions, presented on the computer screen, to indicate their (a) social security number, (b) race, (c) sex, and (d) educational level.

Subjects were then immediately administered the learning tasks and cognitive tasks with instructions. Half the learning blocks (5 study times X 2 replicates = 10 blocks) were administered before the cognitive tasks; half, after. Half of the subjects received one set of words first (i.e., Blocks 1-10, in random order, separately for each subject) and the other set last (i.e., Blocks 11-20); the other half of the subjects received the reverse order.

The 7 cognitive tasks were administered in a random order. For each of the cognitive tasks, subjects were instructed to "work as quickly as possible without making any mistakes." For the learning tasks, subjects were shown an example of an associated pair; they were told that pairs could be presented for either 0.5, 1, 2, 4, or 8 s.

Two 5-min breaks were inserted at various points during the session. Sessions lasted from 2 to 3 hours. After the session, subjects left their testing stations and were accompanied to another room, where they waited for all subjects to finish.

Results

Overview of Analysis Strategy

Error and latency data were analyzed separately. The unit of analysis was block scores, percent correct or latency, computed over the 10 items in each block. Both sets of scores were subjected to a multivariate analysis of variance (MANOVA) using the general procedures outlined by O'Brien and Kaiser (1985). For the individual differences analysis only, we extended the MANOVA model, following a suggestion by O'Brien (personal communication, 1 May 1985), to test hypotheses of interaction between the cognitive ability scores and the repeated-measures factors. The MANOVA approach has advantages over the traditional mixed-model approach to analyzing repeated measures data because it does not assume the typically violated condition of sphericity in the data.

We computed each subject's block scores, and a series of contrast scores for the repeated-measures factors of session (1st versus 2nd), study time (.5-, 1-, 2-, 4-, or 8-s per pair), block within session (1st versus 2nd), and their interactions. The five-level study time factor was reparameterized as a set of four orthogonal contrast scores (in log study time, so as to get equally spaced intervals). Each contrast score was analyzed with respect to the full between-subjects model, to test the effects for the constant, gender, session order (1 versus 2), and their interactions.

The analysis employed a weighted-means hypothesis-testing strategy with respect to the between-subjects factors. Thus, group comparisons are given in harmonic means (over sex and group), and differences (d) between groups or blocks are unweighted comparisons. All significance testing throughout this paper was with alpha = .05.

Error Analysis

The main factor of interest in the within-subjects analysis was study time, which had a significant overall effect on percent correct, F (4, 389) = 282.05. A trend analysis showed that the form of the learning curve could be well approximated by a model that included only the linear, F (1, 392) = 1129.79, and quadratic, F (1, 392) = 38.23, components, R^2 (2, 4) = .9996. The two higher-order trend components added nothing to the goodness of model fit, as shown by a comparison between the full four-component model and the restricted two-component model, F (2, 389) < 1. (This result was found in all experiments, and therefore the cubic and quartic trends were eliminated for all subsequent analyses involving the study time factor.)

Figure 2a shows a plot of retention percent correct (PC) against study time. (Results for Experiments 1 and 2 are plotted together to facilitate later comparisons; ignore for now the plot for Experiment 2). The plot shows expected values of PC at each study time as determined by the two-component model:

$$\text{PC(study-time)} = (44.6 * \text{AVERAGE}) + (7.6 * \text{LINEAR}) + (-.7 * \text{QUADRATIC}),$$

where AVERAGE, LINEAR, and QUADRATIC were coded respectively as [1 1 1 1 1], [-2 -1 0 1 2], and [2 -1 -2 -1 2] for the five study-time conditions [.5 1 2 4 8] s. This model was a good approximation to the actual values of PC for the five study times (for all experiments R^2 > .999) and allows easier comparisons between experiments.

Although we were mostly interested in the effect of study time, we also noted within-session learning effects. Subjects did better on the second same-study-time block within a session, d = 2.8,[3] F (1, 392) = 11.02. However, they did worse on the second versus the first session, reflecting fatigue or proactive interference, d = 3.3, F (1, 392) = 10.72. Two interaction effects involving the session factor were also noted, but could not be easily interpreted due to the confounding influences of learning-to-learn and fatigue. These were interactions between session and study time, F (2, 392) = 5.11, and session and replication, F (1, 392) = 7.79.

In the between-subjects analysis, only gender was significant, with females correctly recalling more items, F (1, 392) = 17.04, d = 5.8. Most, but not all, of the variation in the gender effect size was due to females' generally higher vocabulary knowledge scores (83.6% versus 80.5%), as indicated by a significant relationship with the verbal knowledge covariate which accounted for 80% of the variance in the gender effect. No differences were found between groups administered the two orders of block sets, and the gender-by-group interaction was not significant.

Individual Differences in Errors: Models

Table 1 presents the individual-differences models tested throughout all the experiments. Each model is a multiple linear regression of a learning dependent variable on a set of cognitive component variables. All variables are based on either percent correct or latency scores from the various tasks. The learning variable (Y) is one of five scores we analyzed: a learning contrast score (AVERAGE, LINEAR, and QUADRATIC), as specified above, or a performance score for one of the endpoint study-time conditions (.5 s and 8 s). The learning contrast scores represent either the overall performance level on the learning task (AVERAGE), the change in performance realized as a result of a doubling of study time (LINEAR), or the degree of deviation from linearity experienced as a function of changes in study time (QUADRATIC). This latter variable essentially represents the degree of relatively early growth in the learning function, that is, the degree of positive acceleration in the growth curve. Because of the way it is coded (see above), high negative scores represent highly accelerated learning (with percent correct as the variable) and a score of zero represents

[3]Throughout we use d to indicate the difference between two harmonic means.

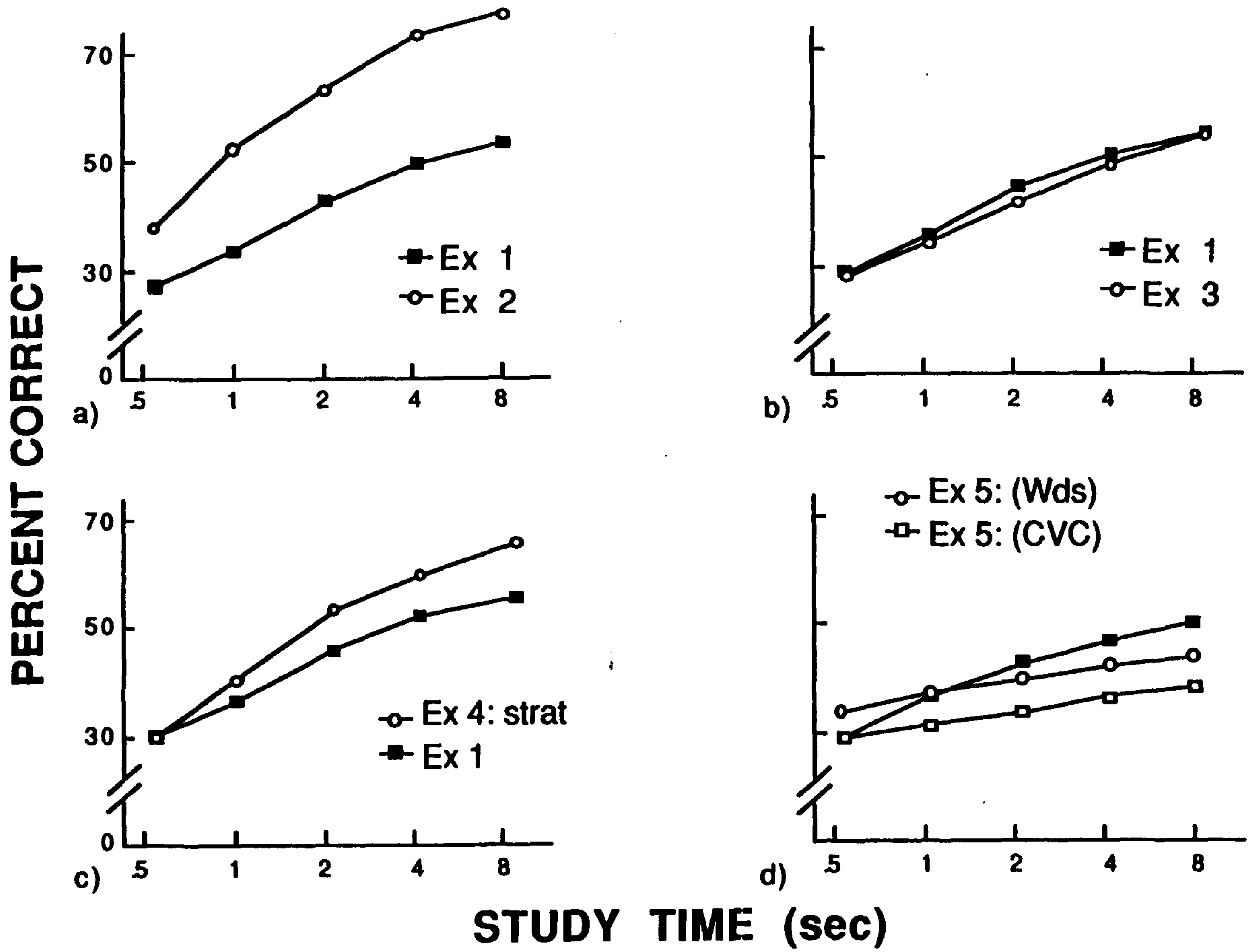

Figure 2. **Percent correct as a function of study time per pair for Experiments (a) 1 vs. 2, (b) 1 vs. 3, (c) 1 vs. 4 (strategy group only), and (d) 1 vs. 5 (both CVC and WORD conditions); Experiment 1 is repeated in all four plots to facilitate comparisons. Curves were generated by second-order polynomical equations, and in all cases R2 > .99.**

straight linear growth. High positive scores turn out to be uncommon in the data, but they represent slow early growth followed by a late spurt.

Table 1. **Regression Models Tested in Individual Differences Analyses**

Models

1: Yi = b1(Ki).
2: Yi = b2(Ki) + b3(RTi).

Estimating Component Correlations by the Part-Correlation Method

3: Yi = b4(Ki) + b5(RTi) + b6(CRTi).
4: Yi = b7(Ki) + b8(RTi) + b9(CRTi) + b10(PIi).
5: Yi = b11(Ki) + b12(RTi) + b13(CRTi) + b14(PIi) + b15(NIi).
6: Yi = b16(Ki) + b17(RTi) + b18(CRTi) + b19(PIi) + b20(NIi) + b21(MIi).

Estimating Component Correlations by the Difference-Score Method

7: Yi = b22(Ki) + b23(CRTi - RTi).
8: Yi = b24(Ki) + b25(PIi - CRTi).
9: Yi = b26(Ki) + b27(NIi - PIi).
10: Yi = b28(Ki) + b29(MIi - NIi).

Notes. Yi is person i's AVERAGE, LINEAR, or QUADRATIC learning contrast score, or person i's learning performance in either the .5-s or 8-s study-time condition, depending on the analysis. The b values in Tables 2 -- 14 are b_1, b_3, b_6, b_{10}, b_{15}, b_{21}, b_{16}, b_{23}, b_{25}, b_{27}, b_{29} from this table. (K = Percent Correct on Meaning-Identity Judgment; RT = RT on Simple Reaction; *CRT* = RT on Choice Reaction; *PI* = RT on Physical-Identity Judgment; *NI* = RT on Name-Identity Judgment; *MI* = RT on Meaning-Identity Judgment.)

Each model in Table 1 is designed to estimate the correlation between a cognitive component (KNOWLEDGE and the processing components from Figure 1) and the dependent variable (one of the five learning scores, Y). Model 1 estimates the correlation between KNOWLEDGE and Y in the form of the coefficient b_1 (when all variables are standardized to 0 mean and unit variance, $b = r$). Model 6 is an alternative estimate of the correlation between KNOWLEDGE and Y, in b_{16}. The difference is that in Model 6, the correlation is between KNOWLEDGE and Y, *statistically controlling for all the processing speed variables* (b is commonly referred to in the statistics literature as part r, or as the *coefficient of partial determination*).

Model 2 is used to estimate the correlation between REACTION TIME and Y, in b_3. Note that this is a part correlation controlling for KNOWLEDGE. Models 3 through 6 are used to estimate the correlations between DECISION TIME, COMPARISON TIME, LTM-ACCESS TIME, and LTM-SEARCH TIME and Y, in b_6, b_{10}, b_{15}, and b_{21}, respectively. For example, b_6 in Model 3 is an estimate of the correlation between Y and the DECISION TIME processing component; and b_{10} in Model 4 is an estimate of the correlation between Y and the COMPARISON TIME processing component.

The justification for the part-correlation approach to estimating the correlation between processing-stage RT and Y is as follows. The part correlation between task RT and Y, holding RT on component subtasks constant, is an estimate of the correlation between whatever is unique on the task, and Y. What is unique is the processing stage required by the task that is not required by the component subtasks. The motivation for separate models, which represent a hierarchical approach to stage identification, as opposed to estimating all part correlations from Model 6, is that what is unique changes depending on what other variables are in the model. The uniqueness corresponds to the inserted stage (as depicted in Figure 1) only when the other variables in the model represent component subtasks.

Models 7 through 10 are also used to estimate the correlations between DECISION TIME, COMPARISON TIME, LTM-ACCESS TIME, and LTM-SEARCH TIME and Y, in b_{23}, b_{25}, b_{27}, and b_{29}, respectively. In these models, the target component (e.g., LTM-ACCESS TIME) is estimated by subtracting RT for the predecessor task (e.g., Physical-Identity Judgment) from RT for the target task (e.g., Name-Identity Judgment), where predecessor and target tasks are adjacent in Figure 1 (see also the Method Section).

Note that pairs of models (3 and 7; 4 and 8; 5 and 9; 6 and 10) merely represent two different ways of estimating the relationship between the duration of a particular processing component (e.g., LTM-ACCESS TIME) and the dependent variable, Y. The difference-score models estimate the duration of the processing component by subtraction; the part-correlation models estimate the duration of the processing component by regression. Which estimate is better depends on which of two sets of assumptions one is willing to make. The part-correlation models assume that the duration of the isolated component (e.g., LTM-ACCESS TIME) is uncorrelated with reaction time on any of the predecessor tasks (e.g., for LTM-ACCESS TIME that would be the knowledge task, simple reaction, choice reaction, and physical-identity task). The difference-score models assume that a processing stage (e.g., the LTM-access processing stage) is of a constant duration regardless of the task in which it is embedded. That is, if LTM-ACCESS TIME is estimated to be 200 ms in the context of the name-identity task, then we assume, by the difference-score model, that the LTM-access process also takes 200 ms to complete when it occurs in the meaning-identity task.

These two assumptions, the part-correlation model's "uncorrelated component" assumption, and the difference score model's "constant process duration" assumption, define the two models (Donaldson, 1983). There is no simple way to determine which assumption is more tenable, though one could construct an argument for one or the other model. Rather than doing so, in this study we present the results of both analyses: When the two analyses agree, we can feel fairly confident of the existence of a correlation between a processing component and a learning variable.

Individual Differences in Errors: Results

Table 2 presents the results of applying the models in Table 1 to the learning task data. The coefficients in the b column are estimates of the correlation between the row component (e.g., LTM-ACCESS TIME) and the learning variable (either AVERAGE, LINEAR, QUADRATIC, .5-s condition, or 8-s condition); the associated t statistic is used to test the hypothesis that the correlation is zero.

Table 2. **Retention-Cognitive Ability Relationships (Experiment 1, N = 396)**

		Learning Contrast Score					
		AVERAGE		LINEAR		QUADRATIC	
Component	**Model**	**b**	**t**	**b**	**t**	**b**	**t**
		Part-Correlation Analysis					
KNOWLEDGE	1	.375	8.01**	.241	4.91**	-.047	-.93
KNOWLEDGE	6	.334	7.08**	.232	4.60**	-.015	-.28
REACTION TIME	2	-.105	-2.25*	.070	-1.42	.025	.48
DECISION TIME	3	-.112	-2.38*	-.079	-1.58	-.054	-1.05
COMPARISON TIME	4	-.003	-.06	.060	1.10	-.034	-.61
LTM-ACCESS TIME	5	-.010	-.13	.074	.95	.076	.94
LTM-SEARCH TIME	6	-.211	-3.44**	-.033	-.50	.166	2.47*
		Difference-Score Analysis					
DECISION TIME	7	-.029	-.62	-.023	-.46	-.058	-1.14
COMPARISON TIME	8	.043	.92	.079	1.62	.001	.01
LTM-ACCESS TIME	9	-.011	-.23	.027	.55	.049	.97
LTM-SEARCH TIME	10	-.195	-4.14**	-.035	-.70	.107	2.08*

		Study Time Condition			
		.5 sec		8 sec	
Component	**Model**	**b**	**t**	**b**	**t**
		Part-Correlation Analysis			
KNOWLEDGE	1	.312	6.45**	.340	7.16**
KNOWLEDGE	6	.268	5.55**	.318	6.58**
REACTION TIME	2	-.090	-1.88	-.087	-1.84
DECISION TIME	3	-.105	-2.18*	-.126	-2.63**
COMPARISON TIME	4	.093	-1.75	.024	.45
LTM-ACCESS TIME	5	-.044	-.59	.047	.62
LTM-SEARCH TIME	6	-.228	-3.63**	-.108	-1.72
		Difference-Score Analysis			
DECISION TIME	7	-.033	-.68	-.051	-1.07
COMPARISON TIME	8	-.029	-.60	.072	1.52
LTM-ACCESS TIME	9	-.011	-.23	.016	.33
LTM-SEARCH TIME	10	-.226	-4.72**	-.111	-2.30*

Note. By the model, the results for KNOWLEDGE and REACTION TIME are the same in the two analyses. The *b* coefficients and *t* statistics are based on the models in Table 1. See text and Figure 1 for a mapping of tasks and components

*$p < .05$.

**$p < .01$.

The table shows that KNOWLEDGE predicted both the general likelihood that a pair would be remembered (AVERAGE) and the degree of linear improvement as a function of study time (LINEAR). The simple-effects (study-time condition) covariate analysis is consistent with the contrast analysis. KNOWLEDGE predicted retention after both .5-s and 8-s study.

In both analyses, LTM-SEARCH TIME predicted both the general likelihood of remembering (AVERAGE) and the degree of deviation from linearity (QUADRATIC). Because the overall trend of the learning curve is negatively accelerated, the relationship with QUADRATIC indicates that fast memory search is associated with rapid initial growth in degree of learning. Consistent with this finding, LTM-SEARCH TIME predicted retention after .5-s study, but not after 8-s study. No other covariate was a significant predictor of any of the learning outcome scores in both analyses.

It is perhaps easiest to appreciate the observed pattern of covariate relationships through an examination of Figure 3, which shows the plot of percent correct as a function of study time for subjects with differing cognitive-skill profiles. The four curves show the expected trend for subjects who scored one standard deviation from the mean, either above (high) or below (low) in KNOWLEDGE, and either below (fast) or above (slow) in LTM-SEARCH TIME. To isolate the impact of variation in these two cognitive skills, the hypothetical subjects were assumed to score at the Experiment 1 mean on all the other covariates. Also, because the part-correlation analysis (compared to the difference score analysis) showed stronger relationships between the criterion variables and the covariate, the model used to produce the curves was the full model that included the set of all six information processing scores as covariates. Appendix A explains the underlying equations that produced these plots.

