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ABSTRACT

Results are reported for a series of 13 studies examining individual differences in information processing efficiency. The tasks used represented different content domains and levels of processing complexity. A total of 680 individuals (balanced between males and females, and aged 18 to 25 years) were tested. Subjects were selected from individuals screened during 1983, 1984, and 1985. Measures of information processing speed showed various relationships to standardized ability measures. Measures of changes in processing speed and efficiency showed little relationship to each other and to standardized ability measures. The results are considered relative to issues of assessing an individual's current levels of information processing efficiency and movement toward more automatic or efficient processing levels. Assessment of the latter is problematic and may require complex tasks performed over intervals of time longer than 3 to 5 hours. Finally, standardized ability measures only partially reflect an individual's current levels of processing efficiency. Thirty-eight tables present study findings, and 47 figures illustrate relationships among measures and subjects. (Author/SLD)

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HUMAN RESOURCES

INDIVIDUAL DIFFERENCES IN SKILL ACQUISITION: INFORMATION PROCESSING EFFICIENCY AND THE DEVELOPMENT OF AUTOMATICITY

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Results are reported for a series of 13 studies examining individual differences in information processing efficiency. The tasks used represented different content domains and levels of processing complexity. Measures of information processing speed showed various relationships to standardized ability measures. Measures of changes in processing speed and efficiency showed little relationship to each other and/or standardized ability measures. The results are considered relative to issues of assessing (a) an individual's current levels of information processing efficiency, and (b) movement toward more automatic or efficient processing levels. Assessment of the latter is problematic and may require complex tasks performed over intervals of time longer than 2-5 hours. Finally, standardized ability measures only partially reflect an individual's current levels of processing efficiency.

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SUMMARY

This research was designed to address several issues regarding the assessment of cognitive skills. One goal was to determine if computer-based assessment procedures could be developed to reliably assess an individual's current levels of cognitive processing efficiency. A second goal was to determine if these procedures could also provide information about changes in processing efficiency with practice. A third goal was to determine if these measures of processing efficiency were related to standardized ability measures. To meet these goals, 13 studies were conducted using cognitive processing tasks varying in complexity and content domain. The results for individual tasks indicated that it is possible to reliably assess various components of cognitive processing efficiency within reasonable periods of time. While all tasks demonstrated practice effects, only the most complex tasks provided evidence of non-trivial changes in processing efficiency over practice. The assessment of movement toward more efficient modes of processing in the more complex tasks would require much more than the 2 hours of subject testing time used here. The measures of processing efficiency showed various relationships to standardized ability measures. While there were significant relationships, the magnitude was not so great that it could be concluded that standardized ability tests adequately reflect levels of processing efficiency. In addition, ability tests provide little or no indication of an individual's rate of performance change in any of the processing tasks. What remains to be determined, however, is if there is stability in performance changes across different tasks. Three considerations need to guide future studies in this area of measuring skill acquisition. First, tasks must be developed that have greater degrees of processing complexity so that significant skill acquisition can occur. Second, longer testing periods will be needed to assess performance changes in such tasks. Third, predictive validity studies using measures of processing efficiency and skill acquisition should include more than existing aptitude scores as criteria and should begin to include measures of performance obtained under controlled learning and instruction conditions.

PREFACE

This is a summary report of all work completed on Air Force Contract #F41689-83-C-0017. The work was conducted as part of the Learning Abilities Measurement Project's (LAMP) general investigation of individual differences in information processing and the role of speed of processing measures in predicting complex learning. Within the context of LAMP, this particular project was concerned with the measurement of individual differences in speed and efficiency of information processing over the course of practice on simple and complex cognitive tasks. Emphasis was on changes in information processing speed and efficiency, how such changes were related across tasks, and whether changes with practice were related to standardized measures of cognitive ability such as those obtained from the Armed Services Vocational Aptitude Battery (ASVAB). The current report is divided into seven sections. Section I provides a discussion of the background and general goals of the research and an overview of the logic of the studies. Section II provides detailed information about the reference ability battery administered to all subjects, subject samples, and analyses of reference test score patterns. Section III provides a description of each information processing task. This includes the logic of the task, materials, design, and total trial and session information. Section IV presents the results of analyses examining the internal validity of task performance; i.e., the extent to which the data conform to expectations regarding condition and practice effects within each task. Section V presents the results of analyses of individual differences in information processing parameters derived from each task, including correlations with reference ability scores. Section VI presents a similar analysis of individual differences in practice parameters derived from each task. Section VII is a summary and general discussion of the research and considers the implications relative to theory, practice and the original goals of this research project.

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I. INTRODUCTION AND OVERVIEW

There has been a recent resurgence of general interest in the topic of learning and skill acquisition. This trend partially represents an awareness of current theoretical and methodological expertise in the modeling of performance on simple and complex cognitive tasks, including many tasks found on aptitude batteries and in academic curricula. Examples include models for performance on inductive and deductive reasoning tasks (e.g., Goldman & Pellegrino, 1984; Rips, 1984; Sternberg, 1977) and spatial reasoning tasks (e.g., Cooper, 1980, 1982; Egan, 1979; Pellegrino & Kail, 1982). Explicit process models for latency and accuracy data are validated in laboratory studies and then applied to the analysis of individual differences in reference ability measures. The analysis of individual differences is based upon estimates of the speed and accuracy of executing specific cognitive processes that are components of overall task performance. Modeling of this type provides a way of examining the current characteristics of the individual with regard to specific information processing skills. Research of this type shows that individuals varying in aptitude (e.g., verbal or spatial aptitude) also vary systematically in the speed and efficiency of executing various elementary processes such as encoding, comparison, visual transformation, semantic inference and fact retrieval. Individual differences in process execution are correlated with individual differences in global and specific psychometric aptitudes. Unfortunately, little effort has gone into examining changes in process execution as a function of repeated practice. While a low or medium aptitude individual may be less efficient in executing one or more cognitive processes, no evidence has been gathered to indicate that such an individual cannot achieve a high level of efficiency and automaticity given reasonable amounts of practice. From an assessment perspective, it would be extremely valuable to know whether initial differences in processing efficiency are maintained over practice or whether there are differential skill acquisition functions that are partially independent of initial aptitude and process efficiency differences.

Attempts have also been made to model performance at different levels of expertise or skill as a skeletal structure for exploring issues about the acquisition of expertise. Such issues include the nature of the transition process and conditions that foster the acquisition of competence. Research of this type typically contrasts individuals of varying levels of expertise. Thus, it tends to be cross-sectional rather than longitudinal, with a resultant inability to map out precisely the nature of the acquisition or practice function. Another difficulty of such research is the inability to ascertain which individuals at low levels of expertise are likely to show significant acquisition functions leading to the development of expertise. While longitudinal research is costly in complex domains where there is a large substantive body of knowledge to be acquired, it is possible to conduct smaller scale studies that ask similar questions about the acquisition of a specific information processing skill. Unfortunately, little research has been conducted on the effects of practice on basic information processing abilities.

Current research on learning and skill acquisition represents a return to questions about the effects of overlearning and extended practice on human performance and retention. As an example, Newell and Rosenbloom (1981) have reported an extensive re-analysis of data on the effects of practice on performance. Their particular emphasis was the mathematical functions representing the relationship between performance and practice. They argued that the class of functions most consistent with a wide range of practice data are also consistent with information processing theories of human performance.

Within the field of information processing, a number of ideas have been offered to account for the macro and micro changes that occur with practice. Anderson (1982) has advanced the idea that knowledge for task execution initially is represented in declarative form, followed by procedural representation in the form of productions. The individual productions necessary for task execution can undergo two types of change with additional practice. First, they become strengthened with repeated execution, thereby reducing the amount of time needed before activation, selection and execution. Second, a set of productions (production system) may be combined into a single complex production with a concomitant increase in speed and efficiency of task execution. This type of production composition is similar to an abbreviation notion advanced by Van Parreren (1978) in which a series of discrete steps is combined representing the gradual elimination of points of conscious control.

Both the strengthening of individual productions and production composition with subsequent strengthening are consistent with the general concept of automaticity that has been discussed extensively, particularly in the area of reading. The general assumption is that specific skills can reach a level of proficiency after extended practice where their execution is rapid and accurate with little or no conscious monitoring. A presumed consequence of this is that processing moves from a state where demands are made on a limited attentional resource pool to a state where no demands are made on attentional resources, thereby freeing up capacity for other tasks (processes) including higher level executive or control functions. A good example of this argument is in the area of reading where it has been argued that comprehension and inference processes cannot be manifest when lower level decoding and word recognition skills are poorly developed, as in beginning readers (e.g., Lesgold & Perfetti, 1981).

A number of issues have arisen in the attempt to study the demands that a particular task (process) makes upon the limited capacity resource pool. A general paradigm for exploring such questions employs primary and secondary tasks where changes in performance on the secondary task (e.g., target detection) are used to index changes in the resource demands of the primary task with practice and stimulus conditions. While the logic of the dual task paradigm is appealing, a number of problems and issues have arisen regarding its effectiveness (see e.g., Hunt & Lansman, 1982). One issue concerns the nature of the relationship between the two tasks (i.e., whether they share common structural components), and another is whether performance in either or both tasks represents a data limited or resource limited process (Norman & Bobrow, 1975). An alternative approach to examining the issue of automaticity is to focus on measures of the speed and accuracy of process or task execution. When the index of automaticity is latency or speed, there is a tendency to focus on changes or differences in the mean. However, an equally useful measure to examine is variance about the mean. When a process is automated, the successive executions of that process should be relatively stable. This will frequently be reflected in the mean but is more obvious when variance over multiple executions is examined. A process that has not achieved a state of automaticity is likely to show a wide range of execution values depending on the amount of resources available for monitoring or controlling process execution at a given point in time.

Schneider and Shiffrin (1977) have also distinguished between co-existing processes that are automatic versus controlled. The latter require monitoring, draw upon the attentional resource pool and never achieve automaticity even after extended practice. Thus, components of the same task may show different acquisition functions, with certain components achieving automaticity while others do not. Attempts have been made to distinguish in simple cognitive tasks those components that can and do achieve a state of automaticity. It appears that one factor affecting the development of automaticity is the consistency of stimulus-response mapping within and across tasks. In decision, search and reaction-time tasks, consistent mappings lead to automaticity as evidenced by declines in process execution latency and evidence of parallel processing. Varied mapping conditions do not lead to states of automaticity as previously defined (Fisk & Schneider, 1982).

A final issue that has been identified is whether there is a single or common pool of available processing resources. One conception of attentional resources is an undifferentiated single resource pool; i.e., all tasks and modalities of information processing draw upon this same resource. An alternative conceptualization involves multiple resource pools associated with different modalities and/or stimulus types, with each having a limited capacity (Wickens, 1980).

The issues and theoretical context outlined above provide a background for the present program of research. The present research concentrated on individual differences in process execution and efficiency in comparison, search and decision tasks sharing a common structure that could be employed with different classes of stimuli--verbal, numerical and geometric (figural) input. To a large extent, these tasks were modeled after or related to tasks that exist on current aptitude batteries measuring specific verbal, numerical and spatial/perceptual abilities. There are two major reasons for adopting this approach to task selection and design. First, the tasks found on ability batteries tap various basic information processing skills and they are known to reliably differentiate among individuals with respect to current cognitive abilities. Thus, they may be construed as assessments of the current state of information processing components. A question then is whether these assessments are predictive of quantitative and qualitative differences in the acquisition of skill as a function of extended practice. For example, individuals who rank low on perceptual speed or spatial relations tasks may show general acquisition functions that differ from high ability individuals in either the general form of the practice-performance function or the parameters of such functions, or both. At a more precise level, specific component processes that achieve automaticity may be differentially associated with initial aptitude levels and individual difference characteristics. The second reason for focusing on information processing tasks closely tied to aptitude test tasks is that refined performance models exist for a variety of the tasks found on such batteries. Thus, it was possible to examine in detail differences in the execution of specific processes as a function of both level of practice and initial aptitude level.

The research described in this report includes 13 studies designed to examine individual differences in information processing efficiency. The overall goal was to determine if computer-based assessment procedures could be developed to accomplish two things. The first was reliable assessment of an individual's current levels of information processing efficiency. The second was assessment of changes in information processing efficiency, or what might be termed movement towards automaticity.

To accomplish these goals, several theoretical, empirical and pragmatic issues were considered. At the theoretical level, there was the question of what constitutes efficient or automated performance. In the current literature, this is defined as forms of proceduralization involving stable execution routines or production systems (e.g., Anderson, 1982). Empirical evidence of such proceduralization is rapid and accurate performance with minimal variance in execution time over trials. This can be translated into asymptotic or near-asymptotic levels of performance on a practice function. Other evidence of efficient and automated performance is the presence of minimal demands on attentional resources as demonstrated in dual task situations.

From an empirical standpoint, there are questions about methods for reliably assessing an individual's current level of efficiency in executing a task or specific subprocesses of a task. While it is often possible to develop models for task performance and show that such models provide a good account of group performance, it is often difficult to achieve the same degree of accountability for the performance of individuals. For example, models fit to group performance often have superior levels of goodness of fit but considerably poorer fits for individual subjects. In fact, many subjects' data often fail to be fit by the overall model or alternative models. This last problem is frequently due to the amount of data one needs to obtain from an individual to achieve reliable model fits and parameter estimates. In studies of information processing efficiency, it may take several hundred trials to reliably estimate performance parameters for individuals. This raises a pragmatic issue about the amount of time to be invested in examining the performance of any person and the benefits from a predictive or diagnostic testing standpoint. One additional issue was whether it is possible to assess, in a reasonable time period, a person's capacity to move towards more efficient or automated performance. Related to this is the question of whether this is a general or situation-specific capacity and whether such a capacity is assessed by current aptitude tests.

The preceding are some important issues that we have tried to address in this program of research. In the remainder of this report, we discuss the results of 13 studies of individual differences in information processing efficiency. Our approach in these studies was relatively straightforward. In 13 different tasks, representing three different domains of information processing, we attempted to assess the speed with which individuals executed specific cognitive processes. The measures of information processing speed can be considered indices of a person's current level of efficiency or automaticity. The question of interest is whether (and how) these speed indices relate to scores from a standard reference ability battery. In each task we also attempted to assess changes in performance as a function of practice. The question was whether parameters of these practice functions were related to standard reference ability scores and also whether they were related to each other.

We began by administering a battery of aptitude tests designed to assess several cognitive abilities. The reference battery contained 10 tests distributed over several factors. The specific factors were perceptual-spatial ability, verbal ability, quantitative ability and inductive reasoning ability. This test battery was administered to a large number of young adults who ranged in age from 18 to 25. From this pool of examinees, we selected separate samples of individuals representing all levels of ability across the different factors. Section II, which immediately follows, provides a detailed treatment of the reference ability battery and the subject samples.

The individuals selected for each sample were then tested on two to three cognitive tasks presented on microcomputers. The tasks represented two or three domains of information processing--perceptual, verbal and quantitative. In an absolute sense, each cognitive task was relatively simple, although they varied among themselves in complexity. Complete task descriptions are contained in Section III. Within each task, there was a systematic problem set that permitted the testing of a process model for task performance with the simultaneous estimation of various processing parameters. The individuals were given multiple sessions of testing on each task before performing a new task. The multiple sessions permitted the assessment of practice effects within each task. In Section IV, we consider issues of internal validation of the performance model for each task. In Section V, we then consider application of the process model to individual subject data and correlations of process measures with reference ability scores. In Section VI, results are presented for individual subject practice effects within each task and correlations of practice parameters with reference ability scores.

II. REFERENCE ABILITY TESTING AND SUBJECT SELECTION

A battery of 10 tests was selected to provide scores reflecting four facets of human ability: verbal, quantitative, perceptual speed/spatial and inductive reasoning. The tests were administered in a single 2-hour testing session. A 10-minute break was allowed approximately halfway through the test battery. From 25 to 60 subjects were tested at a time. The tests were duplicated and compiled into a single booklet. All responses were made in the booklet. The following is a description of each of the tests included in the battery. They are presented in the order of administration.

Test Descriptions

Identical Pictures (IP; Ekstrom, French, & Harman, 1976): There are 96 items in a five-alternative forced-choice format. The test is administered in two 1.5-minute halves. The items are relatively simple line drawings and the task is to find the one alternative that matches the standard. This test helps define the perceptual speed factor (PS; Thurstone, 1938) or clerical-perceptual speed (CPS; Cattell, 1971) and is mildly correlated with simple spatial tests.

Comprehensive Ability Battery Perceptual subtest (CABP; Hakstian & Cattell, 1976): There are 72 pairs of letter or number strings which either match or mismatch. The string lengths vary from 7 to 9 alphanumerics; the letters are presented in both upper- and lowercase. Four and one-half minutes are allowed for the test. This test also helps define the perceptual speed factor.

Primary Mental Abilities Space subtest (PMA; Thurstone, 1962): There are 30 standards, each with five alternatives. The figures are simple asymmetric line drawings. All five alternatives must be evaluated to determine if they are simply rotated in the picture plane and thus match, or are rotated and mirror-reflected and thus mismatch. This is a relatively simple spatial ability test and helps define the Spatial Relations subfactor (Lohman, 1979).

Advanced Vocabulary Test I (VOC4; Ekstrom, et al., 1976): The test consists of 36 five-alternative vocabulary items. The alternative that is the closest synonym is correct. The test is divided into two 18-item halves; 4 minutes are allowed for each half. This test, as all vocabulary tests, helps define verbal ability (v:ed from Vernon, 1961; Gc from Cattell, 1971; V from Thurstone, 1938).

Advanced Vocabulary Test II (VOC5; Ekstrom, et al., 1976): This is a four-alternative variant of VOC4. There are 18 vocabulary items on each of two halves of the test. Four minutes are allowed for each half. This test also helps define verbal ability.

Cognitive Abilities Test, Verbal Analogies subtest (VA, level H; Thorndike & Hagen, 1971): The test consists of 25 five-alternative verbal analogy items presented, A : B :: C : D1 D2 D3 D4 D5. The rule relating the A and B terms must be used to select the correct alternative such that the resulting C, D pair parallels the A,B stem as closely as possible. Eight minutes are allowed for the test. This test helps define verbal intelligence (as above), an induction factor (I, Thurstone, 1938; Bennett, Seashore, & Wesman, 1974) or general intelligence, depending upon the other tests in the battery.

Cognitive Abilities Test, Figural Classification (FC, level H; Thorndike & Hagen, 1971): There are 25 five-alternative figural classification items which must be solved in 12 minutes. Each item consists of a stem containing three figural/geometric terms and five similar alternatives. The one alternative that best matches properties of the stem must be selected. This test also helps define an induction factor, general intelligence or fluid intelligence (Gf, Cattell, 1971) and may load somewhat on a spatial factor.

Cognitive Abilities Test, Figural Analogies (FA, level H; Thorndike & Hagen, 1971): There are 25 five-alternative items which must be completed in 10 minutes. The stimuli are geometric/figural as used in the FC test but the item structure and solution requirements are similar to those of the VA test. This test also helps define the induction factor, is a marker for Cattell's Gf and general intelligence but may also share some variance with a spatial factor.

Cognitive Abilities Test, Quantitative Relations (QR, level H; Thorndike & Hagen, 1971): There are 25 items presented for a total of 10 minutes. Each item consists of two similar halves. Each problem half (A and B) contains a set of information which must be used to compute a singular value; the values from the two halves must be compared to determine if A is greater than, less than or equal to B. Thus each item has three alternatives. A knowledge of relatively simple arithmetic, algebraic and geometric rules is required to derive the value for each half of the problem. This test may help define a quantitative reasoning or general reasoning factor.

Cognitive Abilities Test, Equation Building (EB, level H; Thorndike & Hagen, 1971): Twelve minutes are allocated to solve the 15 five-alternative problems in this subtest. Each problem stem consists of a string of 3 or 4 numbers (integer or fraction) followed by 2 to 4 arithmetic operators (add, subtract, multiply, divide, square root) and sometimes a set of parentheses. The operators or operators and parentheses must be combined in various ways to produce a unique value that matches (only) one of the five alternatives. A complete knowledge of the rules for executing the order of arithmetic operations is necessary. This test may also help define a quantitative factor or a general reasoning factor.

Subject Selection

Potential subjects were tested just prior to the beginning of data collection on the experimental tasks. A total of 680 individuals were tested. From the group of individuals available for experimental testing, groups of 24 to 64 subjects were selected. These subjects were selected from individuals screened at various times during 1983, 1984 and 1985. Subject selection was not rigid but followed several guidelines. First, a balance of males and females was included in each group. Second, subject age was constrained to be between 18 and 25. Third, an attempt was made to select subjects with a balance of ability profiles on the four groups of tests. This was accomplished by assigning subjects a rating of High, Medium or Low on the verbal, quantitative, spatial/perceptual and reasoning test groups. Using these profile scores, approximately equal numbers of subjects were selected from each level. This selection was further constrained to ensure a reasonable mixture of subjects that had a consistent level of performance across the test categories and those with a mixture of high, medium and low performances.

Test Battery Results

Simple distributional characteristics for the entire sample of 680 subjects on each of the tests are presented in Table 1. The means and standard deviations for the tests show no evidence of either ceiling or floor effects. Although not reported, the higher order product moments for each of the tests were evaluated for evidence of distributional abnormality and none was found. The means and standard deviations for these tests are reported in Table 1 separately for the five samples that participated in the experimental testing sessions. A visual inspection of these values shows that the five samples were comparable among themselves and are quite similar to the larger total sample. Of particular concern is whether our sample of individuals is representative of the population at large since it is highly likely that sampling individuals within a university community will lead to above-average scores. This could unduly restrict the range of abilities represented in the sample, thereby affecting subsequent correlational analyses using the reference ability test score data. We, therefore, attempted to determine how

Table 1. Summary Statistics on Reference Test Scores by Subject Samples

	All subjects N = 680		Sample 1 N = 60		Sample 2 N = 63	
Test	Mean	SD	Mean	SD	Mean	SD
IP	79.39	12.01	82.12	11.22	74.11	14.87
CABP	60.09	9.16	60.62	8.72	58.95	8.86
PMA	45.99	13.15	46.23	12.41	47.51	12.15
VOC4	16.28	6.14	16.23	6.03	15.50	4.93
VOC5	15.76	6.66	16.05	6.13	14.66	5.85
VA	18.05	3.50	18.45	3.22	18.28	3.32
FC	18.55	3.81	18.85	4.08	18.97	3.46
FA	18.26	3.05	18.23	3.21	18.49	2.93
QR	20.72	3.66	21.68	2.90	21.35	3.13
EB	10.63	2.91	10.83	3.22	10.97	2.87

	Sample 3 N = 64		Sample 4 N = 24		Sample 5 N = 43	
IP	78.52	12.80	79.75	9.35	78.46	11.91
CABP	60.69	8.95	58.75	8.78	56.60	11.02
PMA	49.22	12.35	49.79	12.57	44.02	13.77
VOC4	20.63	6.87	17.22	4.97	19.32	6.68
VOC5	20.29	6.89	17.60	5.84	19.19	7.93
VA	19.06	3.28	18.75	2.66	19.09	3.85
FC	19.42	3.63	19.46	3.04	19.14	3.32
FA	18.97	2.87	18.58	2.45	18.53	2.81
QR	21.36	4.07	21.38	4.11	21.12	3.37
EB	10.86	3.09	10.63	3.02	10.72	2.90

our mean values related to published normative data for the various reference tests in our battery. The statistics available from the test publishers were not uniformly presented nor was it always possible to find data for a comparable or roughly comparable age sample (e.g., grade 12 or above). It was possible, however, to ascertain whether our mean score for each test was above or below the seventy-fifth percentile score for normative data. For all tests except the IP, CABP, and PMA, our mean value was at or below the seventy-fifth percentile score. For the other three tests, all of which represent perceptual speed and spatial ability, our mean value was substantially higher than the seventy-fifth percentile. Nevertheless, our sample of subjects still had substantial variability in performance on these three tests and the standard deviations were largest for just these tests. Thus, our test score results indicate that the range of ability in our sample of subjects was more than sufficient to test hypotheses regarding ability relationships with information processing performance measures.

The intercorrelation matrix of the 10 tests is presented in Table 2. The correlations are based on the entire sample of 680 subjects. Although the tests were selected to provide an index of a subject's ability in several categories, this was an a priori selection. To determine the actual underlying ability dimensions assessed by this battery, in this sample, the correlation matrix was subjected to factor analysis.

Table 2. Reference Test Intercorrelation Matrix

	IP	CABP	PMA	VOC4	VOC5	VA	FC	FA	QR
CABP	.321								
PMA	.269	.194							
VOC4	.002	-.037	.102						
VOC5	.026	-.053	.097	.819					
VA	.108	.001	.256	.509	.532				
FC	.096	.066	.360	.233	.224	.402			
FA	.180	.192	.458	.198	.182	.331	.458		
QR	.094	.174	.406	.218	.221	.345	.414	.443	
EB	.043	.129	.309	.147	.139	.199	.348	.377	.511

As a first approximation to discovering the underlying latent structure of the tests, the correlations were submitted to a Principal Components analysis. Using the unit eigenvalue criterion, three factors were retained and rotated to a Varimax solution. The eigenvalues for the three factors were 3.39, 1.80 and 1.16. The three factors accounted for a total of 64% (N = 680) (.26, .24, and .14) of the diagonal variance. The rotated factor pattern is shown in Table 3. The first factor appears to represent a general ability factor but perhaps is better characterized as Cattell's Gf because of the mixture of non-verbal reasoning loadings (FA, FC, QR and EB). The second factor is clearly verbal ability, defined by VOC4, VOC5 and VA, and in Cattell's theory this would be Gc. The final factor is best defined by the two perceptual speed tests (IP and CABP) but it is also reasonably saturated by the PMA space test. The FA test shows a moderate loading just under .25. This appears to be the expected perceptual speed/spatial factor. This factor is not clear relative to others reported in the literature because we lack more spatial ability tests including those less speeded and of greater difficulty.

Table 3. Varimax Rotated Factor Pattern

Test	Gf	Gc	PS/Spatial	Communality
IP	*	*	.887	.707
CABP	*	*	.773	.565
PMA	.621	*	.363	.520
VOC4	*	.910	*	.838
VOC5	*	.922	*	.857
VA	.348	.695	*	.608
FC	.680	*	*	.518
FA	.704	*	*	.568
QR	.765	*	*	.613
EB	.744	*	*	.558

*Indicates loadings below .25.

Following this preliminary analysis, a maximum likelihood solution for three factors was obtained. Squared multiple correlations were used as initial communality estimates and the factor axes were obliquely rotated. The solution proved to be substantially the same as from the Principal Components analysis, with the same tests defining the same factors. One interesting difference between the two solutions is that the spatial and general (or Gf) factors are correlated .35, which is evidenced by the higher 1st factor loading of the spatial tests. The verbal factor is uncorrelated with the other two.

A final maximum likelihood factor analysis was performed extracting four factors and rotating them to an oblique solution. The verbal factor (VA, VOC4, VOC5) remained intact. The new factor which emerged was a clear general factor loading all of the tests. The perceptual speed/spatial and Gf-like factors remained, with some alterations in their loadings. However, the perceptual speed/spatial factor was correlated .36 with the general factor and the general and Gf-like factor were correlated .71.

In some regards, this provides the best description of the data. The four-factor solution accounts for 72% of the raw, unweighted variance, 8% more than the three-factor solution. A Chi-square test of the null hypothesis of four common factors being sufficient could not be rejected (Chi-square (11) = 14.33, p = .215) while the three-factor null could be. However, this description of the data costs parsimony by adding an additional model parameter and substantial factor intercorrelations. Furthermore, extraction of a broad general factor does not clarify the description of the other factors. In our estimate, the preferred solution is the three-factor Principal Components solution with Varimax rotated axes shown in Table 3. This solution was used in deriving factor scores for all subsequent individual differences correlations.

III. DESCRIPTION OF INFORMATION PROCESSING TASKS

The 13 information processing tasks that were administered to subjects represented five task batteries. Task Battery I was administered to subject sample 1, Task Battery II was administered to subject sample 2, Task Battery III was administered to subject sample 3, Task Battery IV was administered to subject sample 4, and Task Battery V was administered to subject sample 5. All tasks were presented on Terak 8510b graphics computer systems.

The task batteries differ not only in the types of tasks presented but also goals of the testing. As we progressed on this project, it became apparent that more complex tasks were needed to assess changes in performance with practice. Similarly, it became apparent that as task complexity increased, there was a need to examine more sessions of practice. These changes in task characteristics are reflected in the composition of each task battery. In Task Battery I, we have three very simple tasks, all of which represent simple judgment tasks with highly familiar content. In Task Battery II, the three tasks represent the introduction of unfamiliar content and/or more complicated processing in the form of multiple search and comparison tasks. In Task Battery III, the search tasks become further complicated with the introduction of multiple target searches. A mental rotation task is also introduced with stimuli of varying presentation frequency. In Task Battery IV, we continue to use the complex search tasks but extended the amount of practice to further explore changes with practice. Finally, in Task Battery V, we use the one complicated search task that showed substantial practice effects, and introduce a variant of a complex perceptual matching task but with variations in item composition to examine how problem context affects performance and transfer.

Task Battery I

Perceptual Matching I. Each trial of this task consisted of the simultaneous presentation of a pair of matrices containing 3, 5, 7, or 9 alphanumerics. The task was to determine if the pair was the same or different. The matrix pairs varied in terms of the degree of difference, with either 0, 1, 2, or all of the elements mismatched. A session consisted of the presentation of 96 matrix pairs with 48 positive and 48 negative matches. The intertrial interval was 2 seconds. Each subject received 8 sessions on this task for a total of 768 trials.

The materials were designed such that both upper- and lowercase letters and numbers were used with equal frequency. The 48 positive trials (0 mismatch) represented 12 instances of each matrix size. The 48 negative trials represented 4 instances of each matrix size and mismatch condition (1, 2 or all). There were four different random orders of the material set and each random order was constructed such that each successive set of 24 trials represented a full replication of the within-subjects design.

Our assumptions about processing in this task were that time to respond same or different should be a systematic function of problem characteristics. In the case of same judgments, latency should linearly increase with matrix size. The slope of the function relating overall reaction time to matrix size reflects the time for a single encoding and comparison cycle, while the intercept reflects choice and motor response processes. In the case of different judgments, latency should also be a systematic function of the number of elements processed prior to finding a mismatch. The slope of this function should be identical to that for same judgments given adjustments for self-terminating process execution when differences were detected. For both same and different judgments, process components and average reaction time should decrease with practice.

Attribute Comparison. Each trial in this task consisted of the presentation of a pair of words preceded by a matching criterion. Four pair types were used: Physical Identity (dog-dog), Name Identity (DOG-dog), Category Identity (DOG-cat), and Mismatch (DOG-table). The criteria for judging same or different were Physically Same, Name Same, or Category Same. The task was to determine if the pair of words met the matching criterion and respond true or false. A session consisted of 180 individual trials representing 60 trials for each matching condition with 15 instances for each pair type within matching condition. The intertrial interval was 2 seconds. Each subject received 6 sessions representing a total of 1080 trials.

The materials consisted of 180 separate item pairs, representing 45 unique physically identical pairs, 45 unique name identical pairs, 45 unique category identical pairs and 45 unique mismatch pairs. Extensive counterbalancing was done with respect to word appearance on the left and right and the use of upper- and lowercase lettering. Each of the 180 pairs appeared under the three different matching instructions. The pairs were constructed from 45 high frequency words representing 5 high frequency instances from each of nine semantic categories.

Our assumptions about processing in this task were that latency would be a systematic function of both pair type and matching criterion. Physical identity judgments should be faster than name identity judgments, which in turn should be faster than category identity judgments (e.g., Posner, Boies, Eichelman, & Taylor, 1969). Furthermore, if subjects are performing in a highly efficient manner with respect to attribute processing, then physical identity pairs should be responded to rapidly in all conditions. Similarly, name identity pairs should be responded to with equal latency in both the name and category judgment conditions. Finally, overall latency and specific components of processing should systematically decrease over sessions.