Note that the Fast, High-Knowledge subjects scored much better than the Slow, Low-Knowledge subjects at all exposure rates; the gap in percent correct between these two groups grew with increases in study time. To get a sense for the magnitude of difference, note that Fast, High-Knowledge subjects have learned more after 1-s exposure than Slow, Low-Knowledge subjects have after 8-s exposure. It is even more revealing to compare the two groups of mixed skill level--the Slow, High-Knowledge and Fast, Low-Knowledge subjects. With short study time, speed is more important than knowledge, in that Fast, Low-Knowledge subjects outperform Slow, High-Knowledge subjects. But with increases in study time, the importance of a knowledge advantage increases while the importance of the speed advantage wanes, as reflected in the crossing of the curves at 4 s.

Another way of making this same point is through the covariate analysis of simple effects. In this series of analyses, the dependent variables were percent-correct scores at each of the five study times, considered separately. Aside from this difference, the analysis paralleled the analysis of contrast scores. The important contrast is between the results for the .5-s and the 8-s study-time conditions, which is also shown in Table 2 (results from the intermediate conditions followed the same trend, and discussion of those can thus be omitted).

For the full covariate analysis (the part-correlation method), in the .5-s condition, the only significant predictors of percent correct were KNOWLEDGE, t (6) = 5.55, b = .268, and LTM-SEARCH TIME, t (6) = -3.63, b = -.228. In the 8-s condition, however, KNOWLEDGE was still a significant predictor, t (6) = 6.58, b = .318; but LTM-SEARCH TIME was not, t (6) = -1.72, b = -.108.

Thus, in both analyses it can be seen that verbal knowledge was a reliable predictor of learning regardless of study time, and, in fact, it increased in importance with greater study time. On the

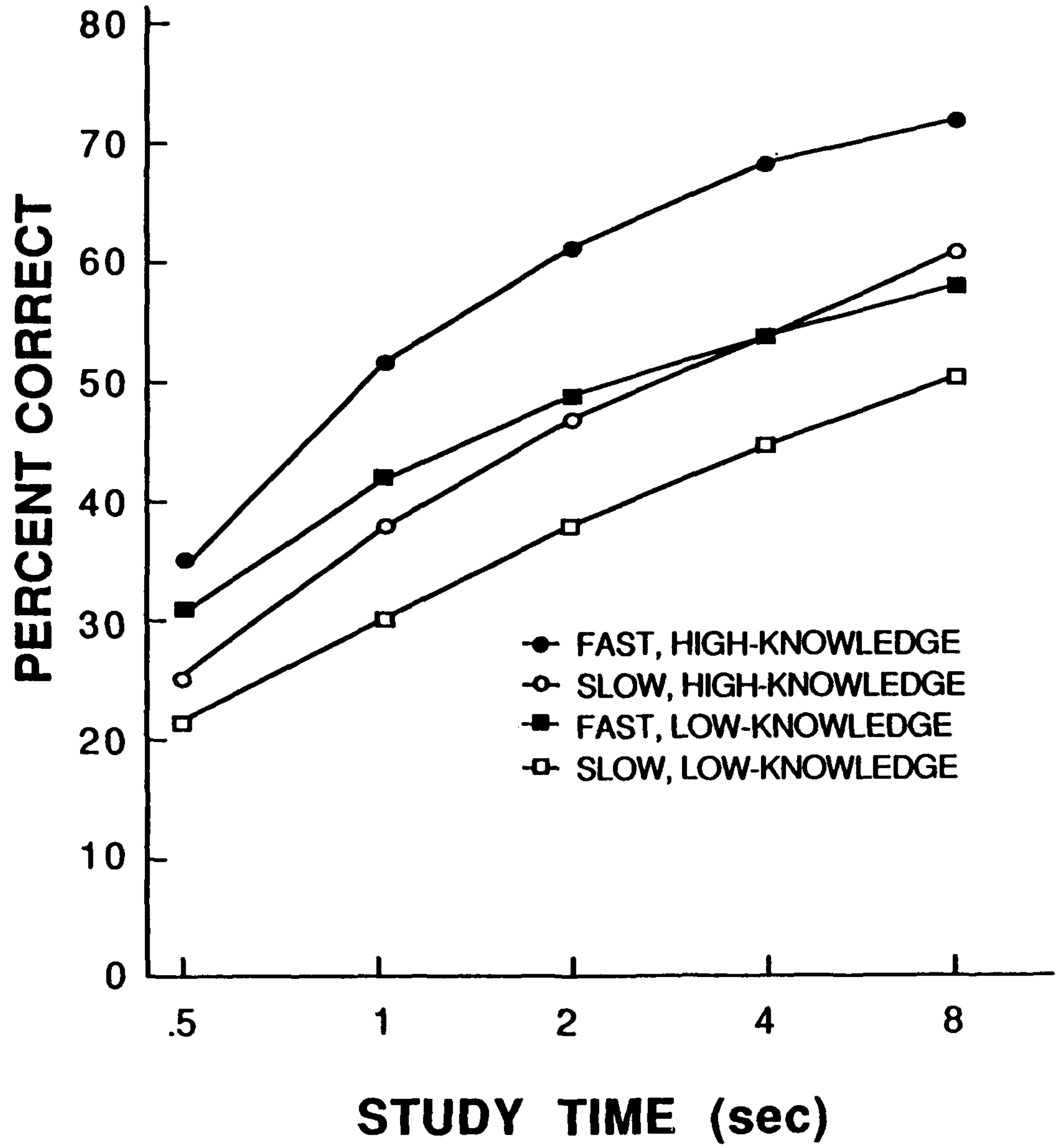

Figure 3. **Expected value of percent correct as a function of study time per pair for various skill profiles in Experiment 1. See text and Appendix A for discussion of how curves were produced.**

other hand, while memory-search speed predicted learning with limited study time, its predictive importance decreased with liberal study time.

Latency Analysis

Our primary interest was the effect of study time on the time it took to select a response alternative, which we henceforth refer to as "retrieval time." Study time had a significant effect on retrieval time, F (2, 392) = 2399.09, for both correct responses, F (2, 392) = 91.90, and incorrect responses, F (2, 392) = 368.48. For correct responses, retrieval time increased linearly with (log) study time, F (1, 392) = 635.43, although modestly (b = .07). For incorrect responses, the relationship also was linear in log study time, F (1, 392) = 91.90, but the rate of increase was almost three times greater (b = .18).

These results are displayed in Figures 4a and 5a, which show the response time curves yielded by the two-component model (ignore for now the Experiment 2 curve[s] which is [are] overlaid on the Experiment 1 curve in Figure 4a [and 5a]). Figure 4a shows average retrieval time, and Figure 5a plots retrieval time separately for correct versus incorrect items. The plots show that retrieval time increases approximately linearly with each doubling of study time; this is the case overall, and also separately for correct and incorrect responses.

There were some gender differences in retrieval time. Males responded faster than did females overall, d = .40, F (1, 392) = 7.44, and faster on correct responses, d = .39 s, F (1, 388) = 10.0. There were no significant differences due to group or gender-by-group interaction effects. Gender also interacted with the degree of linear increase in response time, in that females showed a steeper increase than did males, F (1, 392) = 17.3.

The analysis of overall response time permitted the assessment of practice effects, but because of the way in which data were collapsed, it was not possible to break out this analysis by correct versus incorrect (too many missing observations). Subjects responded faster with practice, both within session, F (1, 392) = 225.19, and over sessions, F (1, 392) = 818.93. A significant session-by-replication effect reflected a greater block-to-block response time decrease during the first session than the second, F (1, 392) = 116.31. The degree of linear increase in retrieval time was moderated by session, F (1, 392) = 8.3, and by block-within-session, F (1, 392) = 9.3. In these cases, the linear increase was slightly steeper in the first block within session, and in the first session. In sum, subjects retrieved faster with practice, especially early in practice. The fact that subjects committed more errors in the second session might indicate a retrieval speed-accuracy tradeoff, however.

Individual Differences in Response Time

The major questions concerning individual differences in response latency had to do with whether subject knowledge and processing speed predicted average retrieval time and the shape of the retrieval time curve as a function of study time. Table 3 shows the covariate analysis of the AVERAGE, LINEAR, and QUADRATIC contrast scores for overall retrieval time. Both COMPARISON TIME and LTM-SEARCH TIME were related to AVERAGE retrieval time. KNOWLEDGE and LTM-SEARCH TIME also predicted the amount of retrieval time increase (LINEAR) experienced as a function of study time: Both High-Knowledge and Fast-LTM-Search subjects showed a smaller study-time effect.

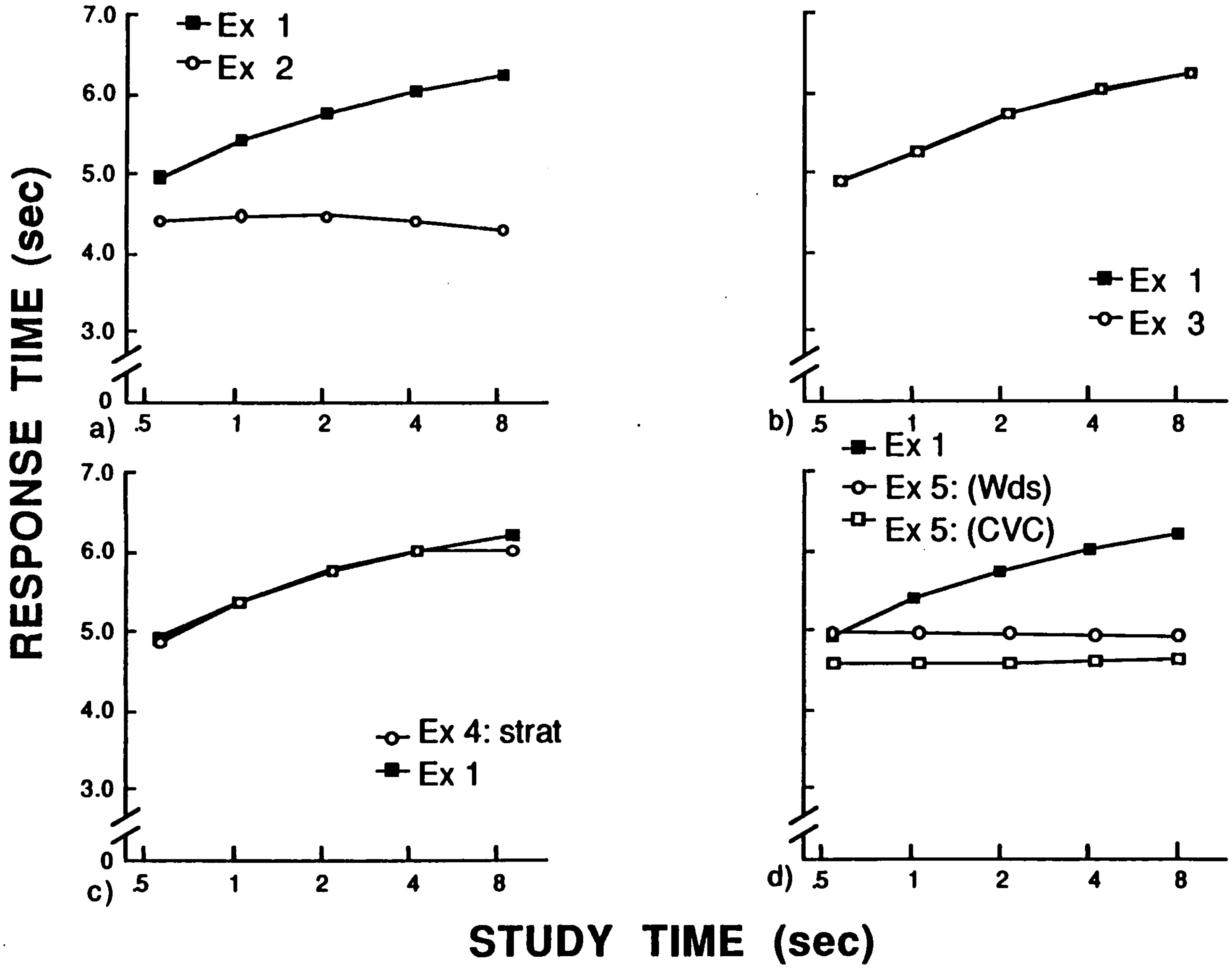

Figure 4. Multiple-choice response time as a function of study time per pair for Experiments (a) 1 vs. 2, (b) 1 vs. 3, (c) 1 vs. 4 (strategy group only), and (d) 1 vs. 5 (both CVC and WORD conditions); Experiment 1 repeated in all four plots to facilitate comparisons. Curves were generated by second-order polynomial equations, and in all cases R2 > .99.

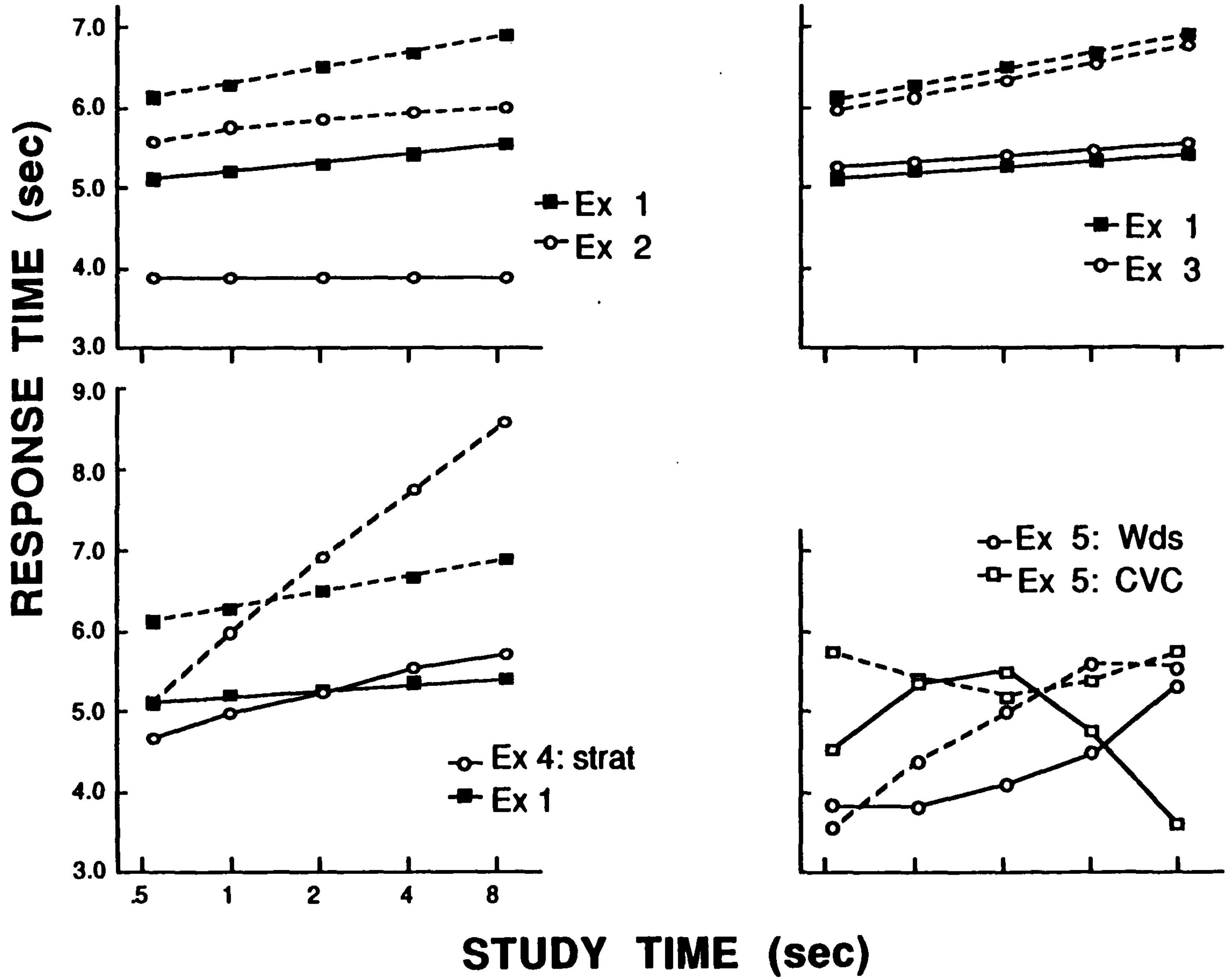

Figure 5. Response time as a function of study time per pair separately for correct (solid) and incorrect (dashed) items for Experiments 1-5. Curves were generated by second-order polynomial equations, and in all cases R2 > .99.

Table 3. **Retrieval Time-Cognitive Ability Relationships (Experiment 1, N = 396)**

		Retrieval-Time Contrast Score					
		AVERAGE		LINEAR		QUADRATIC	
Component	**Model**	**b**	**t**	**b**	**t**	**b**	**t**
Part-Correlation Analysis (correct + incorrect items)							
KNOWLEDGE	1	.041	.81	-.245	-5.00**	-.092	-1.84
KNOWLEDGE	6	.070	1.38	-.218	-4.38**	-.111	-2.15*
REACTION TIME	2	.034	.68	-.044	-.90	-.040	-.79
DECISION TIME	3	-.092	1.81	.053	1.06	-.037	-.73
COMPARISON TIME	4	.192	.46**	.118	2.15	-.075	-1.33
LTM-ACCESS TIME	5	.153	1.95	.048	.62	-.012	-.15
LTM-SEARCH TIME	6	.180	2.75**	.186	2.87**	.103	-1.53
Difference-Score Analysis							
DECISION TIME	7	.055	1.08	.068	1.40	-.007	-.14
COMPARISON TIME	8	.108	2.16*	.063	1.29-	.043-	.86
LTM-ACCESS TIME	9	.055	1.08	.007	.15	.008	.16
LTM-SEARCH TIME	10	.208	4.10**	.159	3.20**	-.108	-2.11*

Note. By the model, the results for KNOWLEDGE and REACTION TIME are the same in the two analyses. The *b* coefficients and *t* statistics are based on the models in Table 1. See text and Figure 1 for a mapping of tasks and components.

*$p < .05$.

**$p < .01$.

Table 4 shows the breakout by correct versus incorrect responses. Consistent with the overall analysis, COMPARISON TIME predicted AVERAGE retrieval time for both correct and incorrect responses. But LTM-SEARCH TIME predicted AVERAGE only for correct responses, and KNOWLEDGE predicted AVERAGE only for incorrect responses. Both KNOWLEDGE and LTM-SEARCH TIME predicted the degree of LINEAR increase in retrieval time with study time, which is the result obtained for the overall analysis, but only for correct responses.