Fact Retrieval. This task actually consisted of four subtasks. The four subtasks represented each of four fact types: addition, subtraction, multiplication and division. Each trial consisted of the presentation of a true or false mathematical fact such as 6 x 8 = 54 which was to be judged relative to truth value. For each fact type a session consisted of 128 or 144 items, half true and half false. The intertrial interval was 2 seconds. An individual was tested for four sessions on each fact type before shifting to a new fact type and the sequence of fact types was counterbalanced over subjects. Thus, each subject was tested on 512 to 576 problems in each fact area.

In each fact area, the problems were selected such that they systematically varied in terms of the sum, difference, product or quotient. The problems in each set were based on the numbers 1 to 12. The sums for addition ranged from 3 to 23, the differences for subtraction ranged from 1 to 11, the products for multiplication ranged from 2 to 132, and the quotients for division ranged from 1 to 12. False items also varied in terms of the magnitude of the difference between the presented and correct alternative. We expected problem verification latency to vary as a function of problem characteristics; e.g., in true addition problems reaction time should be a linear function of sum or sum squared (Ashcraft, 1982). The slope of this function reflects retrieval speed and efficiency while the intercept reflects choice and motor response processes. Finally, average response latency in each fact retrieval task should decrease with practice although the size of the practice effect may be small.

Task Battery II

Perceptual Matching II. On each trial of this task, a pair of random polygons was presented and the subject was to decide if they were the same or different. The materials were drawn from research conducted by Cooper (1980) on individual differences in visual comparison. The polygons varied in complexity as determined by number of points (6, 8, 12, 16 or 24). Each of the five referent stimuli was paired with itself or one of six mismatches (D1-D6) which varied with respect to degree of dissimilarity, with D1 being most similar to the standard and D6 being most dissimilar. Each session consisted of 120 trials, 60 same judgments and 60 different judgments. The 60 same judgment trials involved 12 presentations of each polygon representing one of the five complexity levels. The 60 different judgment trials involved two presentations of each unique pair that occurs when a polygon at one of the five complexity levels is then paired with one of its six possible mismatches (D1-D6). The intertrial interval was 2 seconds, and subjects were tested for 8 sessions for a total of 960 trials.

Our expectations about processing in this task were that reaction time should be a linear function of stimulus complexity. The slope of this function reflects the efficiency of feature processing, with a shallow slope indicating highly efficient processing. The intercept reflects choice and motor response processes. We also expected that reaction time on different judgment trials would also be a linear function of degree of dissimilarity. The slope of this function reflects the efficiency of difference detection, with a flat or shallow slope indicating wholistic processing. The intercept again reflects choice and motor response processes. For both same and different judgments, average latency should decrease with practice.

Visual Search I. In this task, a trial consisted of the presentation of a target graphic symbol followed by a diagonal (top left to bottom right) array of 15 graphic symbols. The subject was to search through the array for the target and make one response if it was present and another response if it was absent. The target systematically varied over trials as did its position and presence in the display. A session consisted of 128 trials, 8 trials for each target position (1-15 and not present). The intertrial interval was 2 seconds. Subjects were tested for four sessions for a total of 512 trials.

The materials used for this task involved a restricted set of unfamiliar graphic symbols, each of which was used equally often as a target and a distractor with equal distribution over the different possible positions in the search array. Thus, the design and balancing of materials created a varied mapping condition in which a particular graphic symbol was sometimes seen and responded to as a target while at other times it was seen and responded to as a distractor.

Reaction time in this task should be a linear function of the position of the target stimulus in the search array (e.g., Neisser, 1963). The slope of this function is an index of the speed of encoding and comparison processes while the intercept reflects choice and motor response processes. Components of processing and average reaction time were expected to decrease over sessions.

Semantic Search I. A trial in this task involved the presentation of a positive or negative category name followed by a diagonal array of six words. The subject's task was to search through the array for an item that matched the category name and make one response if one was present and another if absent. In the case of the positive category names (member search), the subject might see "Animal" and then search for an instance of that category. The position and presence of the target item varied over trials. In the case of the negative category names (non-member search), the subject might see "Not Animal" and then search for an item that met the criterion. The design and materials for this study were identical to Gitomer, Pellegrino, and Bisanz (1983). A session consisted of 84 trials representing an equal number of member and non-member searches with targets equally distributed over the 7 positions (1-6 and not present). The intertrial interval was 2 seconds. The subject was tested for 10 sessions representing a total of 840 total trials.

In both the member and non-member searches, reaction time should be a linear function of target position. The slope of this function represents encoding, semantic retrieval and comparison times while the intercept reflects choice and motor response processes. Slopes for the member and non-member searches should be identical while the intercept for the non-member search should be higher than the intercept for member search reflecting additional time for negative final decisions (see e.g., Gitomer, et al., 1983). Components of processing and average reaction time should decrease over sessions for both the member and non-member searches.

Task Battery III

Visual Search II. This task was similar to Visual Search I with two changes. First, the search array contained 10 rather than 15 graphic symbols. Second, two types of search trials were used: search for a single target versus search for two targets. In the latter case, the trial began with the presentation of two graphic symbols. The array was then presented and the subject was to respond when either of the two symbols was found. In actuality, only one of the two targets was in the array on target-present trials. Subjects received 132 trials per session, half on single-target trials and half on two-target trials, with targets equally distributed over array positions (1-10 and not present). The intertrial interval was 2 seconds. Four sessions of this task were administered for a total of 528 trials.

The materials for this task were identical to those used for the Visual Search I task, as was the counterbalancing of materials over target and distractor conditions and search positions. Thus, the procedures again created a situation of variable mapping in which a particular graphic symbol was responded to both positively and negatively over trials of the experiment.

Reaction time in this task should be a linear function of the position of the target. The slope of the one-target search should be less than the slope of the two-target search. This difference reflects a serial mode of target processing and comparison. With practice, differences in slopes and overall mean reaction times should be reduced for the two versus one target conditions.

Semantic Search II. This task is the same as the the member search condition of Semantic Search I. The major difference is that trials vary in the number of target categories to be considered, either 1, 2 or 4. A session consisted of 126 trials distributed equally over the 1-, 2- and 4-target search conditions with an equal frequency of target occurrence over array positions (1-6 and not present). The intertrial interval was 2 seconds. Subjects were tested for 4 sessions on this task and a total of 504 trials.

The materials for this task consisted of the items used for the member search condition of Semantic Search I. All items came from seven semantic categories and within each category there was a division of individual words with respect to mapping onto the category of target versus distractor. For half of the words selected from a given semantic category, whenever these words appeared in the search list they were fulfilling the role of a target. Thus, when they were seen, they always elicited a positive response. For the other half of the words selected within a given semantic category, whenever they appeared in the search list they were fulfilling the role of distractor. Thus, when they were seen, they always elicited a negative or rejection response since they were passed over as being non-members of the target category specified on a given trial. This division of materials within category produces a constant mapping condition which is in contrast to the varied mapping conditions employed for materials in the visual search tasks. Individual items were balanced in terms of frequency of appearance and array position.

As in Semantic Search I, it is expected that reaction time in each condition should be a linear function of the position of the target. The slope of the linear function for the 4-target search should be greater than the slope for 2-target search, which in turn should be greater than the slope for 1-target search. Differences in slopes and average reaction times should be reduced over sessions for the different search conditions.

Mental Rotation. The design and conduct of this study was substantially different from the eight preceding studies. Subjects were first given an additional pretest battery consisting of two spatial relations tasks (CRT,CABS), and two spatial visualization tasks (DAT,SD). Subjects were then tested on seven sessions of mental rotation followed by a posttest spatial ability battery (which was identical to the pretest battery). Each trial consisted of the presentation of a pair of polygons that were either the same or different. On same judgment trials, the polygons varied in orientation (0 to 180 degrees in 20-degree increments). On different judgment trials, the stimuli were mirror image reflections that varied in orientation (0 to 180 degrees). The subject's task was to determine if the pair were the same or different if rotated in the picture plane. Four stimulus sets (A,B,C,D) were created for this task and four stimulus presentation conditions (X,Y,W,Z) were used. To avoid possible item effects, the stimulus sets were rotated through presentation conditions across subjects. For a given subject, the stimulus set serving in condition X was administered in all seven sessions; condition Y was administered in sessions one, two, and seven; condition W was administered in sessions three, four, and seven; and condition Z was administered in sessions five, six, and seven. Each stimulus set consisted of 140 items (7 figures x 10 rotation values x 2 match conditions). Two randomly mixed stimulus sets were presented on each of the first six sessions (280 trials/session) and all four stimulus sets were presented in the seventh session (560 trials). The intertrial interval was 2 seconds.

As subjects become increasingly practiced at mental rotation, we are able to compare stimulus sets with varying degrees of familiarity. Sessions three and five provide key comparisons of interest, since subjects were well practiced at the task and highly familiar with X stimuli but unfamiliar with the other stimulus set presented during that session. In this way we can separate effects of increased proficiency in mental rotation from effects of stimulus familiarity.

In this task we expect reaction time to be a linear function of angular disparity for the pair of stimuli. The slope of this function represents the speed of mental rotation processes while the intercept reflects encoding, comparison and motor response processes (Pellegrino & Kail, 1982). As indicated above, the design permits a detailed analysis of changes in these processes with practice, particularly as a function of stimulus familiarity at different stages of practice.

Task Battery IV

The two tasks in this battery are identical in form and content to two tasks in Battery III. The major difference was the extension of these tasks with respect to total sessions of testing.

Visual Search III. This task was identical to Visual Search II. On each trial the subject searched through an array of 10 graphics symbols to find a target. Two types of search trials were again used, search for a single target or search for one of two targets. Subjects received 132 trials per session, half on single-target trials and half on two-target trials, with targets equally distributed over array positions (1-10 and not present). Ten sessions of this task were administered for a total of 1320 trials.

Expectations regarding reaction time patterns and practice effects were the same as described previously for Visual Search II.

Semantic Search III. This task was identical to Semantic Search II. On each trial the subject searched through an array of 6 words to find a target. Three types of search trials were used representing 1, 2 or 4 categories to be considered in locating a target. A session consisted of 126 trials distributed equally over the 1-, 2- and 4-target search conditions with an equal frequency of target occurrence over array positions (1-6 and not present). Subjects were tested for 10 sessions representing a total of 1260 trials.

Expectations regarding reaction time patterns and practice effects were identical to those described for Semantic Search II.

Task Battery V

Of the two tasks in this battery, one is identical to a task used in Battery IV. The other is a modification and extension of a task used in Battery II.

Semantic Search IV. This task is identical in form, content and length of testing to the Semantic Search III task described for Battery IV. All performance expectations also remain identical.

Perceptual Matching III. This task is a slight variant of the Perceptual Matching II task described for Battery II. On each trial of this task, a pair of random polygons was presented and the subject was to decide if they were the same or different. The polygons varied in complexity as determined by number of points (6, 8, 12, 16 or 24) and each of the five referent stimuli was paired with itself or one of six mismatches (D1 - D6) which varied with respect to degree of dissimilarity to the referent. Each session consisted of 120 trials, 60 same judgments and 60 different judgments. The structure of a session differed as shown in Table 4. There were two major practice transfer conditions referred to as the Hard Discrimination and Easy Discrimination conditions. Both conditions received identical numbers of presentations of the same judgment items throughout the first eight and last eight sessions of testing. They differed with respect to item composition for different judgments during the first eight sessions of practice. In the Hard condition, the different judgment items were those most similar to the target (D1 - D3)

Table 4. Presentation Conditions for Perceptual Matching III

Session	Hard discrimination			Easy discrimination		
	Same	D1-D3	D4-D6	Same	D1-D3	D4-D6
1	60[a]	60	-	60	-	60
2	60	60	-	60	-	60
3	60	60	-	60	-	60
4	60	60	-	60	-	60
5	60	60	-	60	-	60
6	60	60	-	60	-	60
7	60	60	-	60	-	60
8	60	60	-	60	-	60
9	60	30	30	60	30	30
10	60	30	30	60	30	30
11	60	30	30	60	30	30
12	60	30	30	60	30	30
13	60	30	30	60	30	30
14	60	30	30	60	30	30
15	60	30	30	60	30	30
16	60	30	30	60	30	30

[a]Numbers represent total number of trials of a given type in a given session.

whereas in the Easy condition, the different judgment items were those most dissimilar to the target (D4 - D6). After eight sessions of practice, both groups received the full item set for different judgments (D1 - D6) during the last eight practice sessions. Thus, subjects in both conditions were tested for 1920 trials, 16 sessions with 120 trials/session, with identical numbers of same and different trials and completely equivalent presentation of the critical same judgment items.

Our expectations about processing in this task were that reaction time would be a function of stimulus complexity. The slope of this function reflects the efficiency of feature processing, with a shallow slope indicating highly efficient processing. The intercept reflects choice and motor response processes. We also expected that reaction time on different judgment trials would be a function of degree of similarity. Of particular concern in the present design was how these parameters of task performance would be affected by (a) the difficulty of the discrimination to be performed (i.e., the Hard vs. Easy manipulation) and (b) type of prior practice. Special concern focuses on the second eight sessions where there are identical presentation conditions thus allowing for detailed assessments of transfer from the first eight sessions, particularly as regards performance in the same judgment items and the slope and intercept of the stimulus complexity effect.

IV. INTERNAL VALIDATION OF THE INFORMATION PROCESSING TASKS

In this section we consider overall performance in each information processing task. The general concerns are the same for each task: (a) evidence for systematic variations in performance within each task as a function of item characteristics, (b) the extent to which the data match predictions from process models and the fit of such models to the data, and (c) evidence for systematic practice effects over sessions. Our approach to addressing these three general concerns is the same for each task. First, we examine whether performance (response latency) in a given task is systematically related to the item and task design characteristics. Thus, if a judgment is to be made about stimuli of varying complexity, then we examine whether the complexity variable produced a systematic and significant effect. Similarly, if the task involves search through an array, then we examine whether the time to respond increases as a function of the target position in the array. Such an increase, if linear, would indicate a systematic serial search which is self-terminating when a target is found. In all of our tasks, the variables of interest are within-subjects and their effects on performance are generally well known. Thus, all we initially wish to determine is whether those effects are present and how robust they are. This constitutes a first step toward internal validation (within task) of an implicit or explicit model of task performance.

For each task, the item and task design characteristics are also tied to one or more specific models of information processing. These models specify the particular cognitive processes that hypothetically occur on any given trial and the sequence in which they occur in producing an overall response. The models can be converted into sets of simultaneous equations where an equation is generated for each major item type or condition of a given task. The simultaneous equations can be solved by a parameter estimation program such as STEPIT or by a least squares estimation procedure such as simple or multiple linear regression. The result of this "Model Fitting" is a set of estimates for the times associated with each individual process specified by a given model, as well as measures of the "Goodness of Fit" of the model to the actual data. The goodness-of-fit measures are r squared values representing percent variance accounted for and/or the Root Mean Squared Deviation (RMSD). For many of the tasks, the model predictions are relatively simple and can be represented by linear functions. Thus, slopes and intercepts of least squares regression functions are frequently used as estimates of the time to execute simple processes or sets of processes.

The modeling process can be done at several levels. First, it can be done on overall group mean data. Second, it can be done for group mean data obtained for individual sessions of practice. Third, modeling and parameter estimation can be done for individual subject data, either aggregated over sessions or for individual sessions. When our concern is with systematic practice effects over sessions, then we examine trends in overall reaction time data as well as trends for process parameters. The general expectation about practice effects is that they will follow a simple power function and thus both linear and quadratic trend components should be observed over sessions.

In each of the sections that follows on a specific task, we consider first whether within-task performance was a systematic function of the task design variables. Next we consider whether the variation was in accord with a particular model of task performance and the values obtained from model fitting. Finally, within each task we consider practice effects for both overall reaction time data and more specific measures derived from model fitting.

Task Battery I

Perceptual Matching I. As noted earlier, our assumptions about processing in this task were that time to respond same or different should be a systematic function of problem characteristics. In the case of same judgments, latency should linearly increase with matrix size. The slope of the function relating overall reaction time to matrix size reflects the time for a single encoding and comparison cycle, while the intercept reflects choice and motor response processes. In the case of different judgments, latency should also be a systematic function of the number of elements processed prior to finding a mismatch. The slope of this function should be identical to that for same judgments given adjustments for self-terminating process execution when differences were detected. For both same and different judgments, process components and average reaction time should decrease with practice.

As expected, the perceptual matching task resulted in decreasing response times as a function of increasing degree of mismatch, $F(3, 177) = 272.25$, $p < .001$. The mean latencies for trials with 0, 1, 2, and all mismatches were 1.677, 1.380, 1.232, and .944 seconds, respectively. This finding is consistent with the model for this task. The model predicts efficient self-terminating processing when mismatches are present. The matrix size variable also produced the expected results. Larger matrices produced longer overall response times than smaller matrices, $F(3, 177) = 409.25$, $p < .001$. The mean latencies for matrix sizes of 3, 5, 7, and 9 elements were .976, 1.247, 1.472, and 1.537 seconds, respectively. Figure 1 shows that performance in this task was a systematic function of problem characteristics. Matrices were designed to vary in the number of encoding and comparison cycles necessary to decide if the matrix pair was the same or different. Thus, it was expected that reaction time would be a linear function of the predicted number of processing cycles. Figure 1 shows that this was the case for both same and different judgment trials, with both trial types yielding identical slopes. The

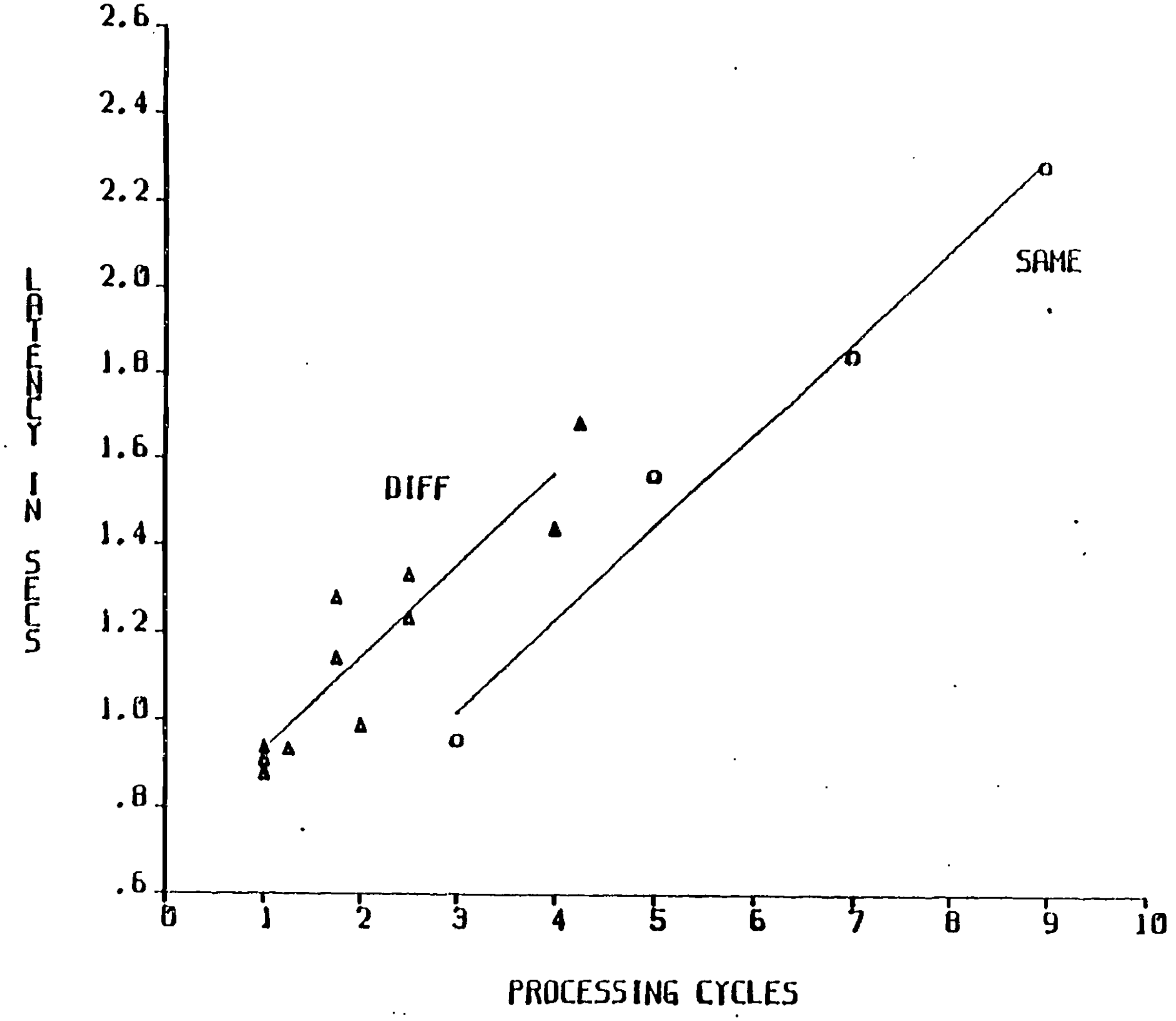

Figure 1. Perceptual Matching I Mean Latencies by Processing Cycles for Same and Different Trials.

intercept difference between the two trial types provides an estimate of the additional time to make a negative decision and response.

Figure 2 shows the mean decision times for same and different trials over sessions. As expected, there were systematic practice effects consistent with a power function. A trend analysis showed significant differences between sessions $F(7, 413) = 19.50$, $p < .001$, and significant linear and quadratic trends, $F(1, 59) = 49.37$, $p < .001$; $F(1, 59) = 13.58$, $p < .01$, respectively. Additionally, Table 5 shows changes in information processing parameters as a function of practice. First, the model fit was excellent for all sessions. Second, there were changes over sessions in all three information processing parameters. These process changes are consistent with the overall practice effect discussed earlier.

Table 5. Model Fitting Results for Session Data in Perceptual Matching I

	Session							
Parameters (msec)	1	2	3	4	5	6	7	8
Preparation-Response	416	375	418	401	387	398	341	362
Different Response	364	354	308	324	332	303	349	319
Encoding-Comparison	244	230	207	207	204	201	205	194
r for Model Fit	.95	.95	.95	.95	.95	.95	.95	.95

The data obtained in Perceptual Matching I confirmed all of our predictions. Both degree of mismatch and matrix size significantly affected response time in the expected direction. Furthermore, performance improved with practice as measured by the overall response time and process parameter estimates for each session. These data provide evidence for significant condition and practice effects, thus internally validating the performance model and expectations concerning performance over sessions.

Attribute Comparison. As noted earlier, our assumptions about processing in this task were that latency would be a systematic function of both pair type and matching criterion. Physical identity judgments should be faster than name identity judgments, which in turn should be faster than category identity judgments (e.g., Posner, et al., 1969). Furthermore, if subjects are performing in a highly efficient manner with respect to attribute processing, then physical identity pairs should be responded to rapidly in all conditions. Similarly, name identity pairs should be responded to with equal latency in both the name and category judgment conditions. Finally, overall latency and specific components of processing should systematically decrease over sessions.

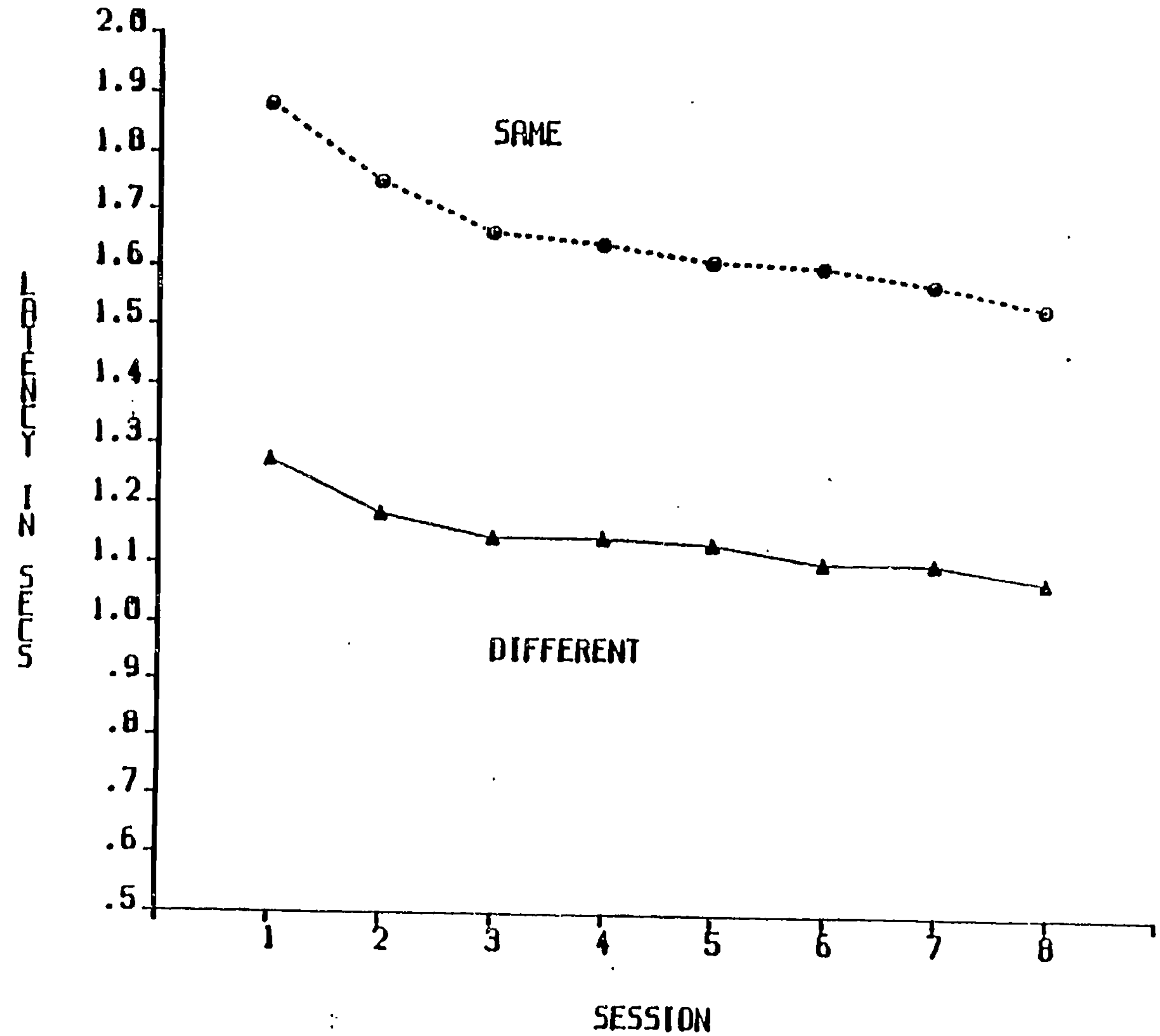

Figure 2. Perceptual Matching I Session Effects for Same and Different Trials.

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Figure 3 depicts the overall latencies for each judgment condition. These data are consistent with the predictions, as supported by a significant main effect of type of judgment, $F(2, 118) = 126.06$, $p < .001$. Physical identity judgments were executed .10 second faster ($M = .77$) than name identity judgments, which were in turn executed .25 second faster ($M = .87$) than category identity judgments ($M = 1.12$).

The latency data also show a significant effect of stimulus type, $F(3,77) = 71.35$, $p < .001$. Attribute matching for pairs like DOG-DOG ($M = .73$) or DOG-dog ($M = .87$) took less time than matching pairs like DOG-CAT ($M = .95$), regardless of judgment type. The data also showed a significant judgment type by stimulus type interaction, $F(6, 354) = 55.76$, $p < .001$. This interaction reflects the additional time required to respond different. Figure 3 provides additional evidence that different judgments take longer than same judgments. Different physical identity judgments were executed .10 second faster ($M = .82$) than different name identity judgements ($M = .92$) which were in turn executed .20 second faster than different category identity judgments ($M = 1.12$).

Changes in performance over 18 sub-sessions in the attribute comparison task are illustrated in Figure 4. The change with practice is consistent with a power function. Furthermore, an analysis of variance on individual sub-session latencies resulted in a significant session effect, $F(17, 1003) = 57.98$, $p < .001$, with significant linear, $F(1, 59) = 93.83$, $p < .001$, and quadratic components, $F(1, 59) = 78.26$, $p < .001$. Detailed model fitting was performed on the latency data, and it was possible to evaluate several alternative models that vary in terms of efficiency of decision making.

To understand the model fitting, it is necessary to consider certain assumptions about processing in this task. On any given trial, a pair of words is presented under a particular judgment criterion. The simplest and most rapid judgment that can be made is physical identity. If we have a pair of physically identical words, then the time to respond will represent the time to encode each word (e), compare their physical representations (c) and then initiate a positive response (r). If we have a pair of physically non-identical words, then the processes will be the same except that a negative response must be made. Typically, there is some additional time (d) to respond that two things are different. A more difficult judgment occurs if the pair of words must be matched on the basis of name identity. Again, we assume that there will be some basic time for encoding the physical stimuli, comparing internal representations and responding. However, it should take some additional time (n) to generate a name code as compared to a physical code. Thus, if we have a pair of words that are not physically identical but are name identical (e.g., DOG - dog), then the total time should be $e + c + n + r$. Finally, a similar situation arises in the case of category identity judgments. Now, we assume that it will take an additional increment in time (s) to retrieve semantic category information for a pair of words that are not physically or name identical but are members of the same category (e.g., DOG - cat). Thus, the total time should be $e + c + n + c + r$. Different models can now be generated to derive predictions for certain item types under various judgment conditions. Consider the fact that if two items are physically identical then they are also name identical and category identical. Thus, a highly efficient processor could use the physical identity information to make name and category judgments under such circumstances.

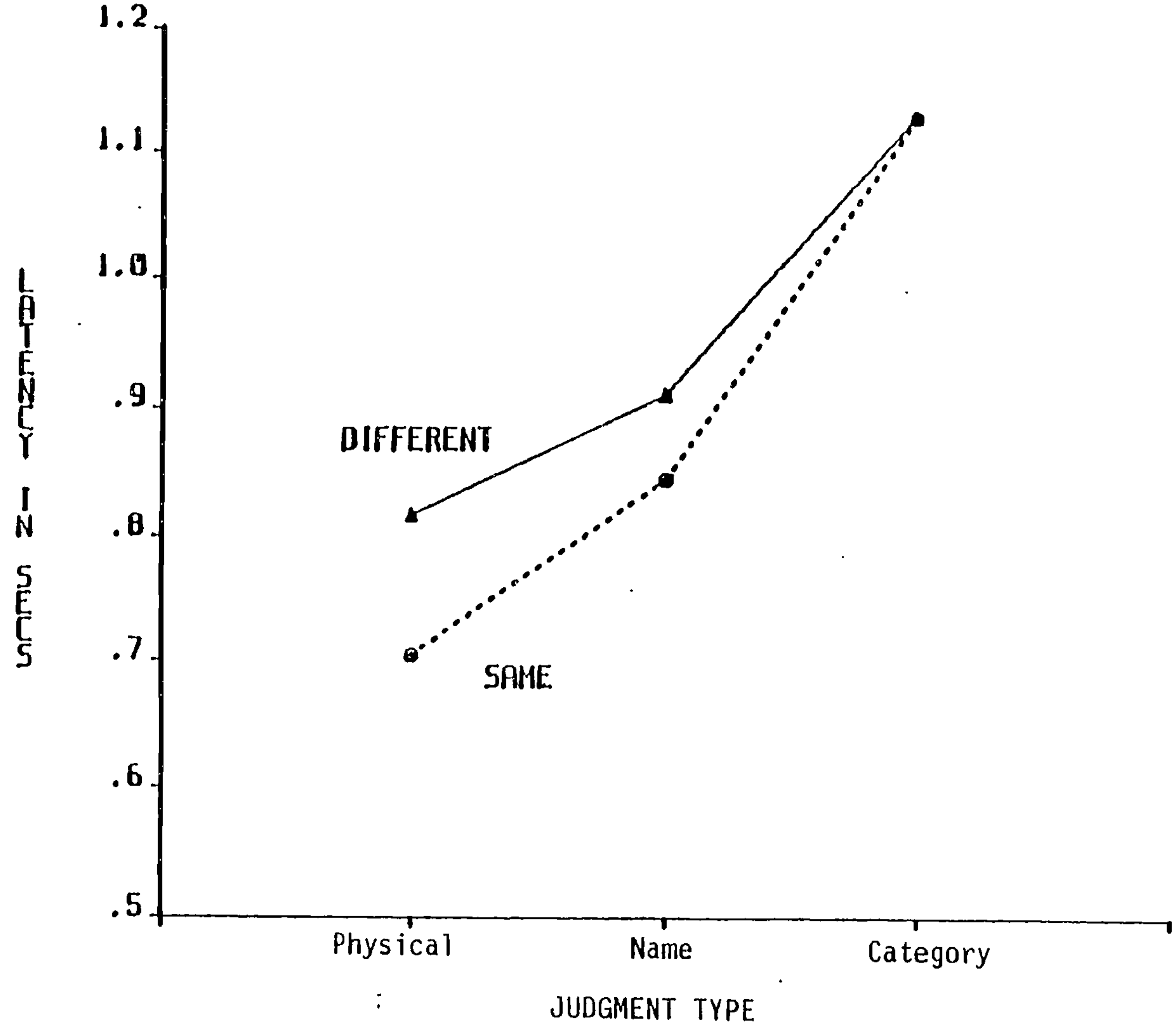

Figure 3. Attribute Comparison Mean Latencies by Judgment Type for Same and Different Trials.