The cell-score analysis helps clarify these relationships. More KNOWLEDGE led to longer times in the .5-s condition for *incorrect* responses. More KNOWLEDGE led to shorter times in the 8-s condition for *correct* responses. The only other consistent relationships were in the 8-s condition, in which retrieval time for correct responses was related to both COMPARISON TIME and LTM-SEARCH TIME.

Figure 6 shows the plot of retrieval time as a function of study time, overall and separately by correct versus incorrect, for subjects with differing skill profiles. The variables used to generate the curves were KNOWLEDGE and LTM-SEARCH TIME. Inspection of both the overall and correct-only plots shows quite clearly that LTM-SEARCH TIME was more critical than KNOWLEDGE in determining both AVERAGE retrieval time and the amount of LINEAR increase in retrieval time. That is, Fast-LTM-Search subjects retrieved faster and showed a much smaller increase in retrieval time as a function of study time than did Slow subjects. In fact, for those items they responded to correctly, Fast subjects retrieved about as quickly after 8 s as they did after .5 s of study.

Table 4. **Retrieval Time-Cognitive Ability Relationships (Experiment 1, N = 396)**

		Retrieval-Time Contrast/Cell Score							
		AVERAGE		LINEAR		.5 sec		8 sec	
Component	**Model**	**b**	**t**	**b**	**t**	**b**	**t**	**b**	**t**
		Part-Correlation Analysis (correct items)							
KNOWLEDGE	1	-.020	-.48	-.201	-4.06**	.087	1.74	-.199	-2.99**
KNOWLEDGE	6	.010	.20	-.167	-3.34**	.094	1.82	-.104	-2.16*
REACTION TIME	2	.063	1.24	-.053	-1.07	.054	1.06	.037	.74
DECISION TIME	3	.104	2.03*	.011	.22	.051	1.00	.089	1.75
COMPARISON TIME	4	.216	3.90**	.110	1.99	.109	1.94*	.272	5.02**
LTM-ACCESS TIME	5	.187	2.39*	.096	1.23	.050	.62	.219	2.88**
LTM-SEARCH TIME	6	.201	3.09**	.224	3.44**	.032	.47	.278	4.44**
		Difference-Score Analysis (correct items)							
DECISION TIME	7	.048	.94	.040	.80	.010	.20	.050	1.00
COMPARISON TIME	8	.123	2.45*	.077	1.55	.064	1.28	.172	3.50**
LTM-ACCESS TIME	9	.070	1.38	.035	.71	.008	.15	.076	1.52
LTM-SEARCH TIME	10	.240	4.76**	.176	3.52**	.076	1.48	.300	6.12**
		Part-Correlation Analysis (incorrect items)							
KNOWLEDGE	1	.116	3.31**	.010	.20	.148	2.95**	.092	1.83
KNOWLEDGE	6	.181	3.56**	.026	.50	.153	2.97**	.104	2.02*
REACTION TIME	2	-.008	-.15	-.096	-1.90	.025	.49	-.080	-1.58
DECISION TIME	3	-.038	-.74	-.017	-.32	.030	.59	.010	.20
COMPARISON TIME	4	.161	2.90**	.111	1.96	.062	1.11	.137	2.44*
LTM-ACCESS TIME	5	.103	1.31	.019	.24	.084	1.05	.076	.96
LTM-SEARCH TIME	6	.108	1.63	.130	1.93*	.033	.49	.109	1.63
		Difference-Score Analysis (incorrect items)							
DECISION TIME	7	.035	.69	.042	.83	.010	.20	.054	1.08
COMPARISON TIME	8	.107	2.14*	.087	1.71	.036	.72	.096	1.91
LTM-ACCESS TIME	9	.029	.58	-.012	-.24	.038	.76	.018	.35
LTM-SEARCH TIME	10	.126	2.48*	.091	1.75	.055	1.08	.095	1.86

Note. By the model, the results for KNOWLEDGE and REACTION TIME are the same in the two analyses. The *b* coefficients and *t* statistics are based on the models in Table 1. See text and Figure 1 for a mapping of tasks and components.

*$p < .05$.

**$p < .01$.

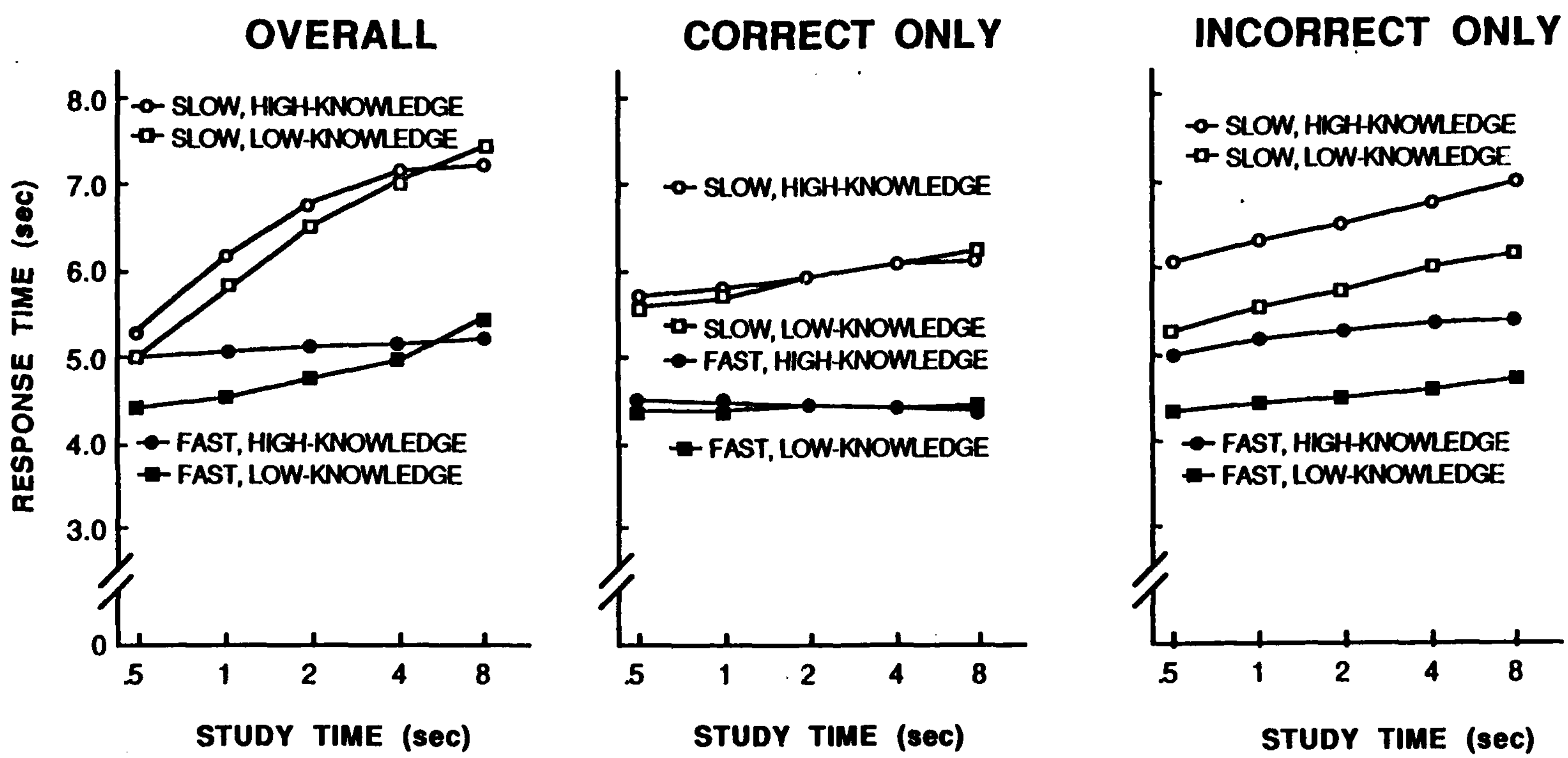

Figure 6. Expected value of (a) response time (averaged over all items), (b) response time for correct items only, and (c) response times for wrong items, as a function of study time per pair for various skill profiles in Experiment 1. See text and Appendix A for discussion of how curves were produced.

The same general relationships hold with incorrect items except that KNOWLEDGE is related to retrieval time in the following way: Controlling for LTM-search speed (i.e., considering fast and slow subjects separately), High-Knowledge subjects are actually slower on average than are Low-Knowledge subjects on items for which they select the incorrect response.

Discussion

Knowledge level, as indicated by vocabulary test score, was found to predict the likelihood of remembering a studied pair, regardless of study time. Knowledge level also predicted the degree of benefit accrued for each increase in study time: More knowledge translated into greater benefit for every increment in study time, as reflected in the correlation between KNOWLEDGE and the LINEAR retention contrast.

The speed with which an individual was able to search through long-term memory was also a predictor of the overall probability that the individual would remember a pair. However, memory-search speed played its most important role under high-information-flow conditions in which the item was presented for only a brief period of time. LTM-SEARCH TIME predicted retention after .5-s exposure but not after 8-s exposure. This result also manifested itself as a relationship between LTM-SEARCH TIME and QUADRATIC, in that Fast-LTM-Search subjects experienced considerable early benefit of increased study time. Their increment-benefit tapered off, relative to others, at higher amounts of study time.

There was some evidence of a study-time cost. The longer that subjects studied a pair, the more time they took in retrieving the pair at test. To our knowledge, this phenomenon, of a fan effect due to *constructed* relations (as opposed to *studied* relations), has not been observed before.

It is possible that our fan effect reflects only different mixtures of "easy" and "hard" pairs at the .5-s and 8-s study conditions. That is, pairs successfully retrieved after .5-s study tend to be easy pairs, even preexperimentally stored pairs, because only an easy pair could be retrieved after such short study. Then, retrieval time would be relatively fast, because easy (preexperimental) pairs are already well learned. In contrast, pairs successfully retrieved after 8-s study would be a mixture of easy pairs and pairs that were true novel associates. Following 8-s study, retrieval times would be longer on average because it would take longer to retrieve relatively weak, novel associates.

The problem with this hypothesis is that it cannot explain our finding of a particularly strong fan effect (i.e., increase in retrieval time associated with increase in study time) for incorrect responses. The alternative--a fan effect due to constructed relations--is consistent with this finding.

The individual differences analysis of retrieval times showed that speed of memory search and speed of comparison predicted retrieval time. The important finding is that these two variables contributed independently to retrieval time: specifically, controlling for comparison time (as well as the other processing time variables), LTM-search speed uniquely added to the prediction of retrieval time. The fact that LTM-search speed also predicted retention is worth examining. As operationalized in this experiment, LTM-search speed is not simply speed of general information processing or motor responding or even perceptual speed. Indeed, it is orthogonal to those components. Fast LTM-Search subjects are those who recognize two words as similar in meaning (e.g., big--tall) almost as quickly as they recognize two words as identical (e.g., big--BIG), indicating quick access to semantic features of words. Therefore, LTM-search speed may be essentially an indication of superior semantic memory organization insofar as organization factors are assumed to be responsible for our ability to access almost instantaneously any of the millions of facts we have stored in memory.

The retrieval time analysis also suggested strategy differences with respect to the knowledge factor. Given plenty of study time, High-Knowledge subjects were faster than Low-Knowledge subjects at selecting a response when they selected the correct response (i.e., in the 8-s condition *r* [KNOWLEDGE, Retrieval Time] = -.20, for correct responses, Table 2); but they were slower than Low-Knowledge subjects in selecting the response when the response was incorrect (i.e., averaging over all conditions, *r* [KNOWLEDGE, Retrieval Time] = + .12, for incorrect responses, Table 2). That is, High-Knowledge subjects search memory longer under conditions in which they do not immediately know the answer.

An interesting question is whether protracted search under uncertainty is a cause or effect of High-Knowledge subjects' learning performance. It could be that High-Knowledge subjects are more restrained than Low-Knowledge subjects in waiting for a convergence of response activation before selecting an alternative. This would help explain the positive relationship between knowledge and the probability of a correct response. On the other hand, this would also suggest that High-Knowledge subjects should be slower than Low-Knowledge subjects on correct responses, when, in fact, we found the opposite to be the case. (Recall that we controlled for speed, and so these findings are not artifacts of any correlation between KNOWLEDGE and any of the processing speed measures; in fact, the results were the same whether KNOWLEDGE was entered first or last into the regression equation.)

A more complicated, but perhaps more plausible explanation is that High-Knowledge subjects have more elaboration material to wade through when selecting a response, but that elaboration material is better organized. Thus, when they know the correct associate, High-Knowledge subjects are able to retrieve the associate quickly. When they do not know the correct associate, High-Knowledge subjects have more pathways (constructed during study) to investigate before terminating response search; consequently they take longer to respond than do Low-Knowledge subjects when they are uncertain of the response.

In summary, the results are consistent with the idea that subjects build elaboration structures during study, but High-Knowledge and Fast-Memory-Search subjects build them at a faster rate and organize them better. Thus, at test, High-Knowledge and Fast-LTM-Search subjects demonstrate more retention, reflecting more structure built. For High-Knowledge subjects, the greater the amount of study, the greater the retention advantage. For Fast-LTM-Search subjects, the retention advantage is greatest following minimal study time.

There is generally a cost, in retrieval time, for the amount of structure built during study. But Fast-LTM-Search subjects avoid the cost altogether; they respond as quickly after 8-s study as they do after .5-s study. And High-Knowledge subjects are able to minimize the cost (compared to Low-Knowledge subjects), for cases in which they know the correct associate. Incorrect responses may be taken as indications that the process of constructing an organized structure was unsuccessful. It is interesting that an organization-effect explanation has been developed to account for the so-called *paradox of expertise* in studies that have experimentally induced the fan effect by pairing terms with multiple associates (Reder & Ross, 1983; Smith, Adams, & Schorr, 1978). In these studies, fan effects are reduced, eliminated, or even reversed through memory organization processes.

EXPERIMENT 2: RECALL VERSUS RECOGNITION

The purpose of the second experiment was to determine whether giving subjects a recognition test, rather than a recall-type test as in Experiment 1, would affect the cognitive-skill-by-learning-ability relationship. Experiment 2 was identical to Experiment 1 except that the multiple-choice test on the paired-associates task required subjects to select the actual response term rather than a synonym. This allowed the correct response to be determined by recognition.

Method

Subjects

Subjects were 710 enlistees who had not participated in Experiment 1. Demographically, subjects were similar to those in Experiment 1. Two subjects were eliminated from the analysis because their data were deviant.

Experimental Tasks

The paired-associates task was identical to that used in Experiment 1, except that the correct alternative and the distractors were actual associates presented in the study block (rather than synonyms of those associates as in Experiment 1). The information-processing measures were the same as those in Experiment 1.

Results

Error Analysis

Study time again had a significant effect on percent correct, F (2, 704) = 2399.1, as can be seen in Figure 2a (Experiment 2). The equation that generated the plot was the following:

PC (study-time) = (63.1 * AVERAGE) + (10.6 * LINEAR) + (-2.0 * QUADRATIC).

Comparing the two functions plotted in Figure 2a shows the difference between recognition (Experiment 2) and recall (Experiment 1). Across all study times, recognition accuracy was better than recall accuracy and the margin of the difference increased with study time. This was reflected as a difference in both the AVERAGE (44.6 versus 63.1) and the LINEAR (7.6 versus 10.6) parameters, for the two experiments.

Again, subjects did better on the second same-study-time block within a session, (d = 1.5, F (1, 704) = 20.35), and worse on the second versus the first session, (d = 1.1, F (1, 704) = 7.55). These learning/fatigue effects were smaller than those in Experiment 1.

Gender was again significant, F (1, 704) = 28.10, with females correctly recalling more items, d = 5.9. No differences were found between groups administered the two orders of block sets, and the gender-by-group interaction was not significant.

Individual Differences in Errors

Consistent with Experiment 1, both KNOWLEDGE and LTM-SEARCH TIME were highly reliable predictors of the overall likelihood of learning, regardless of whether the part-correlation or difference-score estimation was used (see Table 5). Unlike Experiment 1, KNOWLEDGE was unrelated to the degree of linear growth, but it did predict QUADRATIC. Because curves were negatively accelerated (Figure 2a), the covariate relationship reflects the fact that High-Knowledge subjects showed more deviation from linearity in their curves, due to early (toward the .5-s end) acceleration in the growth of percent correct.

LTM-SEARCH TIME again predicted degree of improvement in percent correct as a function of study time (LINEAR), but somewhat oddly, the relationship was positive. Slow LTM SEARCH (high positive value of response time) was related to greater improvements in percent correct with study time (high degree of increase in retention). No other covariate was related to linear improvement.

DECISION TIME was a reliable predictor of both AVERAGE percent correct and QUADRATIC improvement, in both analyses. Degree of deviation from linearity (QUADRATIC) was predicted by KNOWLEDGE and DECISION TIME across both estimation techniques. For both, the pattern was similar; greater skill (knowledge or speed) was associated with more curvilinearity in the growth trend, reflecting rapid initial learning. . No other covariate predicted the quadratic trend.

The within-study-conditions analysis shown in Table 5 provides another perspective on the individual differences results in this experiment. In the .5-s condition, KNOWLEDGE, DECISION TIME, and LTM-SEARCH TIME were significant predictors of percent correct. In the 8-s condition, however, only KNOWLEDGE was a reliable predictor, and in fact its relationship with retention was stronger in the 8-s condition, if response time was controlled for, than in the .5-s condition. This essentially replicates the pattern found in Experiment 1.

Figure 7 shows plots of the expected value for percent correct against study time for subjects with various skill profiles. The curves were computed in exactly the same way as they were in Experiment 1 and are therefore comparable to those curves. The curves in Figure 7 are much steeper than those from Experiment 1, but the qualitative results are similar. Fast, Low-Knowledge subjects do better than Slow, High-Knowledge subjects after only .5-s study, but the relationship is the opposite after 2 s of study. Note that this 1- to 2-s crossover point is earlier than the 4- to 8-s point in Experiment 1.

Inspection of the plot also makes more clear why KNOWLEDGE predicted degree of acceleration (QUADRATIC) rather than average amount of overall improvement (LINEAR). There may have been a ceiling effect on the learning task. A rescaling of the dependent variable (percent correct) could circumvent this problem, but on the other hand it is not necessary. At this point we are interested only in describing any relationships that might exist between the cognitive measures and the measures that summarize the shape of the learning curve.

Latency Analysis

Study time affected retrieval time, $F(1, 704) = 23.8, 42.3$, for the linear and quadratic components, respectively, but the direction was opposite that of Experiment 1: More study time led to faster retrieval, $b = -.55$ (linear), $-.36$ (quadratic). Note these are shallow slopes.

Table 5. **Retention-Cognitive Ability Relationships (Experiment 2, N = 708)**

		Learning Contrast Score					
		AVERAGE		LINEAR		QUADRATIC	
Component	**Model**	**b**	**t**	**b**	**t**	**b**	**t**
		Part-Correlation Analysis					
KNOWLEDGE	1	.352	9.98**	.005	.13	-.152	-4.08**
KNOWLEDGE	6	.332	.36**	.043	1.10	.161	-4.20**
REACTION TIME	2	-.065	-1.85	-.006	-.15	-.025	-.67
DECISION TIME	3	-.210	-5.70**	-.026	-.64	.154	3.90**
COMPARISON TIME	4	-.087	-2.28*	-.009	-.22	-.002	-.05
LTM-ACCESS TIME	5	-.052	-1.10	.085	1.62	-.093	-1.82
LTM-SEARCH TIME	6	-.111	-2.42**	.183	3.65**	-.006	-.12
		Difference-Score Analysis					
DECISION TIME	7	-.128	-3.65**	-.017	-.45	.134	3.61**
COMPARISON TIME	8	-.052	-1.49	-.005	-1.31	-.022	-.60
LTM-ACCESS TIME	9	.032	.91	.049	1.29	-.046	-1.25
LTM-SEARCH TIME	10	-.167	-4.67**	.130	3.38**	.020	.52

		Study Time Condition			
		5 sec		8 sec	
Component	**Model**	**b**	**t**	**b**	**t**
		Part-Correlation Analysis			
KNOWLEDGE	1	.307	8.55**	.264	7.26**
KNOWLEDGE	6	.268	5.55**	.318	6.58**
REACTION TIME	2	-.072	-2.02	-.057	-1.58
DECISION TIME	3	-.173	-4.58**	-.121	-3.13
COMPARISON TIME	4	-.094	-2.42*	.075	2.20
LTM-ACCESS TIME	5	-.144	-2.98**	-.051	-1.02
LTM-SEARCH TIME	6	-.228	-3.63**	.108	1.72
		Difference-Score Analysis			
DECISION TIME	7	-.095	-2.65**	-.063	-1.72
COMPARISON TIME	8	-.065	-1.80	-.054	-1.48
LTM-ACCESS TIME	9	-.009	-.26	.025	.68
LTM-SEARCH TIME	10	-.252	-7.04**	-.076	-2.04*

Note. By the model, the results for KNOWLEDGE and REACTION TIME are the same in the two analyses. The *b* coefficients and *t* statistics are based on the models in Table 1. See text and Figure 1 for a mapping of tasks and components.

*$p < .05$.

**$p < .01$.

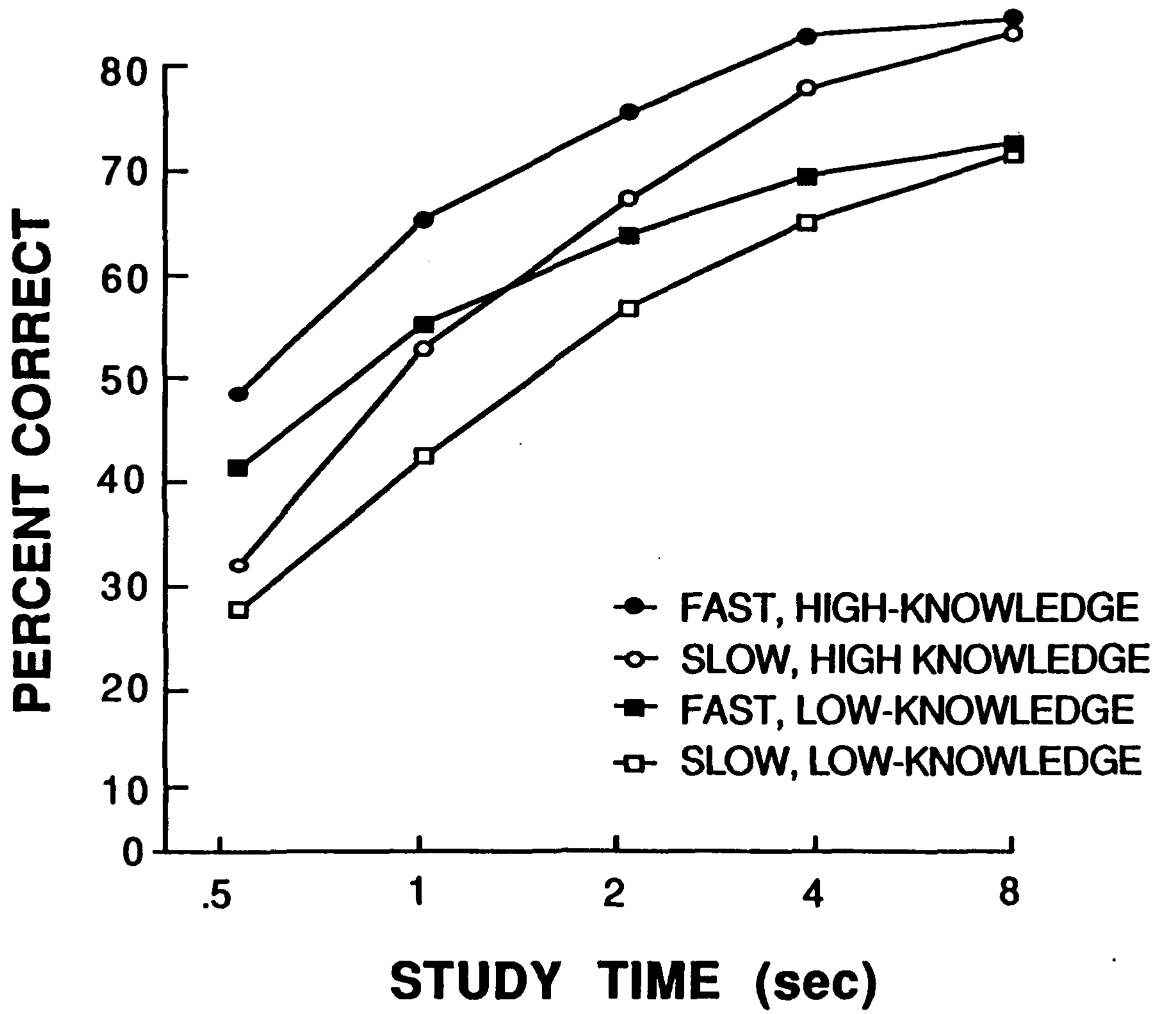

Figure 7. **Expected value of percent correct as a function of study time per pair for various skill profiles in Experiment 2. See text and Appendix A for discussion of how curves were produced.**

Results are displayed in Figures 4a and 5a, which show the response time curves yielded by the two-component model. Figure 4a shows average retrieval time, and Figure 5a shows retrieval time separately for correct versus incorrect items. The plots show that, unlike Experiment 1, retrieval time did not increase with study time, and in fact went down slightly. Figure 5a shows that this is not an artifact of different mixtures of correct and incorrect responses over the two experiments. In Experiment 1, both correct-item and (especially) incorrect-item retrieval times increased with study time, whereas in Experiment 2 only incorrect-item times increased with study time.

Again, males responded faster than females overall, $d = .46$ s , F (1, 704) = 35.7, and faster on correct responses, $d = .40$, F (1, 704) = 41.5. On incorrect responses, males were faster $d = .36$ s, F (1, 704) = 7.1 (there was not a reliable difference in Experiment 1, F (1, 388) = 1.94, although the trend ran in the same direction, $d = .29$ s). There were no significant differences due to group or gender-by-group interaction effects. Again, gender interacted with the degree of linear increase in response time, F(1, 704) = 16.0, in that females showed a steeper increase than males.

Again, subjects responded faster with practice, both within session, F (1, 704) = 145.6, and over sessions, F (1, 704) = 383.2. A significant session-by-replication effect, F (1, 704) = 68.9, reflected the fact that in both experiments there was a greater block-to-block response-time decrease during the first than the second session. The degree of linear increase in retrieval time was moderated by session, F (1, 704) = 30.6. As in Experiment 1, subjects retrieved faster with practice, but this was at the expense of more errors, indicating increased carelessness over time.

Individual Differences in Response Time

In Experiment 1, we found the breakout of correct versus incorrect to be most informative and so we limit our discussion to that analysis, which is presented in Table 6. Considering correct responses, as in Experiment 1, KNOWLEDGE predicted retrieval time in the 8-s condition only (High-Knowledge faster), and it also was significantly related to the degree of LINEAR increase in retrieval time as a function of study time (High-Knowledge flatter). Unlike Experiment 1, KNOWLEDGE also predicted AVERAGE retrieval time. LTM-SEARCH TIME also predicted both AVERAGE retrieval time and retrieval time in the 8-s condition (Fast-LTM-Search faster), as in Experiment 1, but it also predicted retrieval time in the .5-s condition. Finally, DECISION TIME rather than COMPARISON TIME, as in Experiment 1, was the significant other covariate in predicting retrieval time.

Considering incorrect responses, the main finding was that the relationship between KNOWLEDGE and retrieval time was different from what it was in Experiment 1. There we found moderate positive correlations; that is, High-Knowledge subjects took longer responding than did Low-Knowledge subjects when they did not know the answer. In this experiment the correlations were smaller than those from Experiment 1, and in one case (8-s study), even reversed in sign. Mostly, there were no significant differences in response time between Low- and High-Knowledge subjects on incorrect responses. Figure 8 presents the retrieval time plots, which can be compared with those from Figure 6. After taking into account the general trend differences, the results are similar to those from Experiment 1. However, note that the gap between High and Low-Knowledge subjects in response time to incorrect items is greater in Figure 6c. The apparent gap in Figure 8c is not significant, according to the correlational results.

Table 6. **Retrieval Time-Cognitive Ability Relationships (Experiment 2, N = 708)**

		Retrieval-Time Contrast/Cell Score							
		AVERAGE		LINEAR		.5 sec		8 sec	
Component	**Model**	b	t	b	t	b	t	b	t
		Part-Correlation Analysis (correct items)							
KNOWLEDGE	1	-.147	-3.94**	-.172	-4.62**	-.018	-.49	-.194	-5.25**
KNOWLEDGE	6	-.090	-2.48*	-.169	-4.38**	.013	.33	-.150	-4.12**
REACTION TIME	2	.054	1.44	.023	.62	.026	.70	.042	1.14
DECISION TIME	3	.206	5.25**	.061	1.54	.118	2.93**	.182	4.66**
COMPARISON TIME	4	.122	3.02**	.053	1.30	.055	1.33	.100	2.49**
LTM-ACCESS TIME	5	.205	4.14**	.009	.18	.116	2.26*	.160	3.22**
LTM-SEARCH TIME	6	.283	6.01**	.009	.19	.158	3.17**	.212	4.43**
		Difference-Score Analysis (correct items)							
DECISION TIME	7	.131	3.52**	.035	.94	.077	2.05*	.118	3.22**
COMPARISON TIME	8	.084	.26*	.041	1.09	.035	.94	.068	1.83
LTM-ACCESS TIME	9	.023	.61	-.031	-.82	.022	.57	.014	.38
LTM-SEARCH TIME	10	.313	8.57**	.038	.99	.173	4.52**	.245	6.62**
		Part-Correlation Analysis (incorrect items)							
KNOWLEDGE	1	.064	1.60	-.039	-.96	.088	2.35*	-.080	-2.16*
KNOWLEDGE	6	.100	2.44*	-.019	-.46	.118	3.04**	-.062	-1.59
REACTION TIME	2	.012	.30	.003	.07	.025	.66	.018	.48
DECISION TIME	3	.090	2.10*	.054	1.25	.065	1.62	.090	2.24*
COMPARISON TIME	4	.055	1.27	.030	.68	.039	.92	.022	.54
LTM-ACCESS TIME	5	.109	2.03*	.052	.97	.052	1.01	.020	.38
LTM-SEARCH TIME	6	.174	3.35**	.097	1.84	.148	2.95**	.106	2.11*
		Difference-Score Analysis (incorrect items)							
DECISION TIME	7	.063	1.58	.040	1.00	.037	.98	.060	1.60
COMPARISON TIME	8	.015	.37	.005	.12	.027	.71	.009	.24
LTM-ACCESS TIME	9	.038	.94	.019	.48	.001	.02	-.005	-.14
LTM-SEARCH TIME	10	.175	4.30**	.096	2.35*	.139	3.62**	.108	2.80**

Note.. By the model, the results for KNOWLEDGE and REACTION TIME are the same in the two analyses. The *b* coefficients and *t* statistics are based on the models in Table 1. See text and Figure 1 for a mapping of tasks and components.

*$p < .05$.

**$p < .01$.

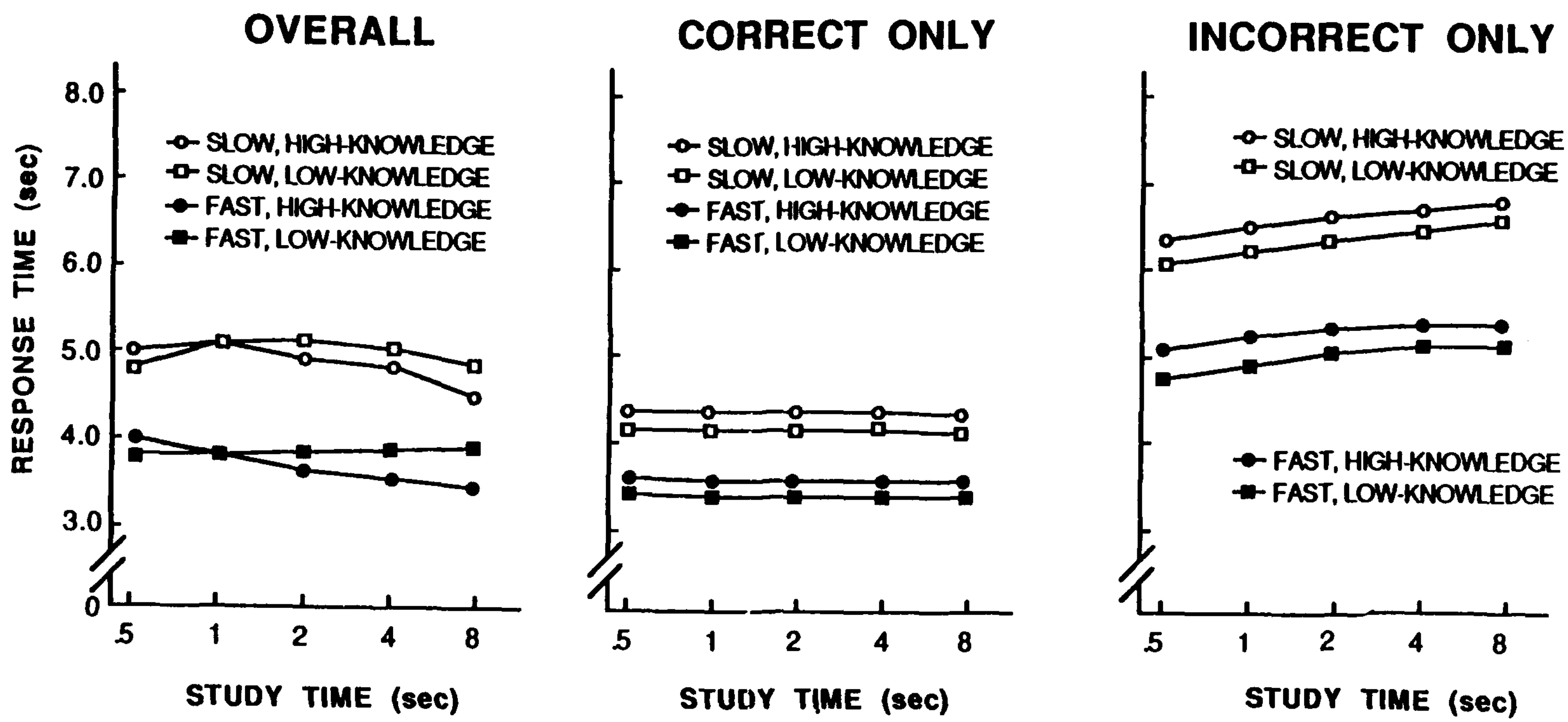

Figure 8. Expected value of (a) response time (averaged over all items), (b) response time for correct item only, and (c) response times for wrong items, as a function of study time per pair for various skill profiles in Experiment 2. See text and Appendix A for discussion of how curves were produced.

Discussion

Two of the conclusions of Experiment 1, that High-Knowledge subjects (a) retain more and (b) benefit more from additional study time, appear not to depend on whether a cued-recall or a recognition test is administered, based on the results of this experiment. Also, this experiment replicated the finding that subjects who can quickly search for information through long-term-memory have an advantage in retention of paired-associates, particularly when study time is extremely short. The fact that these conclusions were reflected in relationships with different dependent variables over the two experiments (LINEAR in Experiment 1; QUADRATIC in Experiment 2) is probably not theoretically important. Both variables reflected the amount of retention benefit accrued as a function of study time; QUADRATIC is simply the more sensitive variable when there is a ceiling effect.

Latency is typically more sensitive than accuracy to differences between recall and recognition testing, and the current study is not an exception. Analysis of retrieval times yielded some contrasts between the two experiments. With a recall test (Experiment 1), retrieval time was shown to increase with study time, on average; with a recognition test (Experiment 2), the relationship between study time and retrieval time was essentially flat (actually, slightly negative). By separating times for correct versus incorrect responses, we were able to show that this differential pattern was not due to different proportions of correct responses in the two experiments. With a recall test (Experiment 1), both correct responses and incorrect responses took longer following more study time. With a recognition test (Experiment 2), incorrect responses took longer following more study time; but time to make a correct response was not affected by study time.

How does the memory-organization theme developed in the discussion of Experiment 1 fare in light of the results from this experiment? The retention data were quite similar for the two experiments, and therefore compatible with the theme. The retrieval-time data were also similar but there were two notable differences: (a) the lack of a fan effect due to constructed relations (study time) in this experiment, and (b) the attenuation (or even lack) of correlations between knowledge and retrieval time for incorrect items in this experiment.

One explanation for these two findings is that a recognition test, in contrast to a recall test, is likely to lead to less extraneous search, that is, search that proceeds from the cue but does not lead to the target. The presence of the target in the recognition test serves as a guide to whether the search is extraneous or not. Who engages in extraneous search? Given a recall test, Slow-LTM-Search subjects do so more than do Fast-LTM-Search subjects, particularly following greater study time, since that time permitted the construction of more extraneous paths to search. Also, High-Knowledge subjects do so more than do Low-Knowledge subjects, when they do not know the correct associate. But with a recognition test, the target cue reduces extraneous search for all groups. Therefore, while Fast subjects still search memory faster overall, there is no longer an interaction between LTM-search speed and study time, as is found with the recall test. And High-Knowledge subjects do not spend significantly longer searching memory than do Low-Knowledge subjects when they do not know the correct associate. The target cue, according to this analysis, effectively reduces the importance of the memory organization advantage, and reduces the cost of having constructed multiple relations (some of which would have lead to extraneous search) during study.

EXPERIMENT 3: SMALLER BLOCKS

The purpose of this experiment was to examine the effects of block size on the relationship between cognitive skill and learning ability. We did this by administering blocks of only 8 items rather than 10. In all other respects, this experiment was identical to Experiment 1.

Method

Subjects

Subjects were 645 Air Force enlistees who had not participated in any of the previous experiments but were demographically similar to those who had.

Experimental Tasks, Design, and Procedures

This experiment was identical to Experiment 1 except that the number of pairs per block was reduced from 10 to 8, for a total of 160 items.