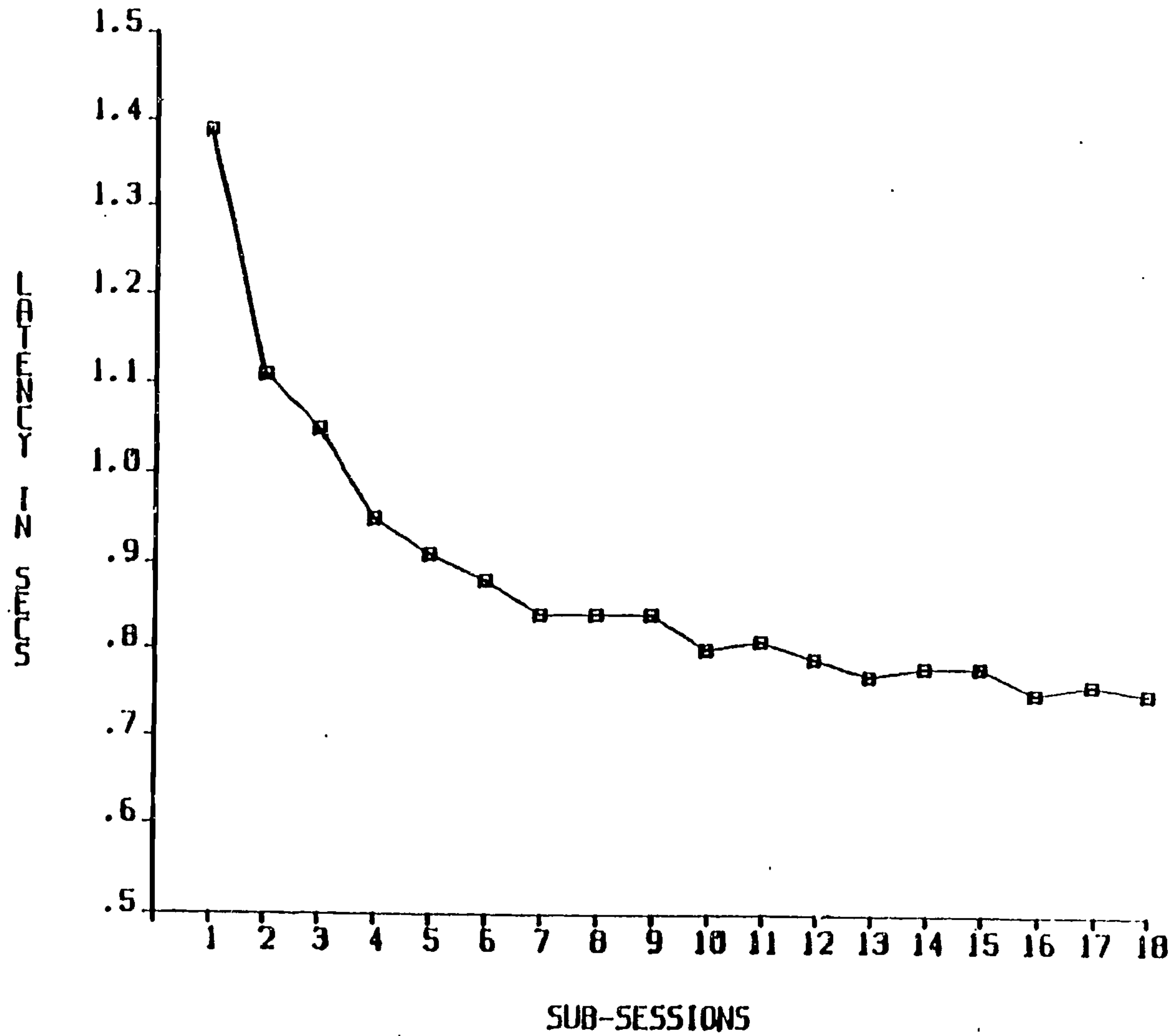

Figure 4. Attribute Comparison Sub-Session Effects.

Similarly, two items that are physically non-identical but name identical are also categorically identical. A highly efficient processor could use the name identity information to make category judgments under these circumstances. At the other extreme is a model of performance in which the individual does not behave so efficiently and instead processes to the highest level possible for any given type of judgment. This is in contrast to a highly efficient processor who processes only to the highest level necessary for any given item and judgment combination. These extreme cases and ones intermediate were considered in evaluating performance in the attribute comparison task.

Table 6 presents the model parameters for the most efficient decision making model, with their respective latency values collapsed across subjects and sessions. Also included in Table 6 are the r and RMSD values for the model, showing an excellent overall fit to the data. Table 7 shows the results of this type of model fitting for each session of testing. In all sessions, the best fitting model was the one that assumes the most efficient form of attribute processing. We were able to estimate four separate processing parameters and their change over sessions. It is interesting to note the relatively small amount of change associated with the category retrieval parameter. This result is consistent with other results on semantic category processing to be presented subsequently.

The task data suggest that there is an effect of decision type, and that the effect is consistent with previous literature, as well as consistent with an efficient decision making model. In addition, the session data suggest that overall response latencies decrease as a function of practice, as do the estimates of each process parameter. Thus, in this task we have internal validation of our model of performance and of our expectations regarding practice effects.

Fact Retrieval. As noted earlier, we expected problem verification latency to vary as a function of problem characteristics; e.g., in true addition problems, reaction time should be a linear function of sum or sum squared (Ashcraft, 1982). The slope of this function reflects retrieval speed and efficiency while the intercept reflects choice and motor response processes. Finally, average response latency in each fact retrieval task should decrease with practice although the size of the practice effect may be small.

Our analyses of the data for each fact retrieval task indicate that decision latency is a systematic linear function of problem characteristics such as the size of the sum, difference, product, or quotient. Figure 5 illustrates an example of this finding with data from the addition task. Reaction time linearly increases with the size of the sum for addition problems.

Figure 6 shows the changes in the mean latencies over sessions for true and false items for all problem types. The general practice effects are small, suggesting that individuals are highly efficient in quantitative fact retrieval even at early points in testing. For all problem types, negative responses were found to take longer than positive responses. The mean latencies for true subtraction, addition, division, and multiplication items were 769, 783, 810, and 783 msec, respectively. False responses showed the same ordering of problem types, with mean latencies for subtraction, addition,

Table 6. Attribute Comparison Mean Latencies and Parameters for Most Efficient Processing Model.

Pair type	Judgment task: Physical identity	Name identity	Category identity
Physical identity (Dog-Dog)	705 (e+c+r)[a]	701 (e+c+r)	775 (e+c+r)
Name identity (DOG-dog)	858 (e+c+r+d)	844 (e+c+n+r)	918 (e+c+n+r)
Category identity (DOG-CAT)	799 (e+c+r+d)	936 (e+c+n+r+d)	1124 (e+c+n+s+r)
Mismatch (DOG-ORANGE)	791 (e+c+r+d)	883 (e+c+n+r+d)	1125 (e+c+n+s+r+d)

[a]e = encode, c = compare, r = respond, n = name retrieval, s = category retrieval, d = different response. Estimated mean values: e+c+r = 744 msec, n = 123 msec, s = 229 msec, d = 54 msec. Model fit: r = .933, RMSD = .034 msec.

Table 7. Model Fitting Results for Session Data in Attribute Comparison

	Model fits (r)			Model parameters (msec)			
Session	Least efficient	Moderate efficient	High efficient	Encoding, comparison & response	Name retrieval	Category retrieval	Different response
1	.78	.89	.95	922	201	213	95
2	.79	.90	.93	731	123	237	30
3	.80	.91	.92	679	125	216	24
4	.78	.90	.92	663	104	220	22
5	.83	.93	.94	641	97	208	22
6	.78	.90	.94	624	118	189	17

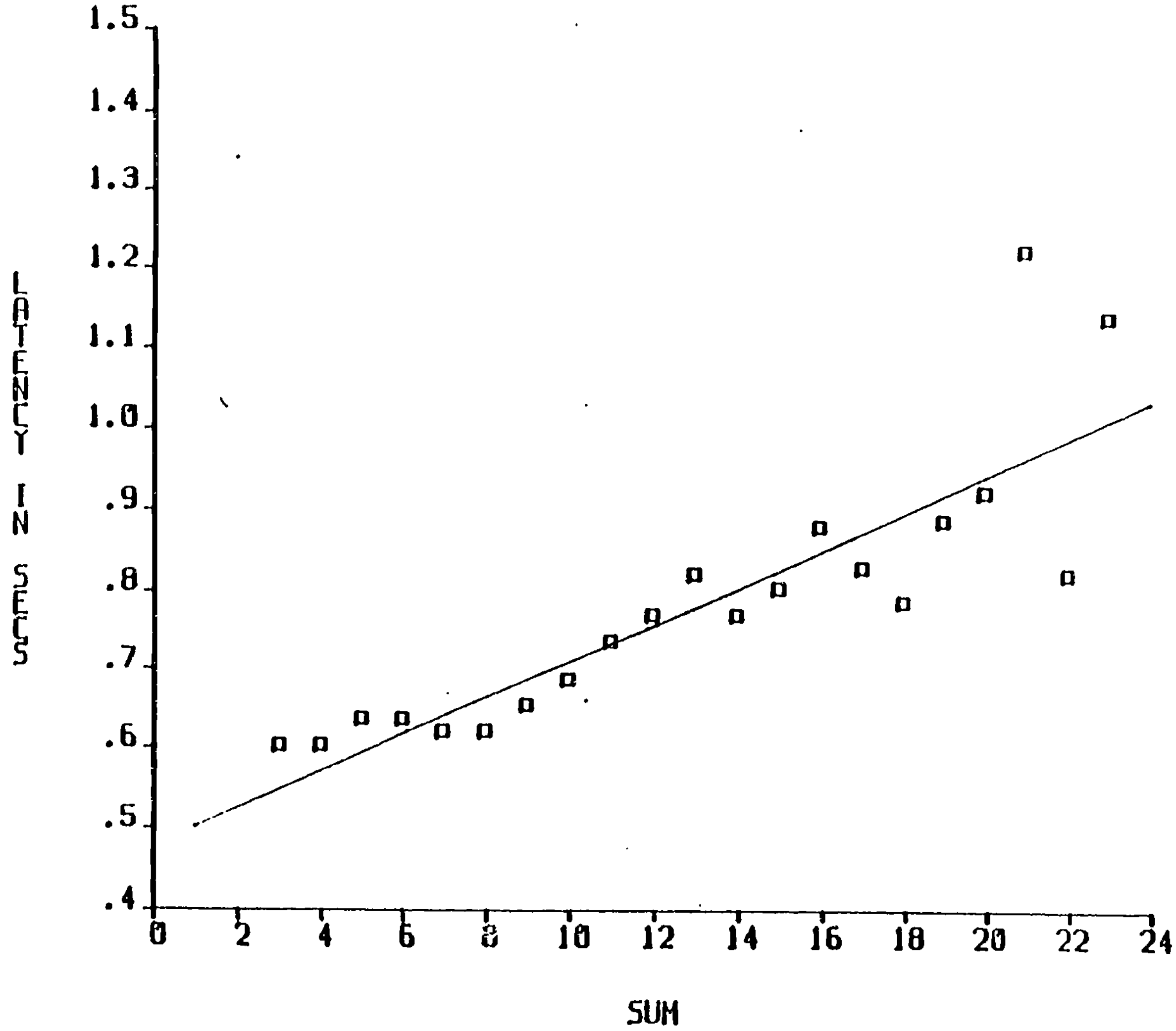

Figure 5. Fact Retrieval Addition Mean Latencies as a Function of Sum.

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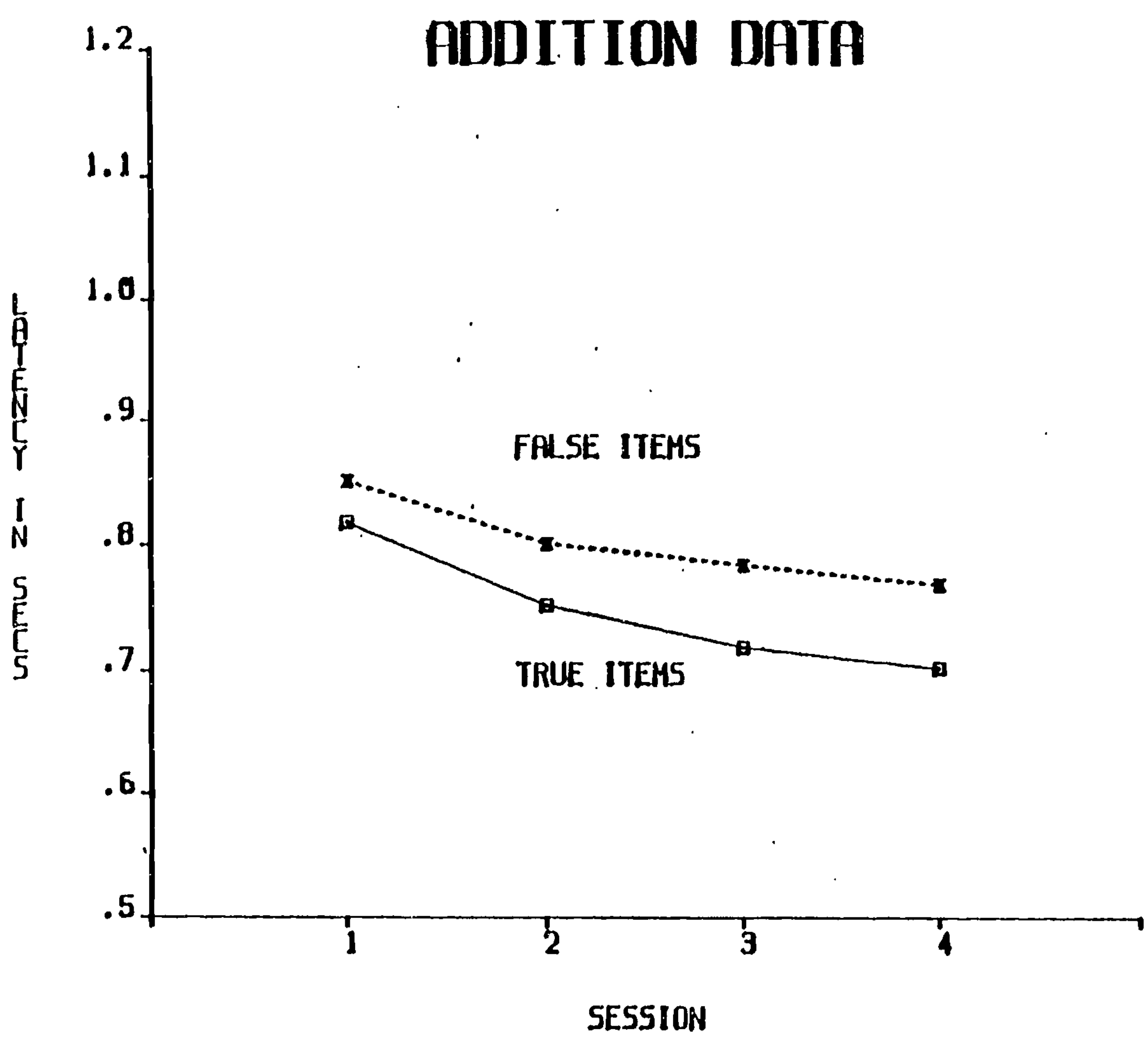


Figure 6. Fact Retrieval Addition, Subtraction, Multiplication, and Division Session Effects for True and False Trials.