Results and Discussion

In our first analysis of the data from this experiment, we found a virtual replication of the findings from Experiment 1; therefore, these will not be reported. This finding permits the conclusion that small changes in block size do not change the essential relationship between cognitive skill and learning.

However, we decided with this data set to examine the effect of study-test lag by computing the difference in study (1 to 8) and test (9 to 16) positions, which were randomly assigned, and performing an analysis of variance on the difference score. We found an effect only for lag = 1, which amounted to about a 20% increment in retention. That is, items were better remembered when they were the last studied and the first tested for, due to short-term memory. There was no difference in expected performance at any other lag. Therefore, we reanalyzed the data from this experiment, eliminating the first tested item (this was simply a data analysis convenience); thus, the analyses reported here are statistics computed for the 7 items in test positions 10 to 16.

Figure 2b shows the effect of decreasing block size from 10 (Experiment 1) to 8 (Experiment 3) items. As may be obvious from the plot, there was no difference in any of the parameters (AVERAGE = 44.6 versus 42.3; LINEAR = 7.6 versus 7.5; QUADRATIC = -.74 versus -.39).

The individual differences analysis of retention (Table 7) also replicated the essential qualitative findings from Experiment 1. KNOWLEDGE predicted both AVERAGE retention and LINEAR increase in retention with study time. In this experiment, KNOWLEDGE also predicted QUADRATIC increase. This resulted in KNOWLEDGE predicting success in both the .5- and 8-s study conditions. Also as in Experiment 1, LTM-SEARCH TIME predicted AVERAGE retention, and retention in the high-information-flow condition (.5-s). Figure 9, which plots percent correct as a function of study time for differing ability profiles, thus is almost identical to the comparable plot (Figure 3) from Experiment 1.

Table 7. Retention-Cognitive Ability Relationships (Experiment 3, N = 645)

		Learning Contrast Score					
		AVERAGE		LINEAR		QUADRATIC	
Component	Model	b	t	b	t	b	t
		Part-Correlation Analysis					
KNOWLEDGE	1	.356	9.64**	.237	6.16**	-.127	-3.23**
KNOWLEDGE	6	.327	8.74**	.231	5.84**-	.113	-2.81**
REACTION TIME	2	-.029	-.78	-.040	-1.03	-.025	-.64
DECISION TIME	3	-.056	-1.48	-.047	-1.19	.002	.04
COMPARISON TIME	4	-.136	-3.37**	-.053	-1.25	.024	.57
LTM-ACCESS TIME	5	-.074	-1.26	.014	.22	.036	.57
LTM-SEARCH TIME	6	-.141	-2.96**	-.030	-.60	.072	1.40
		Difference-Score Analysis					
DECISION TIME	7	-.025	-.68	-.011	-.30	.017	.43
COMPARISON TIME	8	-.072	-1.94	-.015	-.38	.017	.43
LTM-ACCESS TIME	9	-.017	-.47	.012	.30	.014	.35
LTM-SEARCH TIME	10	-.160	-4.28**	-.048	-1.23	.058	1.44

		Study Time Condition			
		.5 sec		8 sec	
Component	Model	b	t	b	t
		Part-Correlation Analysis			
KNOWLEDGE	1	.184	4.74**	.307	8.16**
KNOWLEDGE	6	.161	4.07**	.287	7.46**
REACTION TIME	2	-.010	-.26	-.045	-1.19
DECISION TIME	3	-.053	-1.34	-.031	-.81
COMPARISON TIME	4	-.111	-2.62**	-.109	-2.66**
LTM-ACCESS TIME	5	-.101	-1.61	-.030	-.49
LTM-SEARCH TIME	6	-.111	-2.22*	-.090	-1.83
		Difference-Score Analysis			
DECISION TIME	7	-.035	-.90	.004	.10
COMPARISON TIME	8	-.054	-1.40	-.006	-1.75
LTM-ACCESS TIME	9	-.038	-.99	.006	.16
LTM-SEARCH TIME	10	-.129	-3.26**	-.113	-2.94**

Note. By the model, the results for KNOWLEDGE and REACTION TIME are the same in the two analyses. The *b* coefficients and *t* statistics are based on the models in Table 1. See text and Figure 1 for a mapping of tasks and components.

*$p < .05$.

**$p < .01$.

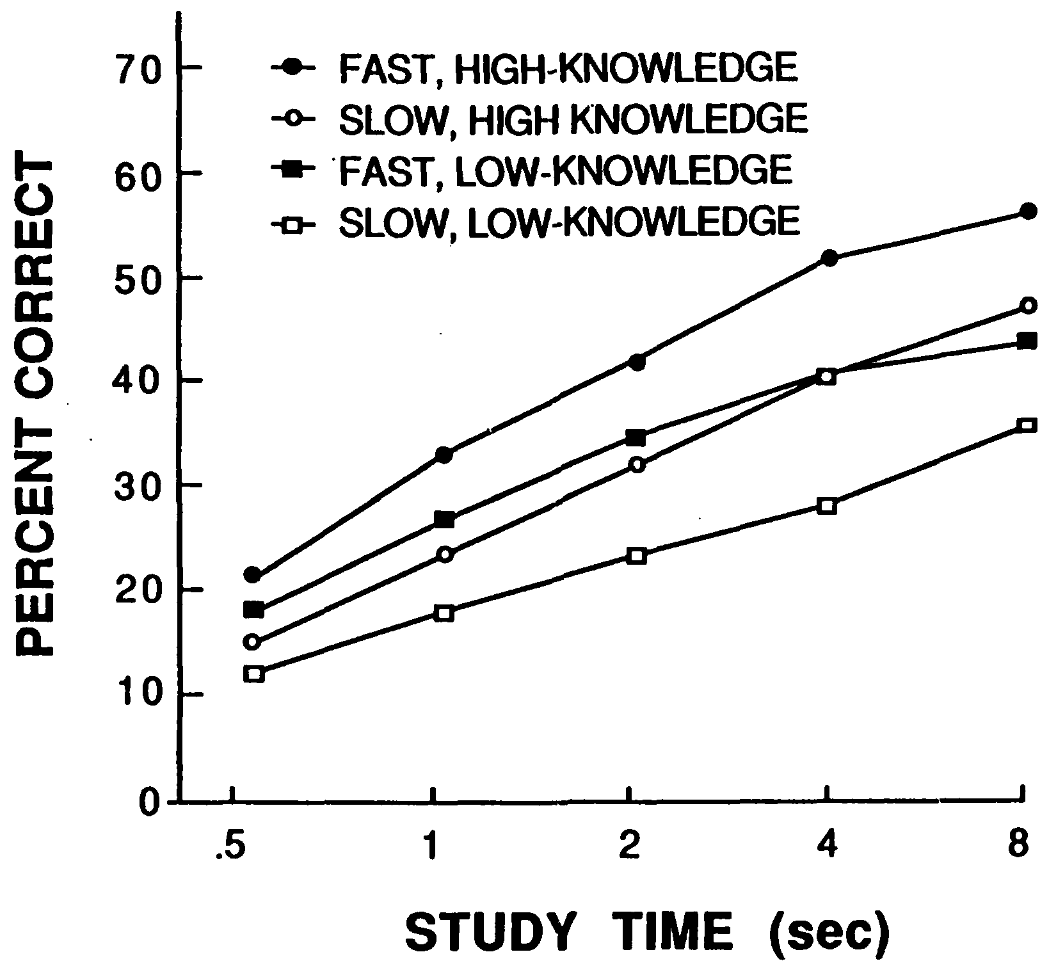

Figure 9. **Expected value of percent correct as a function of study time per pair for various skill profiles in Experiment 3. See text and Appendix A for discussion of how curves were produced.**

There are a few differences in the individual differences analysis of retrieval time (Table 8; Figure 10) but each is consistent with our summary of the essential features of the data from Experiment 1. Thus, we conclude that neither small manipulations in block size nor the elimination of the short-term memory effect has a strong impact on the ability-learning relationship.

EXPERIMENT 4: STRATEGY TRAINING

The purpose of this experiment was to determine the role of strategic knowledge in associative learning. Subjects were randomly assigned to either a control group or a treatment group which was given a 10-minute lesson on how to employ an elaboration strategy in paired-associate learning. Except for the lesson, this experiment was identical to Experiment 1.

The results of this experiment were especially interesting because a number of researchers (Anderson & Bower, 1972; Wang, 1983) have suggested that individual differences in learning may be largely or even entirely due to differences in the availability of effective mnemonic strategies. The design of this study and the fact that considerable information was available on individuals' cognitive skills allowed us to test this hypothesis.

Method

Subjects

Subjects were 593 enlistees who had not participated in any of the previous experiments, but were demographically similar to those who had.

Experimental Tasks, Design, and Procedures

In this experiment, subjects were assigned at random to either a Mnemonic-Strategy-Treatment group ($N = 302$) or to a control group ($N = 291$). The Treatment group was presented a 10-minute lesson on the application of a task-appropriate elaborative processing technique. The lesson emphasized the combined use of sentence mediation, interactive imagery, and rehearsal. After examining three worked-out examples, subjects were administered a practice list of five word pairs, with each pair being exposed for 4 s. After the 5th pair, subjects were administered a 5-alternative multiple-choice recognition test in which all distractors and correct alternatives were response terms from the study list. Following this test was a second practice list of five word pairs, in which distractors and correct alternatives were synonyms of response terms that had occurred in the study list. The text of the strategy lesson is in Appendix B.

All details pertaining to tasks, administration order, and procedures were identical to Experiment 1, with the exception that subjects in the Treatment group worked through the mnemonic strategy lesson before attempting the first 10 blocks of paired associates.

Table 8. Retrieval Time-Cognitive Ability Relationships (Experiment 3, N = 645)

		Retrieval-Time Contrast/Cell Score							
		AVERAGE		LINEAR		.5 sec		8 sec	
Component	Model	b	t	b	t	b	t	b	t
		Part-Correlation Analysis (correct items)							
KNOWLEDGE	1	.002	.05	-.098	-2.49*	.055 1	.39	-.052	-1.33
KNOWLEDGE	6	.083	2.18*	-.042	-1.08	.091	2.29*	.038	1.04
REACTION TIME	2	.037	.94	.013	.32	.052	1.32	.068	1.73
DECISION TIME	3	.068	1.69	-.050	-1.25	.069	1.72	.021	.52
COMPARISON TIME	4	.201	4.71**	.160	3.73**	.099	2.29*	.240	5.67**
LTM-ACCESS TIME	5	.030	.47	.053	.84	.013	.20	.026	.42
LTM-SEARCH TIME	6	.428	8.93**	.262	5.24**	.200	3.92**	.463	9.84**
		Difference-Score Analysis (correct items)							
DECISION TIME	7	.029	.75	-.047	-1.19	.021	.54	-.026	-.66
COMPARISON TIME	8	.114	2.90**	.148	3.80**	.037	.94	.170	4.36**
LTM-ACCESS TIME	9	-.023	-.59	-.026	-.67	-.004	-.10	-.047	-1.19
LTM-SEARCH TIME	10	.387	10.31**	.244	6.22**	.190	4.78**	.427	11.59**
		Part-Correlation Analysis (incorrect items)							
KNOWLEDGE	1	.164	4.17**	.055	1.38	.152	3.89**	.130	3.31**
KNOWLEDGE	6	.210	5.36**	.097	2.41*	.180	4.51**	.183	4.67**
REACTION TIME	2	.007	.18	.009	.23	.048	1.24	.037	.95
DECISION TIME	3	.034	.84	-.006	-.16	.005	.13	.005	.12
COMPARISON TIME	4	.117	2.73	.095	2.18*	.084	1.96*	.150	3.51**
LTM-ACCESS TIME	5	-.026	-.41	.045	.70	-.043	-.68	-.023	-.37
LTM-SEARCH TIME	6	.261	5.21**	.218	4.26**	.142	2.80**	.269	5.40**
		Difference-Score Analysis (incorrect items)							
DECISION TIME	7	.022	.55	-.010	-.26	-.026	-.66	-.019	-.49
COMPARISON TIME	8	.069	1.77	.075	1.88	.061	1.57	.111	2.84**
LTM-ACCESS TIME	9	-.040	-1.61	-.002	-.06	-.046	-1.18	-.054	-1.38
LTM-SEARCH TIME	10	.023	5.83**	.192	4.80**	.136	3.44**	.249	6.39**

Note. By the model, the results for KNOWLEDGE and REACTION TIME are the same in the two analyses. The *b* coefficients and *t* statistics are based on the models in Table 1. See text and Figure 1 for a mapping of tasks and components.

*$p<.05$.

**$p<.01$.

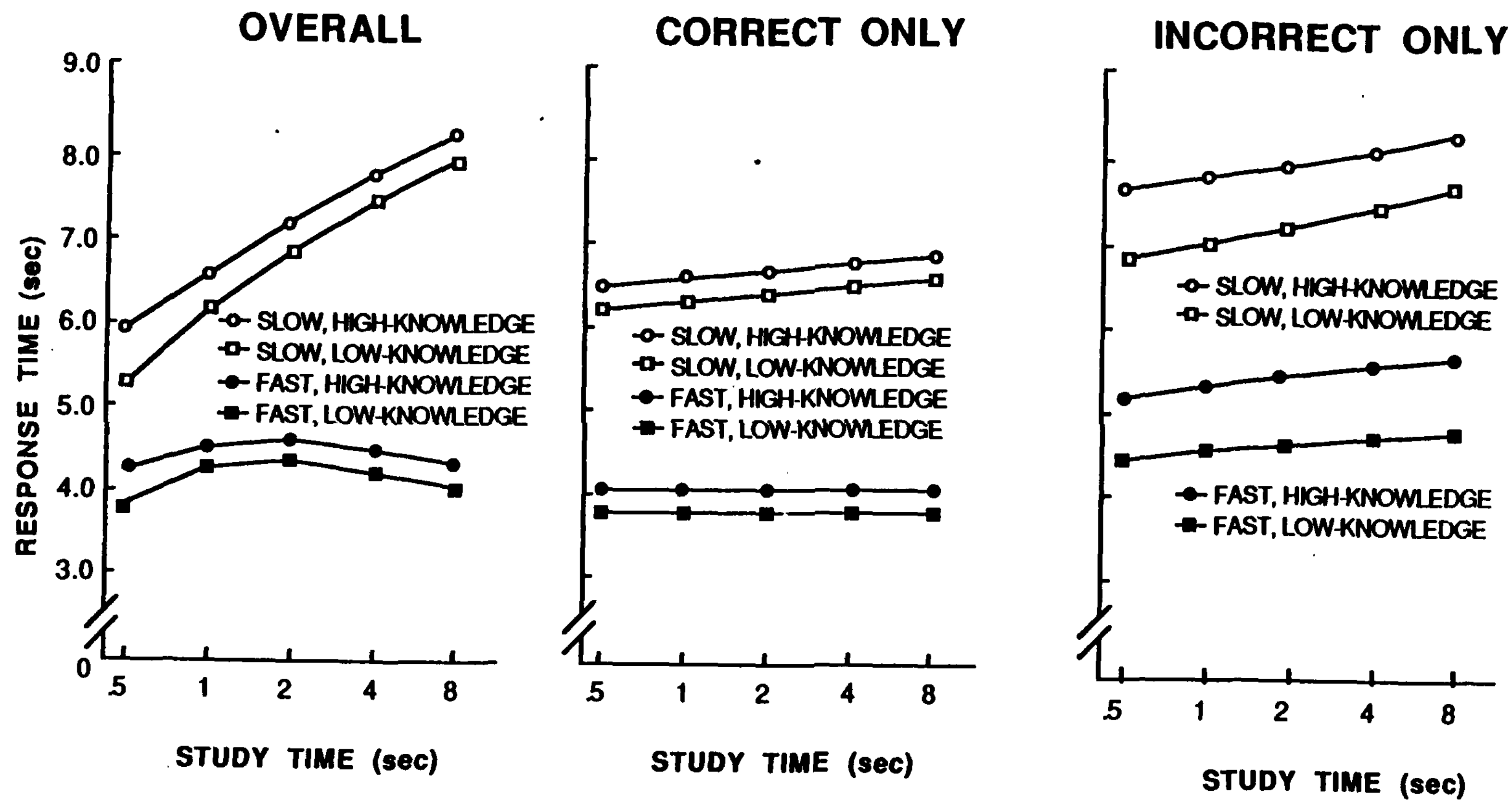

Figure 10. Expected value of (a) response time (averaged over all items), (b) response time for correct items only, and (c) response times for wrong items, as a function of study time per pair for various skill profiles in Experiment 3. See text and Appendix A for discussion of how curves were produced.

Results

We did not expect to find differences between the data from Experiment 1 and data from the control group in this experiment; and except for minor discrepancies, we found none. However, the two samples differed (e.g., data were collected about 1 month apart), and so, we conducted statistical comparisons using data from the control group. But we also will make reference to data from Experiment 1 in contrasting the results from the treatment group.

Error Analysis

Figure 2c shows the plot of retention percent correct against study time for Experiment 1 versus that of the strategy group for Experiment 4. The equation that generated the plot for the strategy group was the following:

PC (study-time) = (51.2 * AVERAGE) + (10.2 * LINEAR) + (-1.0 * QUADRATIC),

The plot shows that although there were no differences between the two groups in the .5-s condition, there were differences after more study time; and, in fact, differences increased with study time. In the statistical analysis, this pattern was reflected as differences in the AVERAGE (44.6 versus 51.2; F (1, 585) = 28.48), LINEAR (7.6 versus 10.2; F (1, 585) = 42.85), and QUADRATIC (-.4 versus -1.0; F (1, 585) = 4.54) parameters.

We also found an interaction between strategy training and replication, F (1, 585) = 15.87. Within a session, subjects in the control condition improved with practice, (d = 2.3, F (1, 287) = 16.43), but those in the strategy training group did not, (d = -0.7, F (1, 298) = 2.01).

No other within-subject contrast or between-subject variable interacted with treatment; thus, for all other variables, the general pattern of results found in Experiment 1 also characterized this experiment.

Individual Differences in Errors

Figure 11 shows the plot of percent correct against study time separately for High- versus Low-Knowledge and Fast- versus Slow-LTM-Search subjects; it is thus directly comparable to Figure 3, which shows the same plot for Experiment 1. It can be seen that there is a steeper rise in percent correct with study time for all four groups.

Table 9 presents the results of the regression analyses for the strategy-training group. These can be compared with Table 2, which shows the same analysis for Experiment 1 (which is essentially the same as the control group in this experiment). LTM-SEARCH TIME was a significant predictor of AVERAGE retention and retention after .5-s study, but not after 8-s study; this is exactly the same pattern as was found without strategy training, in Experiment 1.

KNOWLEDGE was a significant predictor of AVERAGE retention, rises in retention with study time (LINEAR), and fast growth in retention with study time (QUADRATIC); it also was a significant predictor of retention after both .5-s and 8-s study time. These results are identical to the results from Experiment 1, except for the QUADRATIC relationship. However, the relationship with QUADRATIC simply reflects the better overall performance in this group and the resulting increased

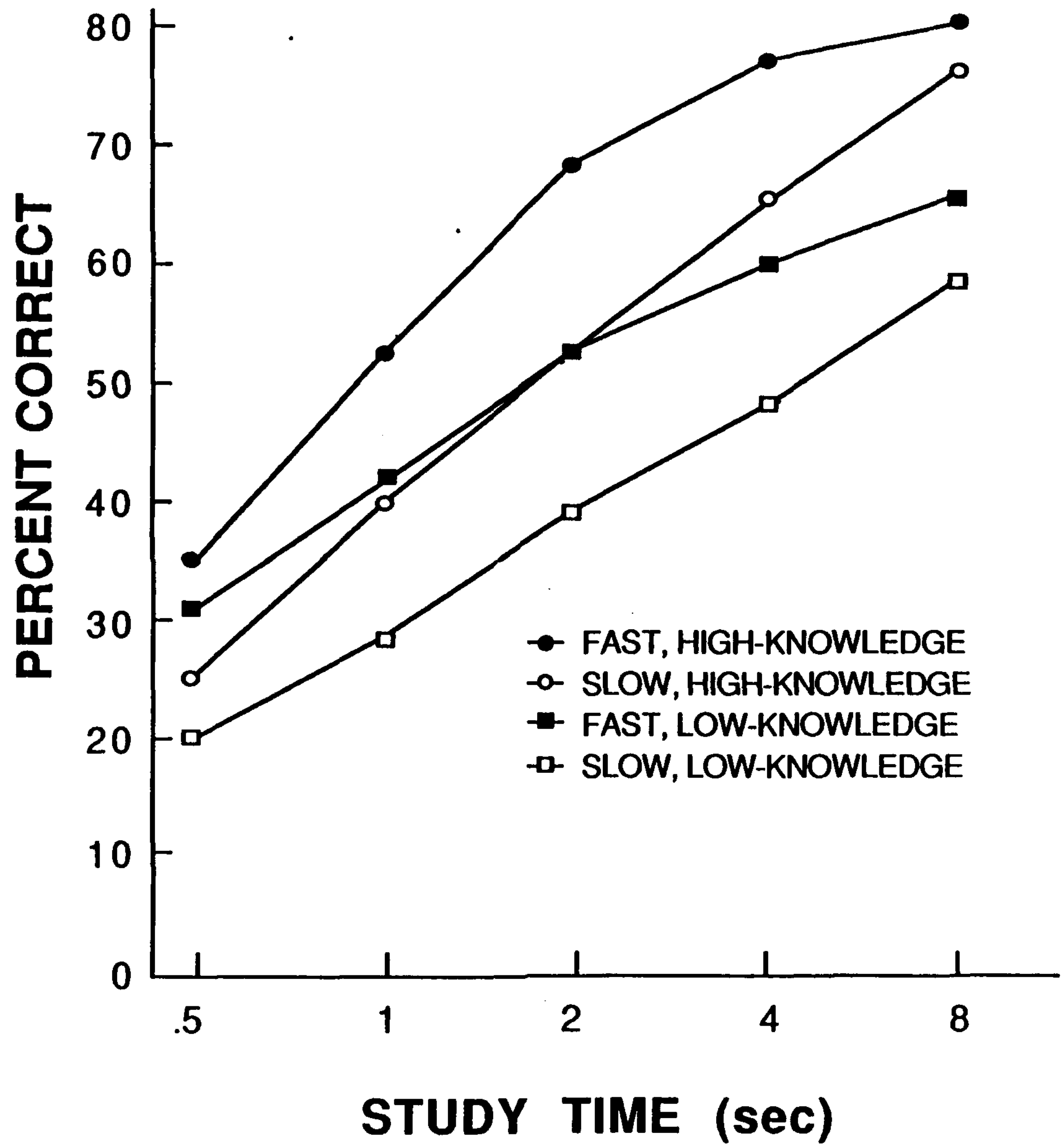

Figure 11. **Expected value of percent correct as a function of study time per pair for various skill profiles in Experiment 4 (strategy group only). See text and Appendix A for discussion of how curves were produced.**

Table 9. **Retention-Cognitive Ability Relationships: Treatment Group (Experiment 4, N = 302)**

		Learning Contrast Score					
		AVERAGE		LINEAR		QUADRATIC	
Component	**Model**	**b**	**t**	**b**	**t**	**b**	**t**
		Part-Correlation Analysis					
KNOWLEDGE	1	.493	9.77**	.274	4.90**	-.211	-3.72**
KNOWLEDGE	6	.462	8.85**	.282	4.75**	.188	-3.13**
REACTION TIME	2	-.116	2.32*	-.097	-1.74	.084	1.49
DECISION TIME	3	-.110	-1.95	-.020	-.31	.058	.90
COMPARISON TIME	4	-.139	-2.10*	.016	.22	.027	.36
LTM-ACCESS TIME	5	-.024	-.27	.030	.30	.196	.20
LTM-SEARCH TIME	6	-.162	-2.44*	.036	.47	.104	1.36
		Difference-Score Analysis					
DECISION TIME	7	-.015	-.31	.040	.71	-.005	-.09
COMPARISON TIME	8	-.112	-2.23	.005	.09	.026	.46
LTM-ACCESS TIME	9	-.008	-.16	.005	.09	.016	.28
LTM-SEARCH TIME	10	-.194	-3.78**	.000	.00	.113	1.92

		Study Time Condition			
		.5 sec		8 sec	
Component	**Model**	**b**	**t**	**b**	**t**
		Part-Correlation Analysis			
KNOWLEDGE	1	.336	6.14**	.427	8.13**
KNOWLEDGE	6	.288	5.13**	.419	7.56**
REACTION TIME	2	-.078	-1.43*	-.082	-1.56*
DECISION TIME	3	-.119	-1.92	-.067	-1.12
COMPARISON TIME	4	-.170	-2.35*	-.105	-1.50
LTM-ACCESS TIME	5	-.084	-.88	.024	.26
LTM-SEARCH TIME	6	-.234	-3.27**	-.055	-.78
		Difference-Score Analysis			
DECISION TIME	7	-.043	-.78	-.003	-.06
COMPARISON TIME	8	-.131	-2.42*	-.084	-1.60
LTM-ACCESS TIME	9	-.034	-.62	-.018	.34
LTM-SEARCH TIME	10	-.243	-4.42**	-.092	-1.69

Note. By the model, the results for KNOWLEDGE and REACTION TIME are the same in the two analyses. The *b* coefficients and *t* statistics are based on the models in Table 1. See text and Figure 1 for a mapping of tasks and components.

*p<.05.

**p<.01.

susceptibility to ceiling, following our line of argumentation for Experiment 2. The quantitative comparison is illuminating. Note that the *b* values for both AVERAGE and LINEAR are higher in Experiment 4 than in Experiment 1. The relationship with QUADRATIC suggests that these values might have been even higher in this experiment were it not for the ceiling. Together, this pattern of results indicates that knowledge played a more important role in determining retention after strategy training than it did without strategy training.

Latency Analysis

The main results of interest were interactions between any of the variables and treatment in predicting retrieval time. The only almost significant interaction was between treatment and the LINEAR contrast, F (1, 585) = 3.86, p = .050, but the effect was not significant when retrieval time was broken down by correct, F (1, 579) = 2.22, versus incorrect items, F (1, 579) = 1.52. Thus, although Figure 5c appears to show an interaction between treatment and study time for incorrect responses (the treatment group appears to have spent more time searching under conditions of uncertainty), the trend was not strong enough to overcome the amount of variability in retrieval time for incorrect responses in the treatment group.

Individual Differences in Response Time

Table 10 shows the relationships between retrieval time and cognitive ability for subjects in the strategy-treatment group. These results can be compared with those of Experiment 1, which are shown in Table 4. Considering LTM-SEARCH TIME, the most striking result one notices in comparing the two tables is that the relationships between search and retrieval times (AVERAGE, .5-s condition, and 8-s condition) are higher for both correct and incorrect responses after strategy training. This result can also be seen in Figure 12, compared to Figure 6, in that the gap between Fast and Slow subjects is greater for the current experiment than it was for Experiment 1 across all study time conditions. A comparison of the two figures shows that the fast are faster and the slow are slower following strategy training. One possible interpretation is that strategy training has the effect of reducing idiosyncratic memory search strategies, and causes memory search in the learning context to operate like memory search in the reaction time task context.

The second category of noteworthy results is expressed as relationships between retrieval time and KNOWLEDGE. As in Experiment 1, KNOWLEDGE predicted the amount of increase in retrieval time (LINEAR) for correct items: High-Knowledge subjects showed smaller increases. Also, the same crossover effect for correct-response retrieval time as was found in Experiment 1 was seen in this Experiment: KNOWLEDGE was positively correlated with retrieval time after .5-s study (High-Knowledge subjects took longer) but negatively correlated after 8-s study (High-Knowledge subjects were faster).

The most important result, however, came in the analysis of incorrect items. The relationship between KNOWLEDGE and retrieval time was positive, as in Experiment 1: High-Knowledge subjects spent longer searching memory in cases where they ultimately selected the incorrect response. The critical finding was that in this experiment, the relationship was much stronger. Considering the results for KNOWLEDGE, controlling for speed (the 6-*df* model), the comparisons for AVERAGE were b_1 = .181, b_4 = .330 (subscripts denote experiment number); the comparison for the .5-s condition were b_1 = .153, b_4 = .307; the comparisons for the 8-s condition were b_1 = .104, b_4 = .194.

Table 10. **Retrieval Time-Cognitive Ability Relationships: Treatment Group (Experiment 4, N = 302)**

		Retrieval-Time Contrast/Cell Score							
		AVERAGE		LINEAR		.5 sec		8 sec	
Component	**Model**	**b**	**t**	**b**	**t**	**b**	**t**	**b**	**t**
		Part-Correlation Analysis (correct items)							
KNOWLEDGE	1	.017	.29	-.243	-4.31**	.150	2.62**	-.136	-2.36*
KNOWLEDGE	6	.146	2.60*	-.225	-3.85**	.238	4.03**	-.014	-.25
REACTION TIME	2	.038	.65	-.068	-1.22	.070	1.22	.027	.47
DECISION TIME	3	-.039	-.58	.137	2.15*	-.115	-1.76	.007	.10
COMPARISON TIME	4	.151	1.95*	.198	2.67**	-.023	-.30	.220	2.88**
LTM-ACCESS TIME	5	.140	1.38	.097	1.00	.078	.77	.168	1.67
LTM-SEARCH TIME	6	.516	7.18**	.135	1.81	.316	4.20**	.510	7.22**
		Difference-Score Analysis (correct items)							
DECISION TIME	7	-.049	-.85	.138	2.47*	-.123	-2.15*	-.010	-.18
COMPARISON TIME	8	.116	2.01*	.141	2.53*	.024	.41	.166	2.92**
LTM-ACCESS TIME	9	.064	1.10	.023	.41	.048	.83	.070	1.21
LTM-SEARCH TIME	10	.393	7.02**	.148	2.54*	.218	3.73**	.409	7.45**
		Part-Correlation Analysis (incorrect items)							
KNOWLEDGE	1	.242	4.25**	.021	.36	.242	4.30**	.118	2.04*
KNOWLEDGE	6	.330	5.61**	.068	1.13	.307	5.22**	.194	3.27**
REACTION TIME	2	-.023	-.40	-.099	-1.69	.026	.47	-.026	-.45
DECISION TIME	3	-.078	-1.21	.034	.51	-.067	-1.04	-.036	-.55
COMPARISON TIME	4	.017	.22	.210	2.71**	-.118	-1.57	.126	1.63
LTM-ACCESS TIME	5	.074	.72	.183	1.78	-.010	-.10	.118	1.16
LTM-SEARCH TIME	6	.328	4.41**	.232	3.02**	.225	3.01**	.311	4.12**
		Difference-Score Analysis (incorrect items)							
DECISION TIME	7	-.044	-.78	.080	1.36	-.064	-1.13	-.012	-.21
COMPARISON TIME	8	.012	.21	.149	2.57*	-.086	-1.52	.092	1.60
LTM-ACCESS TIME	9	.036	.63	.066	1.33	.011	.20	.048	.83
LTM-SEARCH TIME	10	.211	3.65**	.190	3.16**	.127	2.19*	.229	3.91**

Note. By the model, the results for KNOWLEDGE and REACTION TIME are the same in the two analyses. The *b* coefficients and *t* statistics are based on the models in Table 1. See text and Figure 1 for a mapping of tasks and components.

*$p < .05$.

**$p < .01$.

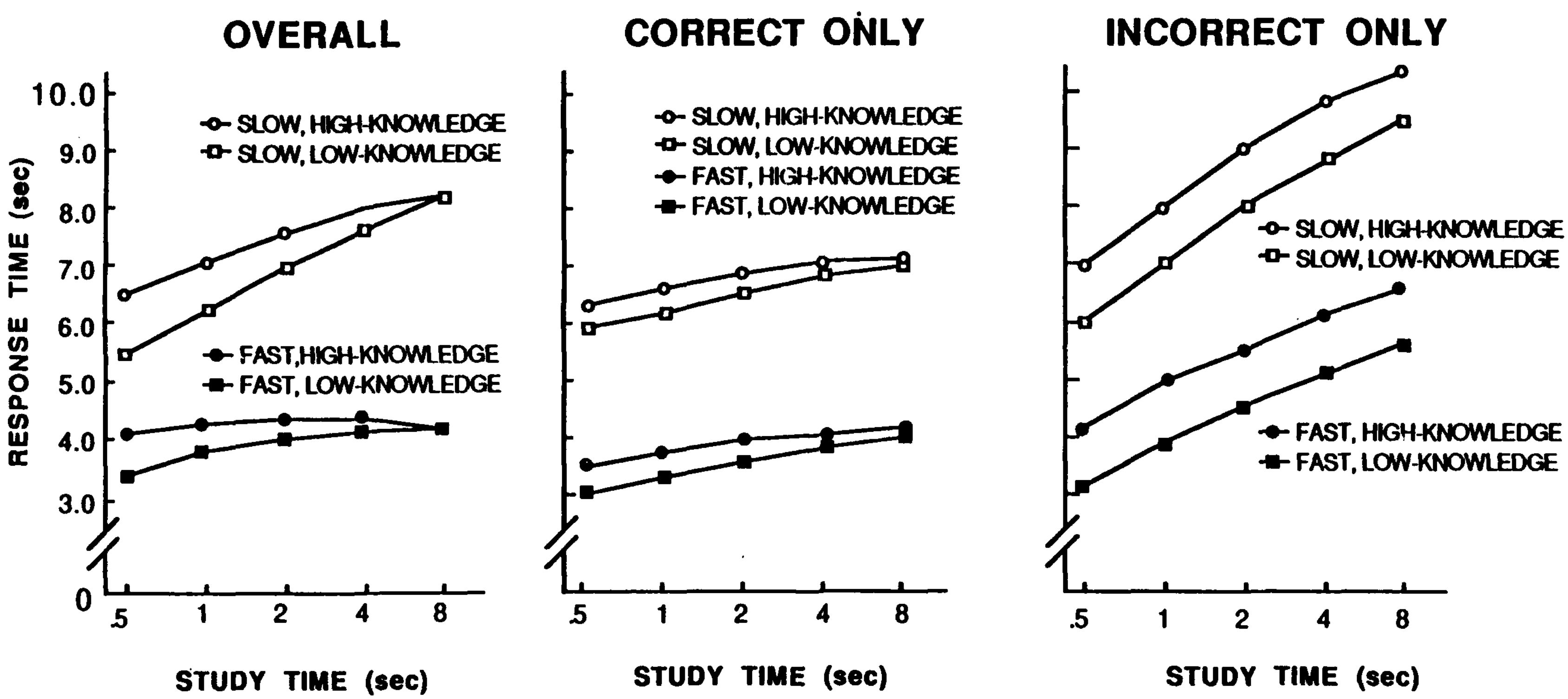

Figure 12. Expected value of (a) response time (averaged over all items), (b) response time for correct items only, and (c) response times for wrong items, as a function of study time per pair for various skill profiles in Experiment 4. See text and Appendix A for discussion of how curves were produced.

Discussion

The main finding from this experiment was that subjects benefitted on average from a short treatment designed to train the use of a mnemonic strategy, but High-Knowledge subjects benefitted more from such training than did others. Further, the training benefit accrued had no apparent cost in retrieval time. Overall (not considering individual differences), retrieval time results for the control and treatment conditions were indistinguishab'e. Considering individual differences in retrieval time, the main finding was that after strategy training, Fast-LTM-Search subjects were faster and Slow-LTM-Search subjects were slower. But more importantly, High-Knowledge subjects were just as fast (perhaps faster) following strategy training on correct responses, but slower following strategy training on incorrect responses.

How can this pattern of results be reconciled with the results from Experiments 1 and 2? We speculated that the advantage of knowledge was that it resulted in more and better organized elaborative structure built per unit study time. The results of this experiment are in accord with that interpretation, but they also suggest a refinement. Retention performance in paired-associates learning reflects not only the declarative knowledge component, which is tapped by our KNOWLEDGE score, but also a procedural or strategic component. No doubt these components are correlated. But they are not the same. It is possible to be low in knowledge but still know effective mnemonic strategies or to be high in knowledge and not know them. Our very brief intervention was enough to reduce the somewhat idiosyncratic portion of the strategic knowledge component that had to do with whether the subject happened to have known about mnemonic strategies. Thus, variation due to this component was reduced, allowing the relationship between declarative knowledge and retention to stand out more clearly. Another way of expressing this same idea is that once everyone knew about mnemonic strategies, the effectiveness of those strategies was determined to a greater degree than before by the level of knowledge available.

EXPERIMENT 5: MIXED PRESENTATION RATES

In Experiments 1 through 4, blocks were homogeneous with respect to presentation rate. In this experiment, presentation rate was mixed within a block: 2 of the 10 items in each block were displayed for .5 s, 2 items were displayed for 1 s, 2 for 2 s, 2 for 4 s, and 2 for 8 s. The order itself was mixed and changed from one block to the next. We thought it was important to examine the mixed versus fixed block format because mixed presentation is likely to tap the ability to allocate processing resources flexibly. That is, the ideal learner in the mixed block would likely allocate attention away from 8-s items, because of diminishing learning benefits after a few seconds, and apply that attention to those items presented only briefly.

There were two versions of this task, administered within subjects. A WORD version presented items identical to those used in Experiment 1. A nonsense syllable version paired consonant-vowel-consonant (CVC) trigram stimuli with word responses. This contrast allowed us to determine whether using nonsense syllables affects the cognitive skill-learning ability relationships.

Method

Subjects

Subjects were 215 enlistees who had not participated in any of the other experiments, but were demographically similar to those who had.

Word-Word Paired-Associate Learning Task

Subjects were presented a study block of 10 pairs, as in Experiment 1. Unlike Experiment 1, presentation rate was mixed within block. Pairs were presented for either 0.5, 1, 2, 4, or 8 s, determined at random, with the constraint that each presentation rate was administered two times in each study block. Presentation rates were randomly assigned to word pairs immediately prior to the administration of the study block; it was unlikely that any two subjects received exactly the same sequence of items (i.e., word pairs nested within presentation rates) in a study block. Testing was identical to that for Experiment 1.