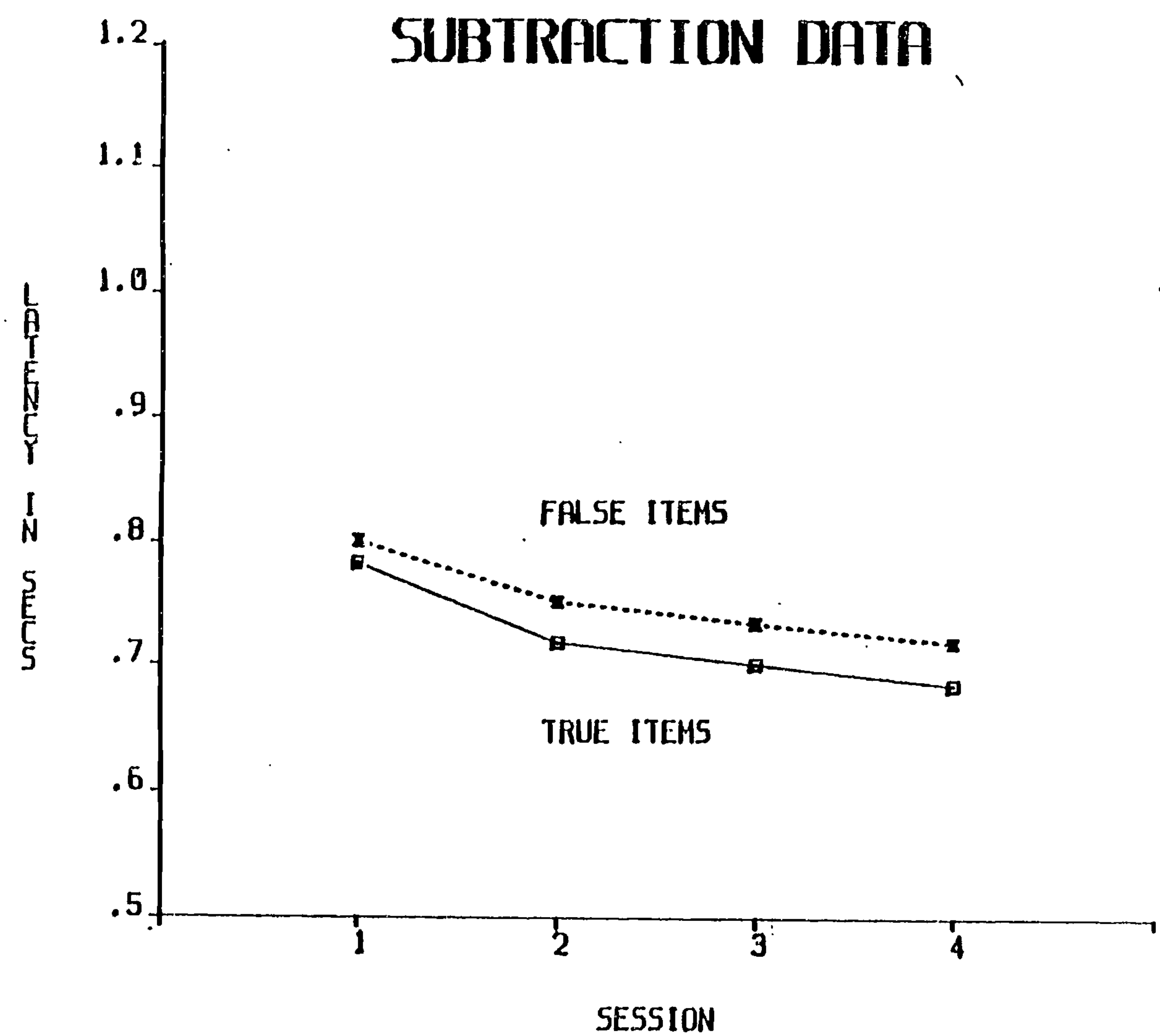
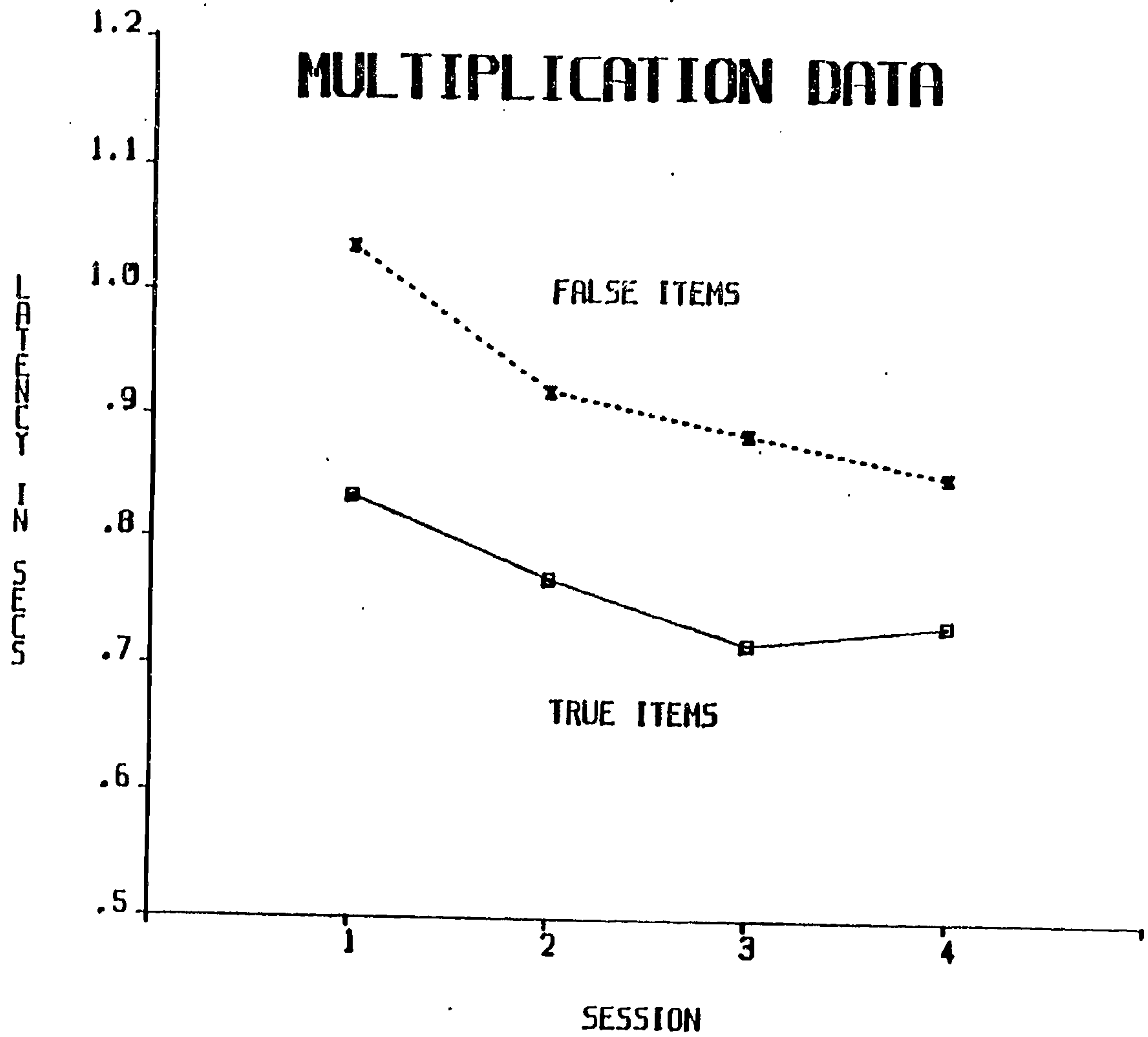


Figure 6 (Continued)



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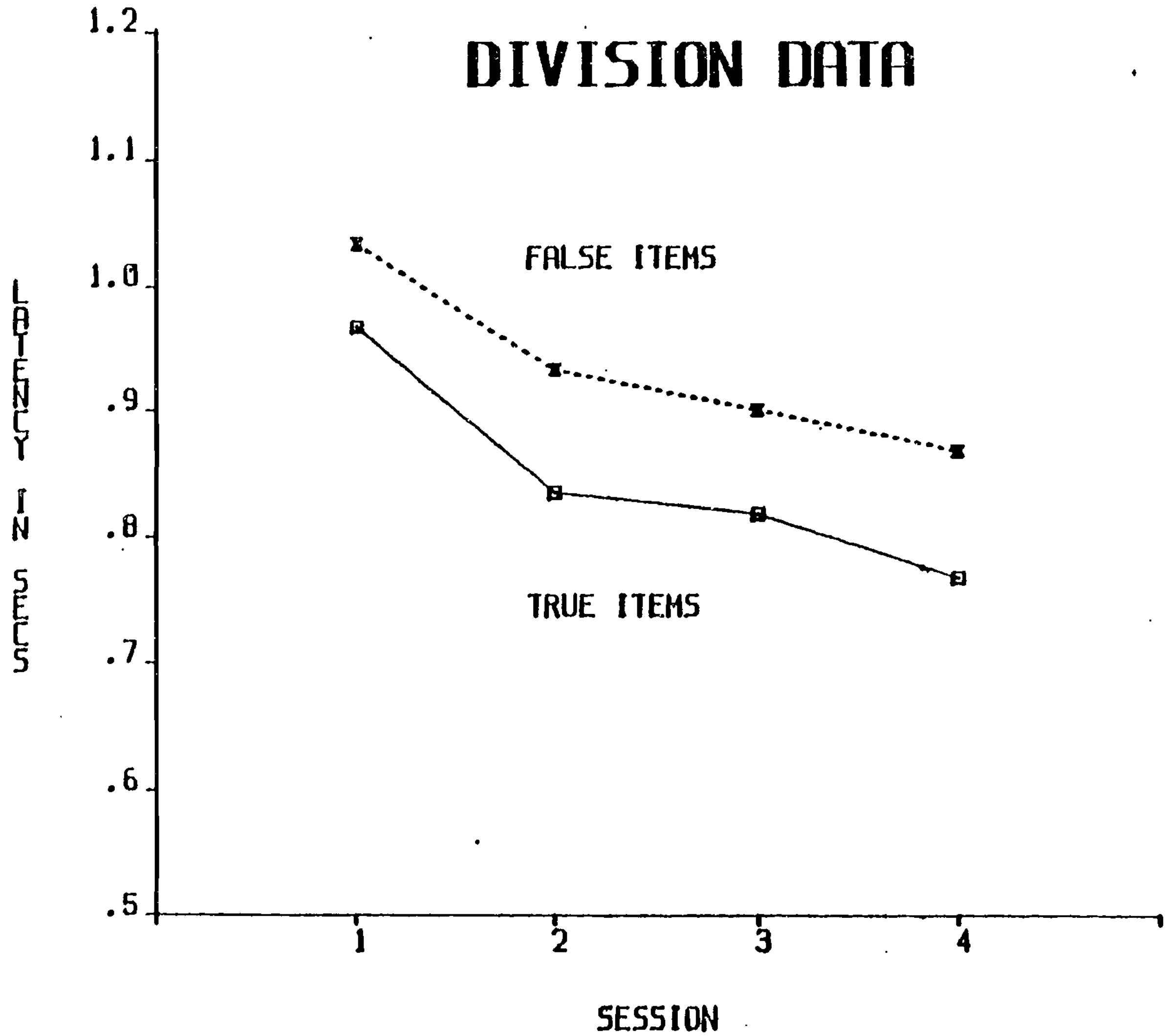


Figure 6 (Concluded)

division, and multiplication of 796, 836, 971, and 977 msec, respectively. Changes in information processing parameters observed over sessions are shown in Table 8 and are consistent with the small overall practice effects for each task.

Table 8. Model Fitting Results for Session Data in Fact Retrieval

Session	Slope (msec)	Intercept (msec)	r
Addition (sum squared)			
1	1.2	627	.89
2	.9	601	.86
3	.7	594	.84
4	.7	583	.88
Addition (sum)			
1	30.1	470	.87
2	22.9	483	.85
3	18.6	499	.82
4	19.1	485	.87
Subtraction			
1	20.48	700	.85
2	16.85	649	.90
3	13.40	639	.85
4	18.43	607	.89
Multiplication			
1	6.5	584	.84
2	4.7	581	.89
3	4.8	541	.91
4	5.1	547	.87
Division			
1	31.43	778	.76
2	24.79	701	.74
3	21.35	696	.69
4	21.59	651	.74

The data obtained from the fact retrieval tasks suggest that decision latency is systematically related to problem characteristics, a finding consistent with our expectations and previous research in this area (Ashcraft, 1982; Groen & Parkman, 1972). In addition, both overall latencies and estimates of processing parameters changed as a function of practice. Overall, these results provide internal validation of our model of performance and suggest that only relatively small improvements in performance with practice can be expected in simple quantitative fact retrieval tasks.

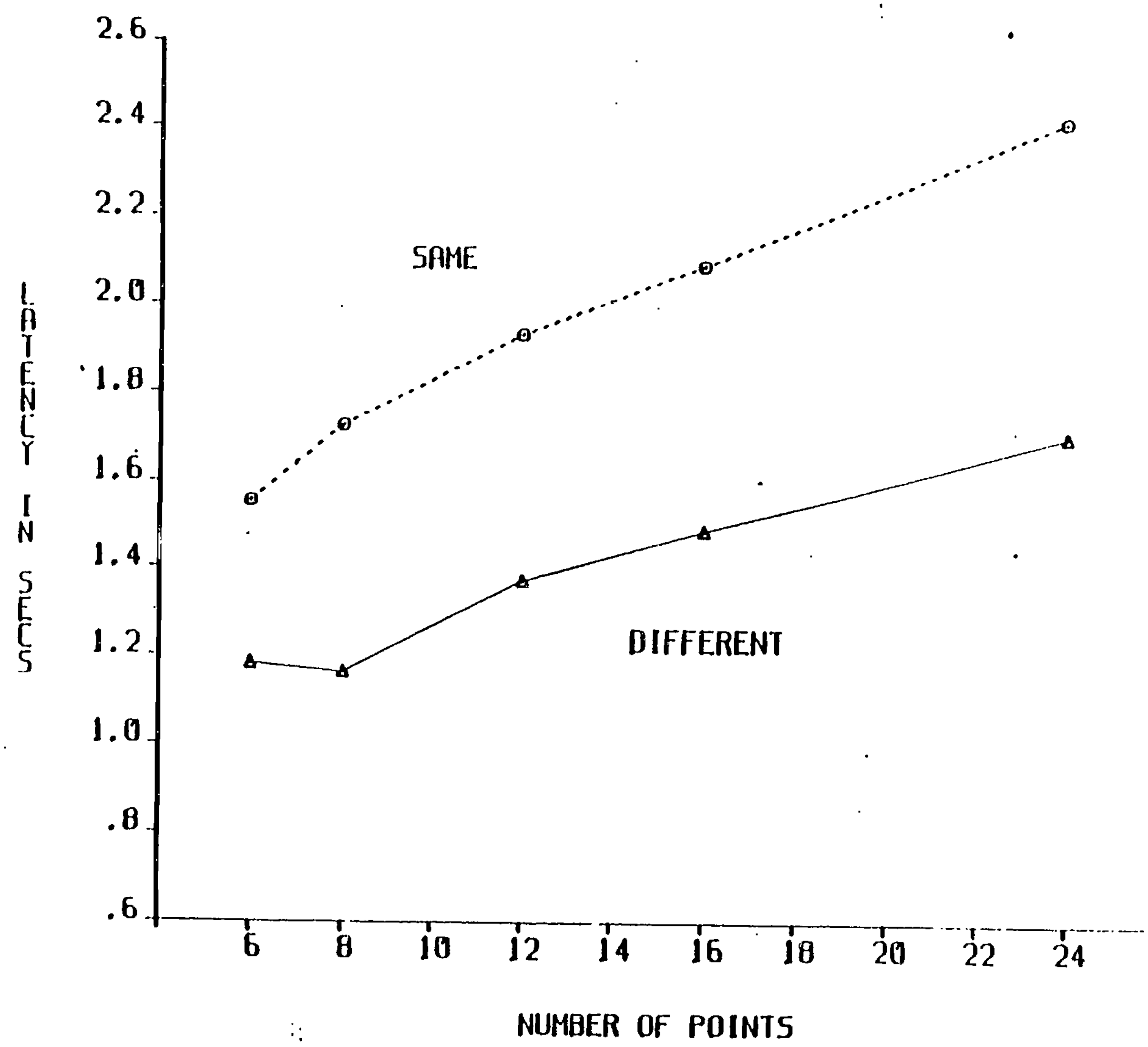
Summary for Task Battery I. The results obtained for the three tasks in this battery have various implications relative to the goals of this research project. First, all three tasks behaved as expected and the models for task performance provided excellent characterizations of the data. Second, it is also clear that practice effects in these tasks are relatively small and tend to be associated with simple motor response and decision processes. Thus, basic processes of perceptual comparison, name retrieval, category retrieval and quantitative fact retrieval are highly efficient at the start of practice and change relatively little over sessions of practice. These tasks seem particularly well suited to detecting an individual's current levels of information processing efficiency. They are not terribly useful for measuring movement towards more efficient levels of processing.