CVC-Word Paired-Associate Learning Task

The format and administration conditions were identical to those of the Word-Word Paired-Associate task, except that stimulus terms were CVC trigrams selected to be of moderately high association value (with a 70-85 rating from the Archer [1960] norms).

Procedure

Subjects were administered 10 word-word task blocks and 10 CVC-word task blocks at the beginning of the session and 10 of each at the end of the session, for a total of 40 learning task blocks (20 word-word task blocks and 20 CVC-word task blocks). CVC-word order was completely crossed with beginning versus end of session. As in the other experiments, the seven cognitive tests were administered in random order during the middle of the session. All other details were identical to Experiment 1, with one exception. In this experiment, the tests used to estimate KNOWLEDGE and LTM-search speed had different items from those in Experiments 1 through 4. In particular the KNOWLEDGE estimator was a much easier test (M = .95 versus .81, in Experiments 1 versus 5), and the SPEED task was more difficult (M = 1.4 s versus 1.7 s, in Experiments 1 versus 5). Thus, individual differences results from this experiment are not strictly comparable to those from the other experiments.

Results

Two kinds of comparisons were of interest to us in this analysis. One was the comparison of the WORD mixed blocks in this experiment versus the WORD homogeneous blocks in Experiment 1. The second was the comparison between WORD stimuli and CVC stimuli.

Analysis of WORD-WORD Pairs

Error Analysis. As can be seen from Figure 2d, mixed blocks did result in a flatter study-time slope, that is, mixed blocks led to better performance in the fastest exposure conditions (<1 s) but worse performance in the slower exposure conditions (>1 s). Thus, it appears that subjects effectively reallocated their attention in the mixed-block case. During the time they were gazing at pairs that were presented for more than 1 s, they continued to process previous pairs that had been presented quickly. This had the effect of impairing retention performance on items presented for more than

1 s (because some of the processing time was usurped for prior, more briefly presented items) and enhancing performance on items presented for less than 1 s.

Given this evidence for time-sharing, we should expect that memory search speed, or some other information processing speed variable, would play a greater role in determining retention performance on the mixed-compared to the homogeneous-block items. And, indeed, we found this to be the case. Table 11 shows that the relationships between LTM-SEARCH TIME and both retention AVERAGE (and also LINEAR but only in the difference score analysis) and retention after both .5- and 8-s study were much higher than similar relationships found for Experiment 1 (Table 2). Note in particular that whereas LTM-SEARCH TIME did not play a significant role in predicting retention after 8-s study in the homogeneous-block case (Experiment 1), it did play a significant role in the mixed-block case. This can be seen in Figure 13a in that unlike Figure 3 (Experiment 1), fast subjects retained more than slow subjects regardless of study time and regardless of KNOWLEDGE level.

The relationships with KNOWLEDGE were similar in the mixed and homogeneous-block experiments, except for the lack of a KNOWLEDGE-LINEAR relationship in the mixed-block case. But again note that in this experiment, KNOWLEDGE was measured with an easier vocabulary test and, consequently, was not as good a discriminator.

Latency Analysis. Figure 4d shows that unlike the homogeneous-blocks case, retrieval time following mixed blocks did not increase with study time; this result is reflected in the lack of a significant relationship between LINEAR and study time, F (1, 209) = 1.20. Separating into correct versus incorrect did not affect this relationship. Apparent differences in Figure 5d are not true differences.

In the individual differences analysis, presented in Table 12, two discrepancies between the homogeneous- and mixed-block experiments stand out. One is that KNOWLEDGE is positively correlated with AVERAGE retrieval time, not only for incorrect responses as in Experiment 1 but also for correct responses. In this experiment, High-Knowledge subjects not only took longer to respond under conditions of uncertainty as in Experiment 1, but they also took longer to generate a response when they knew the correct associate, both on average and in the .5-s condition (see also Figure 14). In keeping with the organization interpretation offered to account for the findings in Experiments 1 and 2, it appears that the mixed study blocks interfered with High-Knowledge subjects' ability to organize effectively the elaborative structures built during study.

A second discrepancy found in the mixed-block experiment is that LTM-SEARCH TIME was not correlated with retrieval time as in Experiment 1. However, this may have simply reflected the lower power in this experiment, due to the smaller N (396 in Experiment 1 versus 212 in this experiment). In all cases, the effects were in the same direction; and in some cases, the bs were larger in this experiment.

Analysis of CVC-Word Pairs

Error Analysis. Figure 2d shows that the results for the CVC-word pairs were similar to those for the word-word pairs, except that CVC pairs were slightly more difficult. This was reflected in the statistical analysis as a significant effect for stimulus type, F (1, 209) = 42.52, and also a significant type-by-LINEAR interaction, F (1, 209) = 5.42. Word pairs were retained better than CVC pairs, d = 5.9; and they benefitted slightly more from increases in study time than did CVC pairs, d = .8.

Table 11. **Retention-Cognitive Ability Relationships: Word Pairs (Experiment 5, N = 212)**

		Learning Contrast Score					
		AVERAGE		LINEAR		QUADRATIC	
Component	**Model**	**b**	**t**	**b**	**t**	**b**	**t**
		Part-Correlation Analysis					
KNOWLEDGE	1	.249	3.71**	.105	1.53	.041	.59
KNOWLEDGE	6	.238	3.70**	.075	1.06	.036	.50
REACTION TIME	2	-.229	-3.47**	-.214	-3.14**	.064	.92
DECISION TIME	3	-.154	-2.28*	-.030	-.42	.045	.63
COMPARISON TIME	4 -	.140	-1.78	-.065	-.78	.052	.61
LTM-ACCESS TIME	5	-.002	-.02 -	.114	-1.03	-.160	-1.42
LTM-SEARCH TIME	6	-.358	-4.85**	-.153	-1.88	.146	1.75
		Difference-Score Analysis					
DECISION TIME	7	-.061	-.89	.048	.68	.019	.27
COMPARISON TIME	8	-.124	-1.85	-.019	-.27	-.044	-.64
LTM-ACCESS TIME	9	.025	.37	.033	.48	-.058	-.82
LTM-SEARCH TIME	10	-.361	-5.76**	-.183	-2.68**	.131	1.90

		Study Time Condition			
		5 sec		8 sec	
Component	**Model**	**b**	**t**	**b**	**t**
		Part-Correlation Analysis			
KNOWLEDGE	1	.248	3.68**	.252	3.74**
KNOWLEDGE	6	.246	3.68**	.231	3.54**
REACTION TIME	2	-.134	-1.99*	-.246	-3.74**
DECISION TIME	3	-.158	-2.31*	-.110	-1.63
COMPARISON TIME	4	-.093	-1.15	-.142	-1.80
LTM-ACCESS TIME	5	.009	.09	-.084	-.80
LTM-SEARCH TIME	6	-.312	-4.06**	-.301	-4.00**
		Difference-Score Analysis			
DECISION TIME	7	-.099	-1.44	-.015	-.21
COMPARISON TIME	8	-.064	-.95	-.140	-2.10*
LTM-ACCESS TIME	9	.016	.24	-.017	-.25
LTM-SEARCH TIME	10	-.293	-4.54**	-.325	-5.10**

Note. By the model, the results for KNOWLEDGE and REACTION TIME are the same in the two analyses. The *b* coefficients and *t* statistics are based on the models in Table 1. See text and Figure 1 for a mapping of tasks and components.

*$p < .05$.

**$p < .01$.

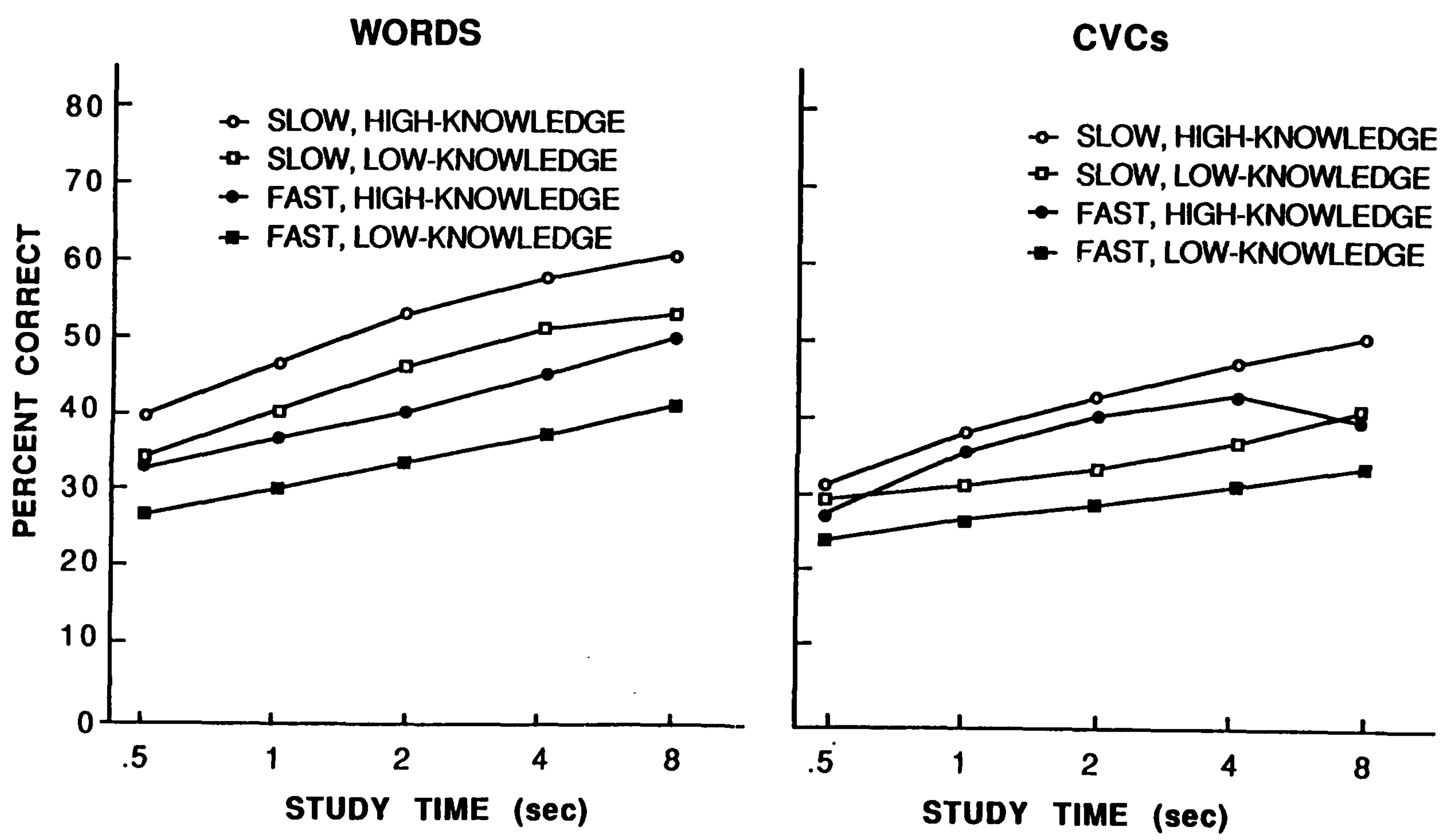

Figure 13. Expected value of percent correct as a function of study time per pair for various skill profiles in Experiment 5, separately for the (a) WORD-WORD pairs, and (b) CVC-WORD pairs. See text and Appendix A for discussion of how curves were produced.

Table 12. **Retrieval Time-Cognitive Ability Relationships: Word Pairs (Experiment 5, N = 212)**

		Retrieval-Time Contrast/Cell Score							
		AVERAGE		LINEAR		.5 sec		8 sec	
Component	**Model**	**b**	**t**	**b**	**t**	**b**	**t**	**b**	**t**
		Part-Correlation Analysis (correct items)							
KNOWLEDGE	1	.188	2.76**	-.112	-1.62	.220	3.25**	.144	2.09*
KNOWLEDGE	6	.156	2.26*	-.073	-1.04	.183	2.62**	.119	1.68
REACTION TIME	2	-.014	-.21	.126	1.83	-.063	-.93	-.022	-.31
DECISION TIME	3	.041	.58	.086	1.21	-.024	-.34	.052	.73
COMPARISON TIME	4	.290	3.56**	-.109	-1.31	.262	3.23**	.217	2.61**
LTM-ACCESS TIME	5	-.011	-.10	.132	1.18	-.024	-.22	.052	.47
LTM-SEARCH TIME	6	.153	1.91	.214	2.63*	.008	.10	.118	1.44
		Difference-Score Analysis (correct items)							
DECISION TIME	7	.043	.62	.035	.50	.00	.00	.056	.80
COMPARISON TIME	8	.210	3.14**	-.076	-1.09	.193	2.89**	.149	2.19*
LTM-ACCESS TIME	9	-.072	-1.05	.108	1.56	-.078	-1.15	-.016	-.23
LTM-SEARCH TIME	10	.205	3.05**	-.254	-3.77	.064	.94	.157	2.31*
		Part-Correlation Analysis (incorrect items)							
KNOWLEDGE	1	.282	4.22**	-.088	-1.27	.294	4.43**	.250	3.72**
KNOWLEDGE	6	.267	3.84**	-.073	-1.01	.277	3.99**	.245	3.50**
REACTION TIME	2	-.084	-1.25	.060	.86	-.096	-1.44	-.060	-.88
DECISION TIME	3	-.041	-.59	-.058	-.81	-.024	-.35	-.071	-1.01
COMPARISON TIME	4	.127	1.56	.071	.84	.116	1.43	.138	1.69
LTM-ACCESS TIME	5	-.018	-.17	-.052	-.46	-.005	-.05	-.032	-.29
LTM-SEARCH TIME	6	.050	.63	.116	1.39	.044	.55	.088	1.08
		Difference-Score Analysis (incorrect items)							
DECISION TIME	7	-.008	-.12	-.075	-1.06	.012	.17	-.044	-.64
COMPARISON TIME	8	.088	1.32	.083	1.20	.073	1.09	.110	1.63
LTM-ACCESS TIME	9	-.043	-.64	-.057	-.81	-.030	-.45	-.058	-.85
LTM-SEARCH TIME	10	.060	.89	.107	1.55	.050	.75	.094	1.40

Note. By the model, the results for KNOWLEDGE and REACTION TIME are the same in the two analyses. The *b* coefficients and *t* statistics are based on the models in Table 1. See text and Figure 1 for a mapping of tasks and components.

*p<.05.

**p<.01.

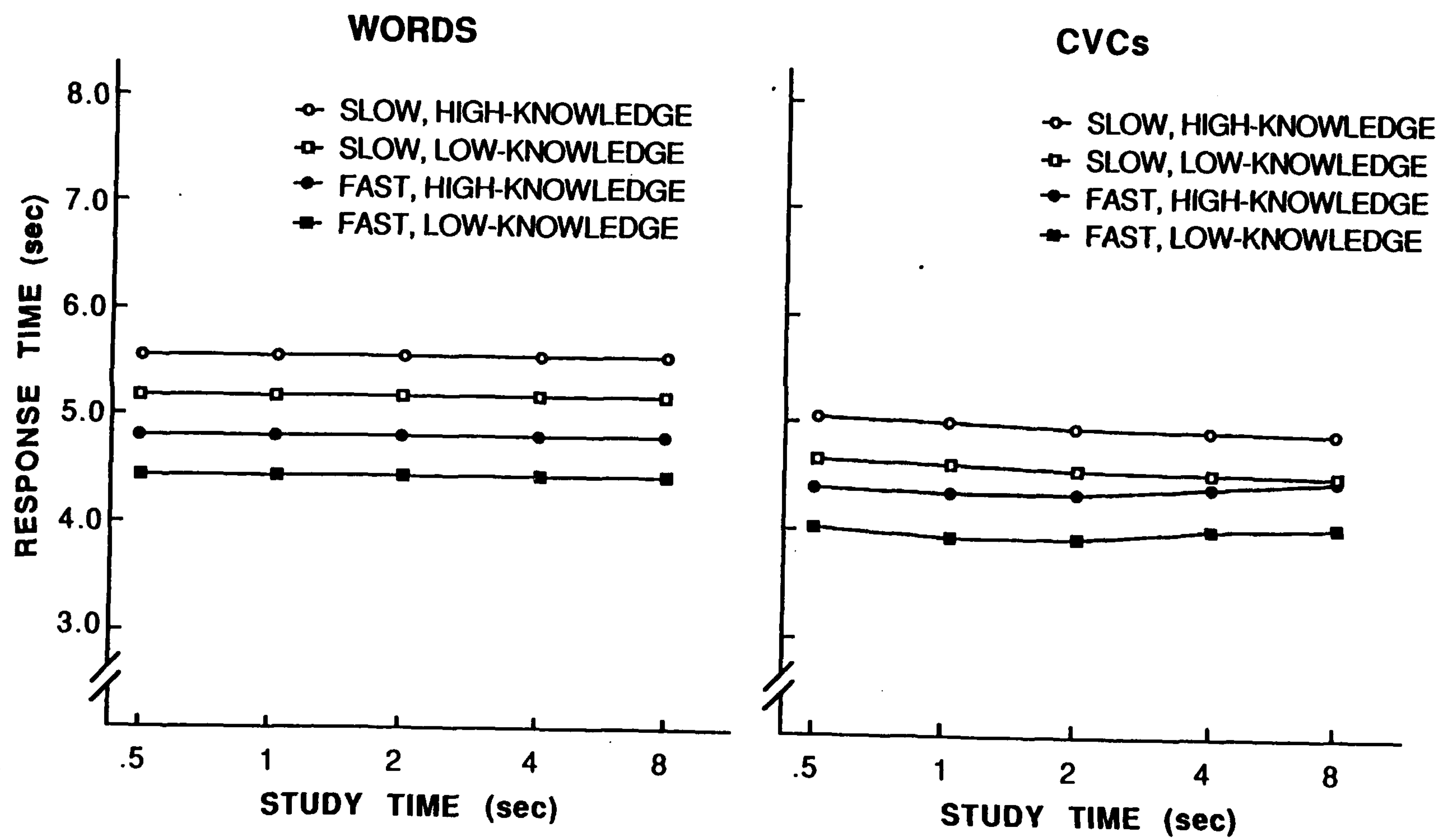

Figure 14. Expected value of (a) response time (averaged over all items), (b) response time for correct items only, and (c) response times for wrong items, as a function of study time per pair for various skill profiles in Experiment 5. See text and Appendix A for discussion of how curves were produced.

The individual differences analysis, presented in Table 13, shows almost an identical pattern between retention and cognitive ability for word and CVC pairs. As was the case with word pairs, with CVC pairs KNOWLEDGE predicted AVERAGE retention and retention in both the .5-s and 8-s conditions (High-Knowledge subjects retained more). In addition, in the CVC analysis KNOWLEDGE predicted LINEAR, indicating that High-Knowledge subjects benefitted more from each increment in study time but the relationship was not qualitatively different from that found with words. The relationships between LTM-SEARCH TIME and retention were also similar to those found in the word condition, but they were slightly lower in magnitude. These results are also plotted in Figure 13b.