Given these results, in Battery II we examined whether more substantial practice effects will be observed if we use tasks with unfamiliar perceptual stimuli and/or tasks which require multiple executions of basic processes in succession, thereby introducing a coordination component.

Task Battery II

Perceptual Matching II. The stimulus design represents two principal variables: stimulus complexity and degree of similarity. Stimulus complexity is defined in terms of the number of points in the figure (6, 8, 12, 16 and 24); this was crossed with judgment type (same and different). Our expectations about processing in this task were that reaction time should be a linear function of stimulus complexity. The slope of this function reflects the efficiency of feature processing, with a shallow slope indicating highly efficient processing. The intercept reflects choice and motor response processes. We also expected that reaction time on different judgment trials would also be a linear function of degree of dissimilarity. The slope of this function reflects the efficiency of difference detection, with a flat or shallow slope indicating wholistic processing. The intercept again reflects choice and motor response processes. For both same and different judgments, average latency should decrease with practice.

The data were first submitted to a repeated measures analysis of variance to assess effects due to judgment type and complexity. There was a main effect of judgment type, $F(1, 60) = 72.40$, $p < .001$, with same responses ($M = 1.987$) executed .606 second slower than different responses ($M = 1.381$). The number of points defining the stimuli also proved to be highly significant, $F(4, 240) = 71.19$, $p < .001$. The means across the five complexity levels increased systematically with means of 1.370, 1.445, 1.650, 1.788 and 2.058, for 6-, 8-, 12-, 16- and 24-point stimuli respectively. Judgment type and complexity significantly interacted, $F(4, 240) = 5.30$, $p < .05$. Both main effects and the interaction are shown in Figure 7. Regression analysis revealed that the two



<u>Figure 7.</u> Perceptual Matching II Mean Latencies by Stimulus Complexity for Same and Different Trials.

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functions differed both in their intercepts (1.339 for same and 0.970 for different) and slopes (.046 for same and .031 for different). The least squares regression lines for both functions provided an excellent fit, r's = .99, attesting to the adequacy of the model for group data. These effects due to stimulus complexity differ greatly from the null effects reported by Cooper (1975) with highly trained subjects and Cooper (1982) with highly selected subjects.

For the different trials, each of the five standards was paired with six versions scaled to reflect a linearly decreasing measure of similarity (Cooper, 1975, 1982). Analyses were performed to evaluate the effect of these systematically varied differences. The analysis of variance revealed a highly significant effect of degree of difference, $F(5, 300) = 220.72$, $p < .001$. A plot of the means for each degree of difference is presented in Figure 8. A linear function fit to the 6 points produced an $r(4) = .893$, $p < .01$, one-tailed. While this demonstrates the adequacy of the model for the group data, the figure suggests substantial non-linear trends. This was confirmed in a trend analysis which showed a large linear effect, $F(1, 60) = 340.26$, $p < .001$, but also revealed significant quadratic, $F(1, 60) = 72.32$, $p < .001$, and cubic trends, $F(1, 60) = 119.34$, $p < .001$. It is probable that these non-linear trends reflect unequal intervals in stimulus scaling.

Analyses of overall practice effects were performed on the mean latencies shown in Figure 9. The analyses were conducted separately for same and different judgment trials. A single factor analysis of variance on same judgment trials yielded a highly significant practice effect, $F(15, 900) = 61.13$, $p < .001$. A trend analysis on same judgment latency produced significant linear, $F(1,60) = 150.67$, $p < .001$, and quadratic effects, $F(1, 60) = 21.94$, $p < .001$, which are consistent with a power function. Practice effects were equally strong for the different trial data. The overall effect of sessions was highly significant, $F(15, 900) = 102.21$, $p < .001$, as were the contrasts reflecting linear, $F(1, 60) = 341.67$, $p < .001$, and quadratic trends, $F(1, 60) = 91.31$, $p < .001$.

The general practice effects illustrated in Figure 9 were examined in detail with respect to parameters of task performance. For both same and different judgment trials, slopes and intercepts of the functions relating reaction time to stimulus complexity and degree of difference, respectively, were obtained for each of the eight sessions of practice. The results for the slope data are shown in Figure 10. For different judgments, the slope represents time to detect a difference given increasing levels of target-distraction similarity. As can be seen in the figure, there was a substantial reduction in the slope of the difference detection function over sessions, indicating that subjects improved substantially in the speed of rejecting highly similar distractor stimuli. For same judgments, the slope represents the increment in time associated with each additional stimulus feature (point). As shown in Figure 10, there was a substantial reduction in the time associated with processing each additional stimulus feature such that by session 8 the slope was only slightly more than 30 msec per point. Thus, with practice, individuals became less sensitive to stimulus differences for both difference detection and identity matching. These results would be expected given evidence in the literature that highly practiced subjects can show relatively flat functions for both same and different judgments (e.g., Cooper 1975, 1982).

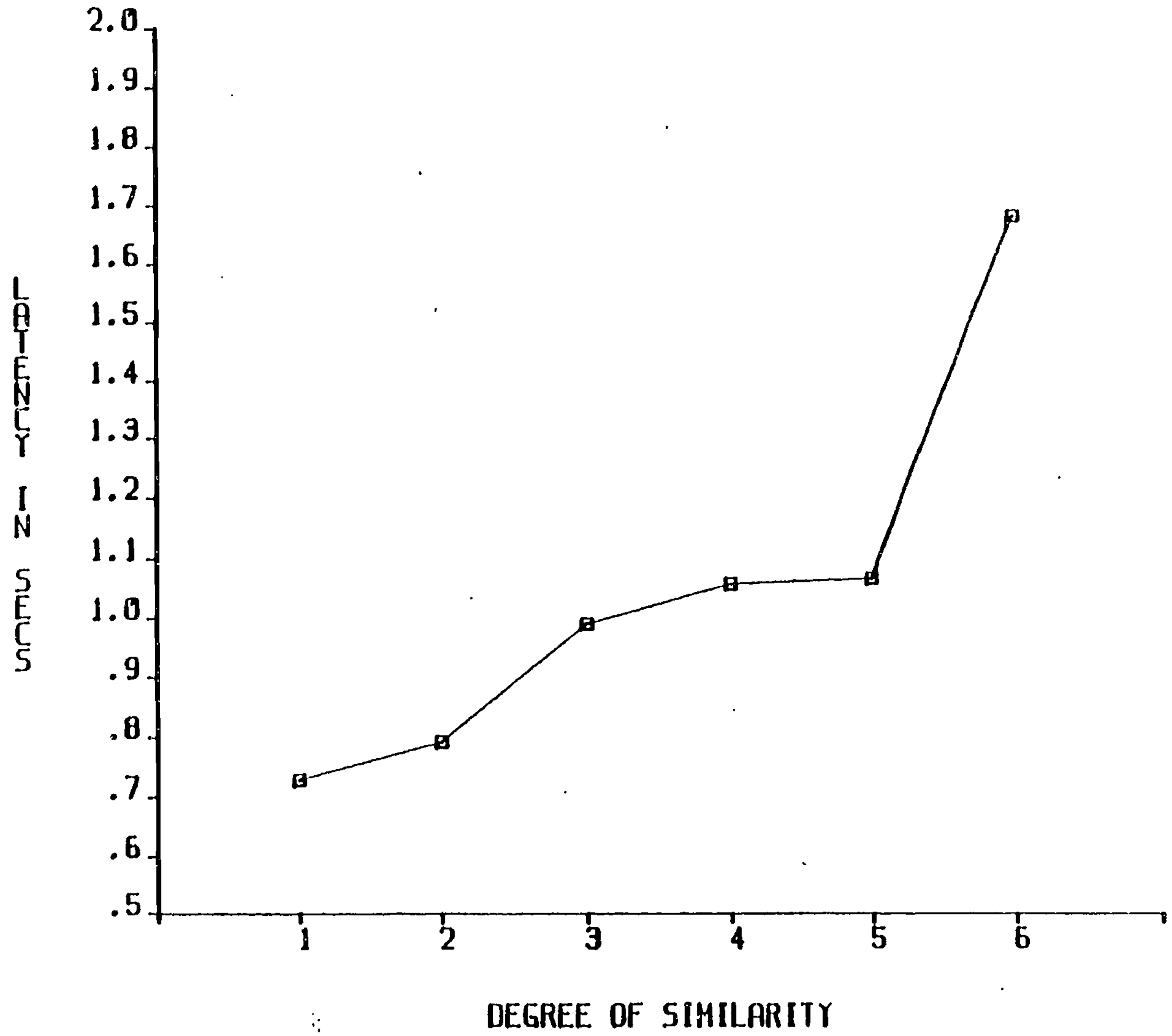


Figure 8. Perceptual Matching II Mean Latencies by Degree of Similarity.

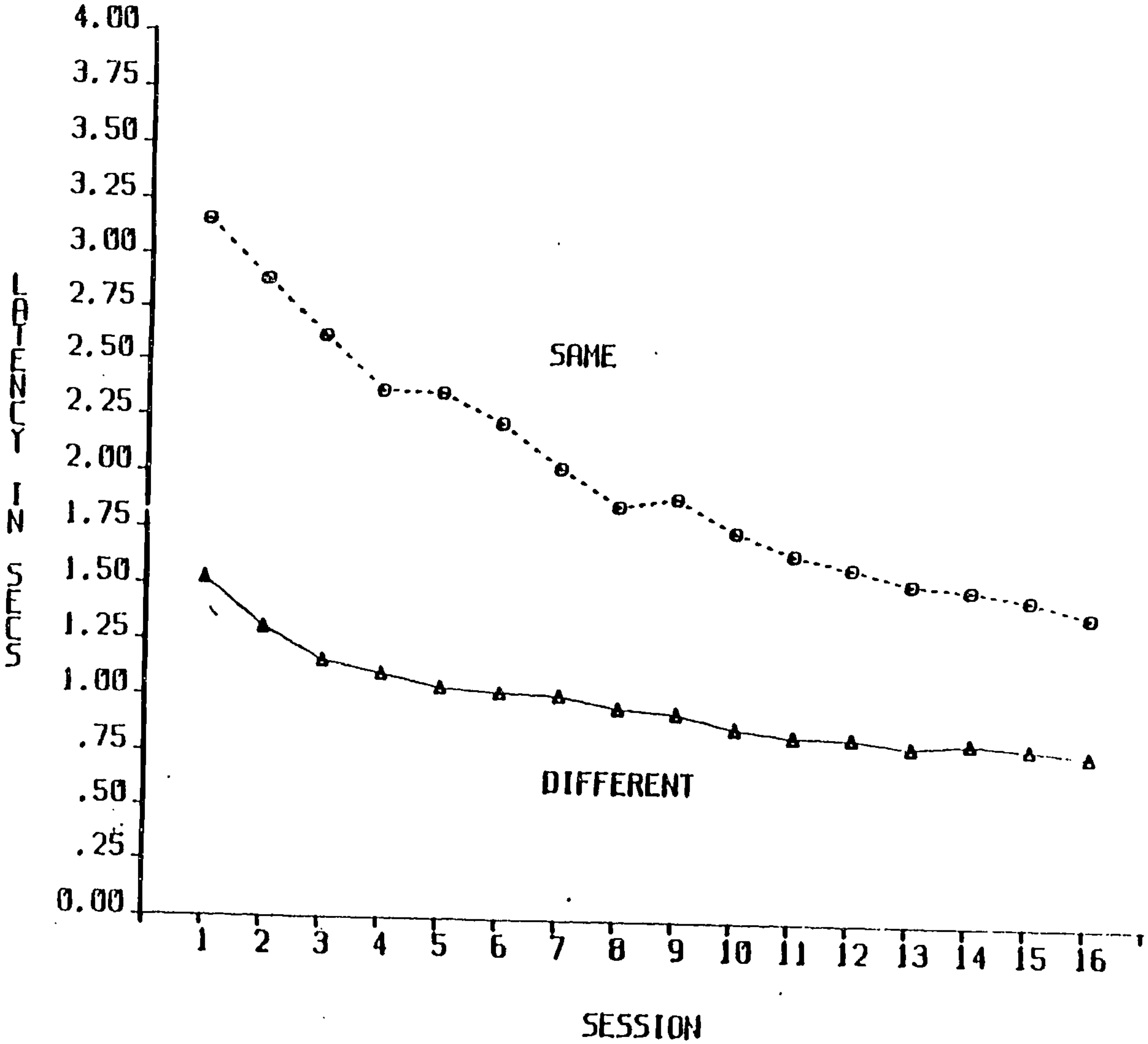
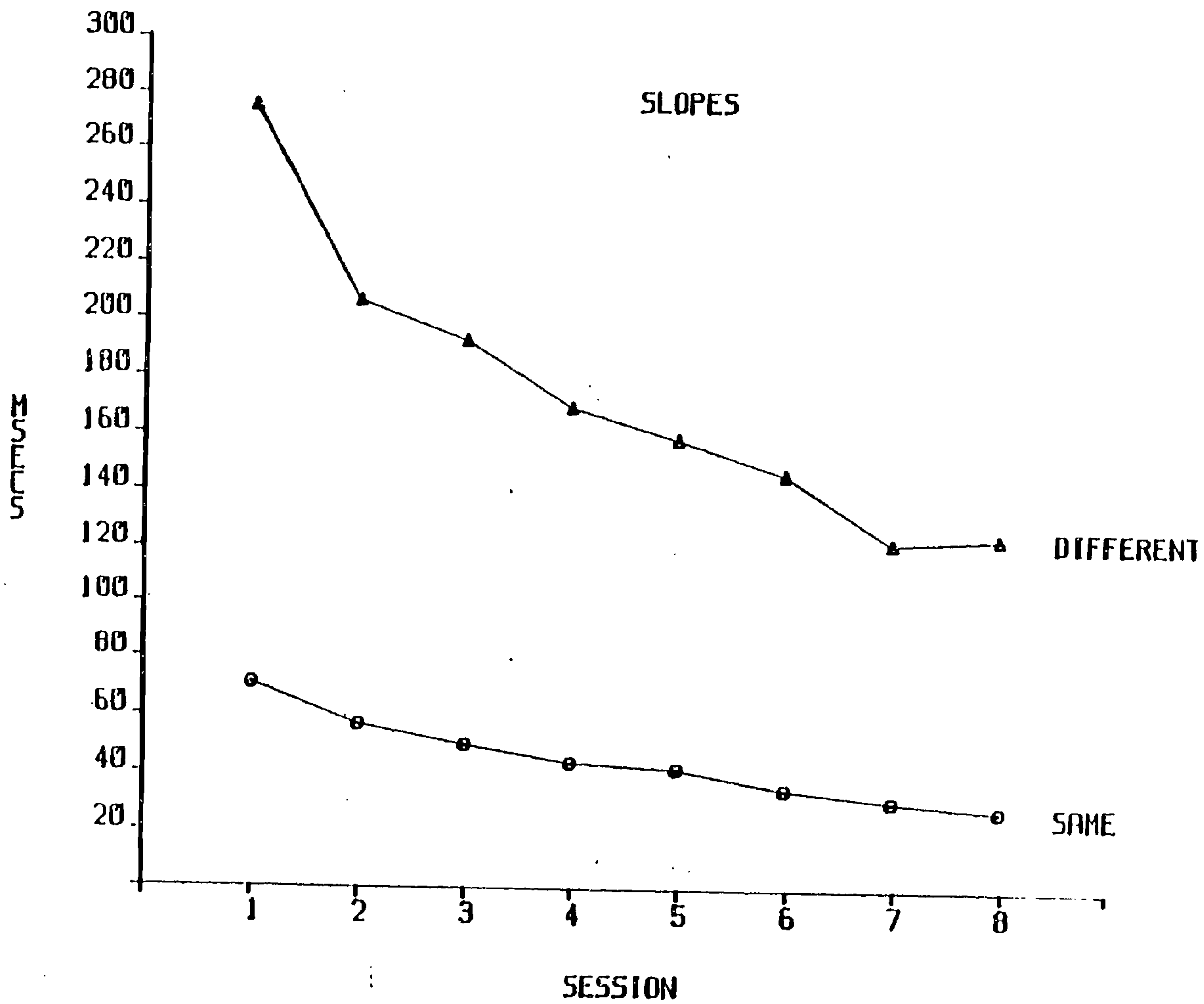


Figure 9. Perceptual Matching II Session Effects for Same and Different Trials.