Latency Analysis. Figure 4d shows that subjects responded .4 s faster with CVCs than they did with word pairs, F = 23.16; this was true for both correct and incorrect responses (Figure 5d). The individual differences analysis (Table 14; Figure 14b) shows that the results for CVCs are virtually indistinguishable from the results for words. For both words and CVCs, KNOWLEDGE is positively correlated with AVERAGE retrieval time on correct items and retrieval time after .5 s on correct items. It is also positively correlated with the same indices on incorrect items. CVC and word retrieval times (AVERAGE, .5 s, and 8 s) also reflect a speed component--in this case, COMPARISON TIME.

Discussion

Taken together, these results suggest that the same kind of processes probably characterize learning regardless of whether word or CVC stimuli are employed. CVC stimuli probably introduce an additional component that in our analyses appeared primarily as noise that served to attenuate the individual differences relationships.

Regardless of whether CVC or word stimuli were used, mixed blocks differed from homogeneous blocks in two important ways. First, retention did not increase as much with study time in the mixed-block case. We have attributed this difference to a time-sharing strategy which resulted in better retention of briefly presented pairs at the expense of retention of pairs presented for a relatively long time. Because subjects were engaged in time-sharing, the importance of memory search speed increased in predicting retention. Second, retrieval time did not increase with study time in the mixed-block case as it did after homogeneous blocks. This too is consistent with the idea that subjects used a time-sharing strategy. Relatively less elaboration-induced interference was experienced for items studied for a long time, because subjects used some of the study time for such items to produce elaborative structures for previously presented items for which less study time had been allowed.

Finally, the fact that CVC pairs were responded to faster than word pairs but not retained as well as word pairs is consistent with our elaboration-organization theme. Less elaborative structure is built per unit study time in the case of CVCs, which results in both poorer retention and less retrieval interference.

GENERAL DISCUSSION

In this study, we have demonstrated how a general model of associative learning, based on the relation-construction principle, could be used to derive predictions about individual differences in learning, and that analysis of individual differences could, in turn, be shown to have implications

Table 13. **Retention-Cognitive Ability Relationships: CVC-Word Pairs (Experiment 5, N = 212)**

		Learning Contrast Score					
		AVERAGE		LINEAR		QUADRATIC	
Component	**Model**	**b**	**t**	**b**	**t**	**b**	**t**
		Part-Correlation Analysis					
KNOWLEDGE	1	.234	3.46**	.160	2.33*	.101	1.46
KNOWLEDGE	6	.215	3.28**	.169	2.39*	.119	1.68
REACTION TIME	2	-.225	-3.39**	-.103	-1.50	-.008	-.12
DECISION TIME	3	-.089	-1.31	-.119	-1.68	-.034	-.48
COMPARISON TIME	4	-.176	-2.20*	-.079	-.95	.070	.83
LTM-ACCESS TIME	5	-.061	-.58	.079	.71	-.067	-.59
LTM-SEARCH TIME	6	-.319	-4.22**	-.175	-2.15*	.292	3.58**
		Difference-Score Analysis					
DECISION TIME	7	-.003	-.05	-.073	-1.05	-.029	-.41
COMPARISON TIME	8	-.166	-2.48*	-.056	-.81	.061	.87
LTM-ACCESS TIME	9	.006	.09	.057	.82	-.060	-.86
LTM-SEARCH TIME	10	-.344	-5.41**	-.175	-2.58**	.234	3.46**

		Study Time Condition			
		.5 sec		8 sec	
Component	**Model**	**b**	**t**	**b**	**t**
		Part-Correlation Analysis			
KNOWLEDGE	1	.215	3.16**	.256	3.81**
KNOWLEDGE	6	.186	2.73**	.256	3.82**
REACTION TIME	2	-.210	-3.13**	-.199	-3.00**
DECISION TIME	3	-.024	-.35	-.145	-2.14*
COMPARISON TIME	4	-.134	-1.65	-.129	-1.62
LTM-ACCESS TIME	5	-.197	-1.83	-.017	-.16
LTM-SEARCH TIME	6	-.159	-2.02*	-.216	-2.80**
		Difference-Score Analysis			
DECISION TIME	7	.051	.74	-.064	-.93
COMPARISON TIME	8	-.146	-2.17*	-.111	-1.65
LTM-ACCESS TIME	9	-.077	-1.13	.014	.20
LTM-SEARCH TIME	10	-.213	-3.20**	-.246	-3.78**

Note. By the model, the results for KNOWLEDGE and REACTION TIME are the same in the two analyses. The *b* coefficients and *t* statistics are based on the models in Table 1. See text and Figure 1 for a mapping of tasks and components.

*p<.05.

**p<.01.

Table 14. Retrieval Time-Cognitive Ability Relationships: CVC-Word Pairs (Experiment 5, N = 212)

		Retrieval-Time Contrast/Cell Score							
		AVERAGE		LINEAR		.5 sec		8 sec	
Component	Model	b	t	b	t	b	t	b	t
		Part-Correlation Analysis (correct items)							
KNOWLEDGE	1	.167	2.44*	-.069	-1.00	.166	2.41*	.117	1.69
KNOWLEDGE	6	.148	2.10*	-.055	-.76	.141	2.20*	.098	1.37
REACTION TIME	2	-.041	-.59	.117	1.68	-.055	-.80	.019	.27
DECISION TIME	3	-.004	-.07	.064	.89	-.007	-.10	.049	.68
COMPARISON TIME	4	.195	2.35*	-.013	-.16	.179	2.14*	.180	2.15*
LTM-ACCESS TIME	5	-.111	-1.00	.186	1.66	-.152	-1.38	.018	.16
LTM-SEARCH TIME	6	.175	2.15*	-.009	-.12	.139	1.71	.107	1.29
		Difference-Score Analysis (correct items)							
DECISION TIME	7	.010	.14	.017	.02	.013	.18	.039	.55
COMPARISON TIME	8	.142	2.09*	.002	.03	.127	1.85	.131	1.91
LTM-ACCESS TIME	9	-.111	-1.63	.114	1.65	-.132	-1.92	-.029	-.41
LTM-SEARCH TIME	10	.179	2.65**	.023	.33	.142	2.09*	.143	2.09*
		Part-Correlation Analysis (incorrect items)							
KNOWLEDGE	1	.210	3.09**	.018	.26	.211	3.11**	.216	3.18**
KNOWLEDGE	6	.189	2.68**	.055	.76	.179	2.56*	.202	2.88**
REACTION TIME	2	-.121	-1.78	.025	.35	-.137	-2.01*	-.125	-1.83
DECISION TIME	3	-.035	-.50	-.042	-.59	-.026	-.37	-.047	-.66
COMPARISON TIME	4	.125	1.52	-.139	-1.64	.159	1.94	.090	1.09
LTM-ACCESS TIME	5	-.106	-.97	.017	.15	-.102	-.93	-.103	-.94
LTM-SEARCH TIME	6	.092	1.13	.099	.32	.052	.64	.108	1.33
		Difference-Score Analysis (incorrect items)							
DECISION TIME	7	.010	.15	-.048	-.67	.024	.35	.001	.01
COMPARISON TIME	8	.077	1.13	-.091	-1.31	.097	1.43	.052	.76
LTM-ACCESS TIME	9	-.092	-1.35	.038	.06	-.096	-1.40	-.083	-1.21
LTM-SEARCH TIME	10	.079	1.15	.033	.48	.057	.84	.078	1.16

Note. By the model, the results for KNOWLEDGE and REACTION TIME are the same in the two analyses. The *b* coefficients and *t* statistics are based on the models in Table 1. See text and Figure 1 for a mapping of tasks and components.

*p < .05.

**p < .01.

for the general model. We proposed that paired-associates learning involves constructing relations between the terms in the pair through a process of elaboration. We drew three predictions regarding individual differences from this model, and each prediction was supported to some extent.

One prediction was that the success of the relation establishment process, and hence learning success, would depend on the amount of material available to be used in forming elaborations. In all conditions of all five experiments, this prediction was supported. Breadth of knowledge, as indicated by a score on a computerized vocabulary test, correlated significantly with retention, ranging from $b = .215$ to $b = .493$. The relationship held regardless of whether a recall or recognition test was given, whether blocks were mixed or homogeneous with respect to study time, whether strategy training was administered, whether words or CVC trigrams were used as stimuli, or whether or not subjects' processing speed was statistically held constant.

The relationship was weakest when CVC stimuli were used and was strongest following strategy training. Both of these findings are consistent with the relation-construction principle. CVC stimuli attenuate the relationship with knowledge because they introduce an additional component of having to generate a semantic associate to a non-word; to do this subjects may engage auditory processes which is both time-consuming and relatively independent of knowledge level. On the other hand, strategy training enhances the relationship with declarative knowledge because it causes the strategic knowledge component of associative learning to be reduced by minimizing the variance in retention due to prior knowledge of mnemonic strategies.

A second prediction was that subjects capable of searching memory quickly would learn better because they would be able to construct more relations per unit study time. This prediction also held throughout all the experiments, but with an important qualification. In the case of homogeneous study-time blocks (Experiments 1 through 4), memory search speed predicted retention probability primarily under conditions of high information flow; that is, when study time was short (*b*s ranged from -.111 to -.234). The relationship was attenuated, to the point of there being no reliable relationship between LTM-SEARCH TIME and retention, under conditions of liberal study time (*b*s ranged from -.005 to -.108).

However, in the mixed-block case, for both word and CVC stimuli, LTM-SEARCH TIME predicted retention regardless of study time; and in fact, the relationship between search speed and retention was generally greater than with homogeneous-study blocks (*b*s ranged from -.159 to -.301). This was due to the fact that in the mixed-blocks case, subjects used a time-sharing strategy in which they continued to process .5-s and 1-s pairs while being presented 4-s and 8-s pairs within a block. This resulted in better performance on the rapidly presented pairs but worse performance on the slowly presented pairs relative to the homogeneous-block case. Further, with mixed blocks, the success of this strategy in terms of retention outcome was more dependent on the speed with which subjects were able to shift focus-of-attention from one pair to the next, as reflected in their LTM-SEARCH TIME score.

A third prediction concerned the cost of the relation-construction process; namely, that increasing interference or fan should accompany increases in study time. We found precisely this result in the homogeneous-block recall experiments (Experiments 1, 3, and 4). That is, the longer subjects studied a pair, the longer they took to retrieve the response at test. This pattern held for both items in which they knew the correct associate (correct-response items) and items in which they did not (incorrect-response items).

Interestingly, this relationship did not hold when subjects were provided a recognition test (Experiment 2). This can be explained by assuming that in the recognition test the effect of potentially interfering extraneous paths (i.e., those paths responsible for the fan effect in the recall test condition) is minimized because activation spreads simultaneously from both stimulus and response terms during the retrieval process. In the recall test, by contrast, activation spreads only from the stimulus term, because it is the only one available. Nevertheless, it is still likely that in both the recall and recognition cases elaborative structure was built during encoding and the fan effect, or lack thereof, reflected purely a retrieval phenomenon. Evidence for this was that in recall testing the fan effect was greater for incorrect items, reflecting the fact that subjects had more potential paths to search for under conditions of more study time, presumably because more had been created at study. Even in the recognition test experiment, a fan effect emerged for incorrect items. Finally, although a fan effect did not emerge for the mixed blocks, it also was the case that the retention increase, as a function of study time, was relatively shallow. Again, this reflected the time-sharing strategy.[4]

The individual differences results were consistent with this model. Memory search speed was highly related to retrieval time when subjects knew the correct associate, especially on a recognition test (Experiment 2) and following strategy training (Experiment 4) where it was more likely that nearly everyone was using the elaboration strategy. And in most cases where there was a fan effect (Experiments 1 and 3), Fast-LTM-Search subjects were less susceptible to fan effects.

In contrast, we predicted that High-Knowledge subjects, because they constructed more elaborations per unit study time, would show greater fan effects. We did not find this result. In fact, in all fixed study-time blocks, we found the opposite: High knowledge was shown to relate consistently to fast average retrieval time, or less susceptibility to fan, or both. Only in the mixed-block case was high knowledge related to slow average retrieval times, but this is hard to interpret because of the time-sharing hypothesis. We did find in all experiments that on incorrect items, high knowledge was related to slow retrieval times. But rather than suggesting a greater fan effect, this suggested an ability-induced strategy difference: Because High-Knowledge subjects constructed more relations, they searched through those relations longer at test whenever they did not know the correct associate. The fact that High-Knowledge subjects actually responded faster than Low-Knowledge subjects when they knew the correct associate suggested that in addition to constructing more elaborations, High-Knowledge subjects probably constructed better-organized elaborations which served to bypass potential interference effects.

In summary, our inquiry into the determinants of associative learning proficiency can be summarized as follows:

1. *Knowledge affects learning success*, because knowledge is the essential material used in generating elaborations and forming links;

2. *Learning strategy affects learning success.* Useful mnemonic strategies generally enhance retention, but they also serve to make knowledge an even more critical determinant of learning. Note also that it takes time (at least 1 s) for a trained elaboration strategy to have an effect;

3. *Memory Search Speed affects learning success*, but primarily when study time is short; and

[4]An alternative explanation was suggested by Randy Fletcher (personal communication, November 1986). That is, in the fixed-block condition, a block pace is established, and subjects respond consistently with the block pace. If 10 items fly by in 5 s, subjects will tend to respond quickly, whereas if 10 items stay on the screen for 80 s, subjects tend to respond slowly. It is not obvious whether any data here establish whether our or Fletcher's explanation is correct.

4. *Study time affects learning success*, but there is a cost. More study time results in more relations constructed; for most subjects (Fast-LTM-Search subjects being the exception), this results in longer retrieval times given a recall test.

Finally, it is worth noting that the success of the analyses we have employed here depended critically on three design features that often are ignored in individual differences investigations. First, and perhaps most importantly, large sample sizes are required for examining individual differences hypotheses. The expected effect size to variability ratio is much higher in individual differences investigations than it is in studies that compare treatment groups, and this results in a requirement for a much larger sample to achieve an equivalent power level. Second, multitrait controls (Campbell & Fiske, 1959) are necessary to isolate the effects of individual differences variables of interest. In this study, we included multiple measures of information processing speed; this allowed us to pinpoint more precisely that the memory search component, rather than some other reaction time component, related to retention and retrieval speed. Third, it is important to specify explicitly a processing model in examining information processing--learning outcome relationships. We examined the differences between difference score and part-correlation models, following Donaldson's (1983) analysis, and relied on these models for estimating component relationships.

Until fairly recently (e.g., Ackerman, Sternberg, & Glaser, 1989), there have been few attempts to link cognitive learning models with individual differences analysis approaches. We hope that some of the methodological suggestions put forward here, and some of the substantive findings that have emerged from this investigation, will assist in triggering a change in this state of affairs.

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APPENDIX A: PRODUCING INDIVIDUAL DIFFERENCES CURVES

The equation that produced the individual differences curves was the following (separately for each experiment):

$$E(Y_{ijk}) = B_0 (X_0) + B_1 (X_1) + B_2 (X_2) \qquad \text{(A1)}$$

where Y_{ijk} is the matrix of expected percent correct at each of the five exposure rates (i = [.5 1 2 4 8]) for subjects with various skill profiles at the jth verbal knowledge level (j = [0, -1, 1] standard deviations from the experiment sample's mean), and at the kth verbal processing speed level (k = [0, -1, 1] standard deviations from the mean), and X_0, X_1 and X_2 are the unit vector, and the vectors of the orthogonal linear and quadratic polynomial coefficients for the 5 study time conditions (X_0 = [1 1 1 1 1]; X_1 = [-2 -1 0 1 2]; X_2 = [2 -1 -2 -1 2]). The B coefficient vectors in equation A1 were defined as follows:

$$B_0 = b_{0jk} + b_{1jk} (MV + jSDV) + b_{2jk} (MR + kSDR) \qquad \text{(A2)}$$

$$B_1 = b_{0jk} + b_{1jk} (MV + jSDV) + b_{2jk} (MR + kSDR) \qquad \text{(A3)}$$

$$B_2 = b_{0jk} + b_{1jk} (MV + jSDV) + b_{2jk} (MR + kSDR) \qquad \text{(A4)}$$

where MV is the mean Verbal Knowledge score for the sample, SDV is the standard deviation of that score, MR is the mean LTM-SEARCH-TIME score, SDR is the standard deviation of that score, and j and k are defined above. In Experiment 1, for example, the following estimates of population means and standard deviations were obtained (percent correct is multiplied by 10; time in centiseconds): MV = 8.2079; Sk = .9660; MR = 14.2066; Ss = 2.7732. The parameters in equations A2-A4 were estimated from the full 5-covariate regression model.

APPENDIX B: STRATEGY-TREATMENT GROUP INSTRUCTIONS (EXPERIMENT 4)

Instructions given to the treatment group (Experiment 4) are as follows (indexed by screen frames, since they were administered by computer):

FRAME 1

In a few minutes you will work through a memorization test. But before we begin testing, we want to give you some helpful hints. In the test you will have to memorize word pairs such as: BOAT = TREE.

Here are four steps to follow in the learning process. Study these carefully!

FRAME 2

Example 1: NAIL = SOFA

Step 1: READ THE WORDS. As you read, meanings and associations should come to mind.

Step 2: CREATE A SHORT, INTERESTING SENTENCE that connects the two words. For this example, an interesting sentence is: "A huge NAIL pierced the SOFA." The more interesting the sentence, the better your memory will be.

Step 3: MAKE A "MENTAL PICTURE" of the sentence. The more bizarre your "mental picture" the better! In this example, you might try to picture a huge nail piercing the middle of a sofa! But keep in mind you must be fast in making your mental picture.

Step 4: REPEAT YOUR SENTENCE to yourself a few times before the next pair appears. OK, let's try this technique out on another pair of words.

FRAME 3

Example 2: BOTTLE = WINDOW

Step 1: READ THE WORDS.

Step 2: CREATE A SHORT, INTERESTING SENTENCE: "The BOTTLE crashed through the WINDOW."

Step 3: CREATE A MENTAL PICTURE. Think of a bottle crashing through a window with glass flying all around.

Step 4: REPEAT YOUR SENTENCE to yourself a few times before the next pair appears.

FRAME 4

Example 3: FREEDOM = WIND

Step 1: READ THE WORDS.

Step 2: CREATE A SHORT, INTERESTING SENTENCE: "The symbol of FREEDOM (the American flag) fluttered in the WIND."

Step 3: MAKE A MENTAL PICTURE. Think of the American flag fluttering in the wind.

Step 4: REPEAT YOUR SENTENCE A FEW TIMES.

In this example a fairly abstract concept, FREEDOM, was symbolized by the American flag.

FRAME 5

Just how easily you can apply this technique will depend on how much time you are allowed on each word pair. Don't be discouraged if at first you find this difficult. All skills require practice!