<u>Figure 10.</u> Perceptual Matching II Session Effects for Same and Different Judgment Slopes.

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Figure 11 shows the session results for the intercepts of the functions relating reaction time to stimulus complexity and degree of target-distraction similarity. The same judgment data show a substantial reduction in the intercept which, together with the slope change for same judgments, suggests a significant change in processing such that subjects treat the initially complex and unfamiliar stimuli as if they had multiple features. By the end of session 8, these stimuli are being treated as relatively simple, homogeneous, and familiar stimuli which can be rapidly judged with regard to identity. Figure 11 also shows the intercept change for the different judgments. The change was much smaller but this would be expected since this intercept is an estimate of the time to determine that two highly dissimilar stimuli do not match. This process parameter should not change substantially and the small observed change can be attributed to a facilitation of motor response processes.

Collectively, these results provide strong support for the internal validity of the model of task performance. The principal design characteristics produced the anticipated effects of complexity, judgment type and degree of similarity. Practice on the task also produced expectedly large group gains in problem solution speed for both same and different judgments, with well-defined and predictable changes in process parameters over sessions.

Visual Search I. Decision latencies in this visual search task were a linear function of the position of the target stimulus in the search array. This is shown in Figure 12. The slope of the function relating latency and target position reflects the time required to encode and then compare each element of the search array with the target stimulus. The intercept is an estimate of choice and motor response time. Mean decision time was shortest when the target appeared in position 2 (M = .913 second) and increased in a linear fashion to 2.217 seconds for position 15. Mean decision time for position 1 (M = 1.005) turned out to be the single anomaly in these data, deviating slightly from a purely linear trend. An analysis of variance of the position data yielded a significant position effect, $F(15, 930) = 240.35$, $p < .001$, with a highly significant linear trend, $F(1, 62) = 382.08$, $p < .001$. The not-present condition produced the longest mean latency (M = 4.087).

The overall practice data were consistent with our expectations of a generally monotonic, decreasing power function. These data are presented in Figure 13. A trend analysis indicated a significant effect of session, $F(7, 434) = 38.72$, $p < .001$, as well as linear, $F(1, 62) = 78.96$, $p < .001$, and quadratic components, $F(1, 62) = 41.42$, $p < .001$. Figure 14 shows the results for the slope and intercept of the linear function relating reaction time to target position for each session of practice. As shown in Figure 14, the slope changed very little over practice and this is to be expected since the slope parameter represents the speed of making individual visual comparisons. The time to execute this process is approximately 100 msec at the start of practice and remains at this level for comparison of the unfamiliar graphic symbols used in this task. In contrast to the slope parameter, the intercept parameter shows a moderate change with practice from approximately 1300 msec to approximately 900 msec. This improvement primarily reflects simple motor response and perceptual orienting processes.

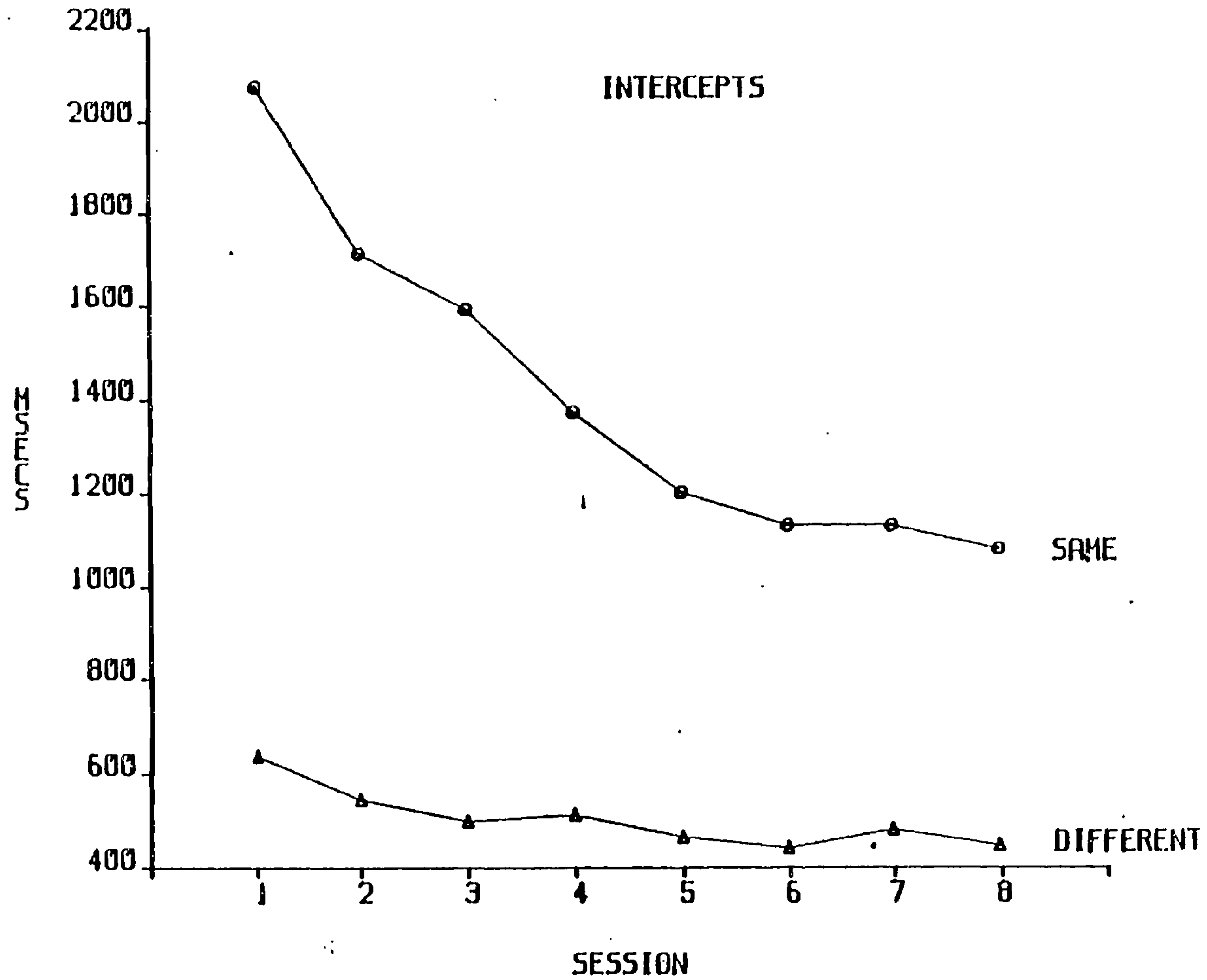

Figure 11. Perceptual Matching II Session Effects for Same and Different Judgment Intercepts.

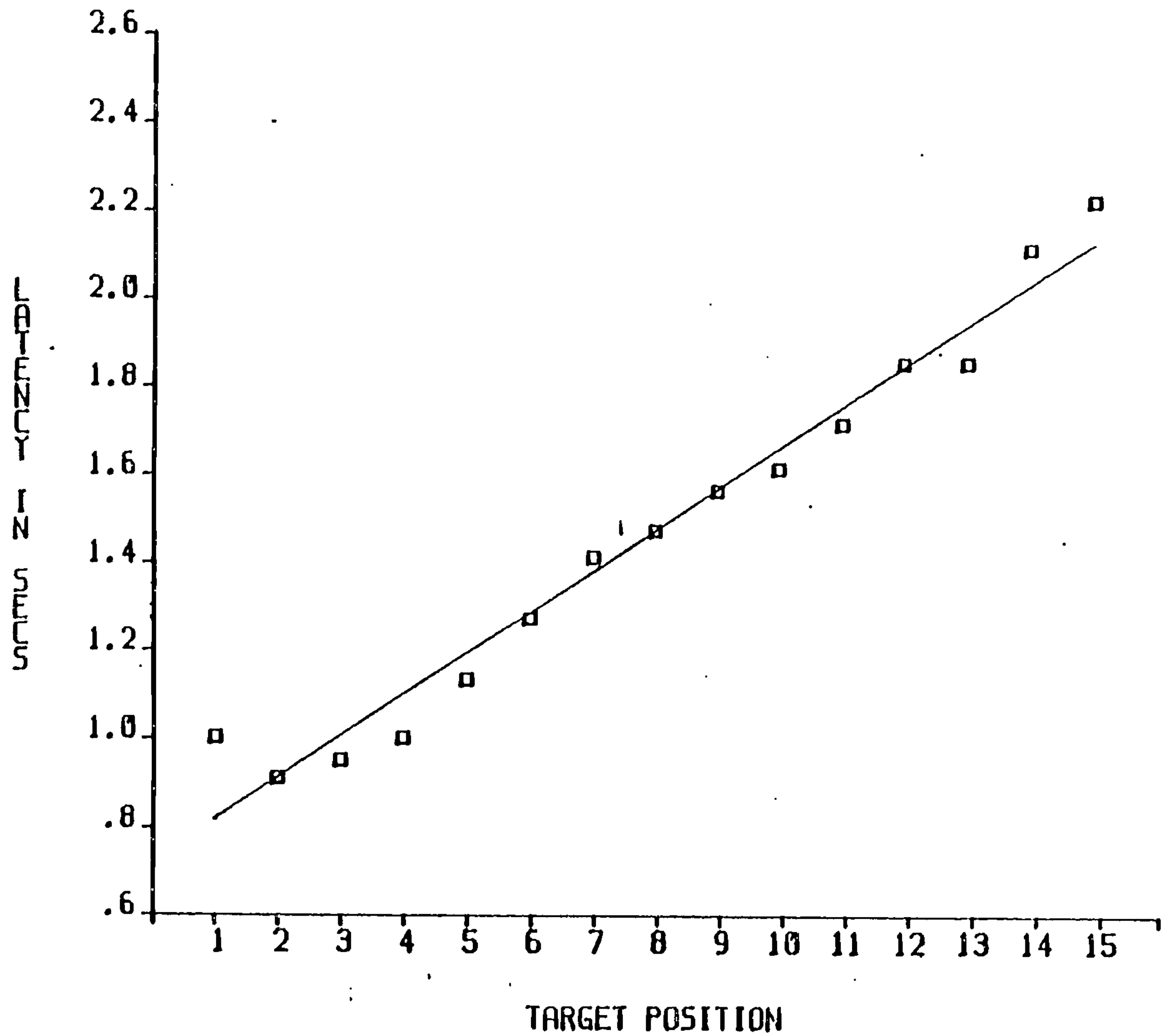

Figure 12. Visual Search I Mean Latencies as a Function of Target Positions.

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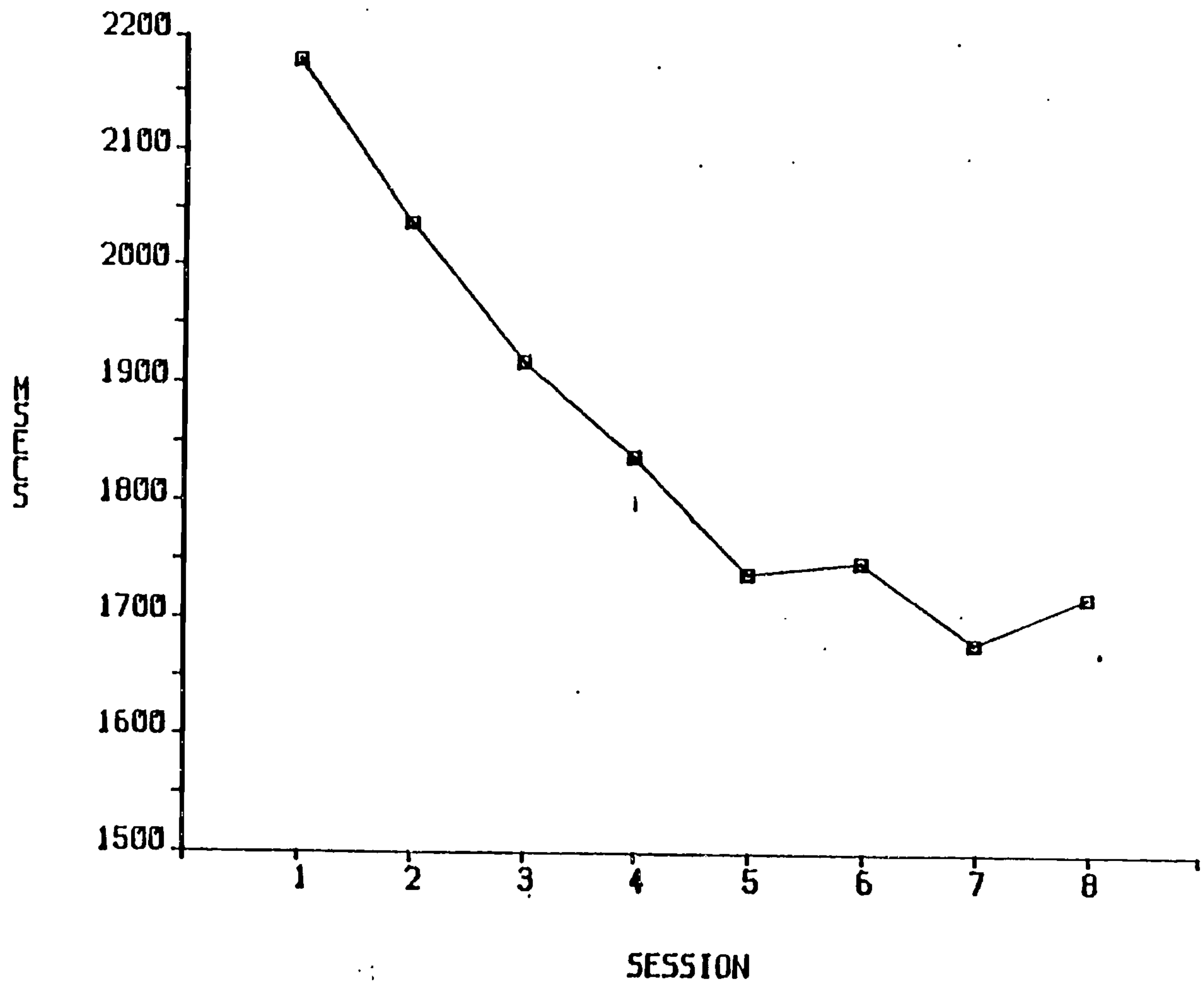


Figure 13. Visual Search I Session Effects.

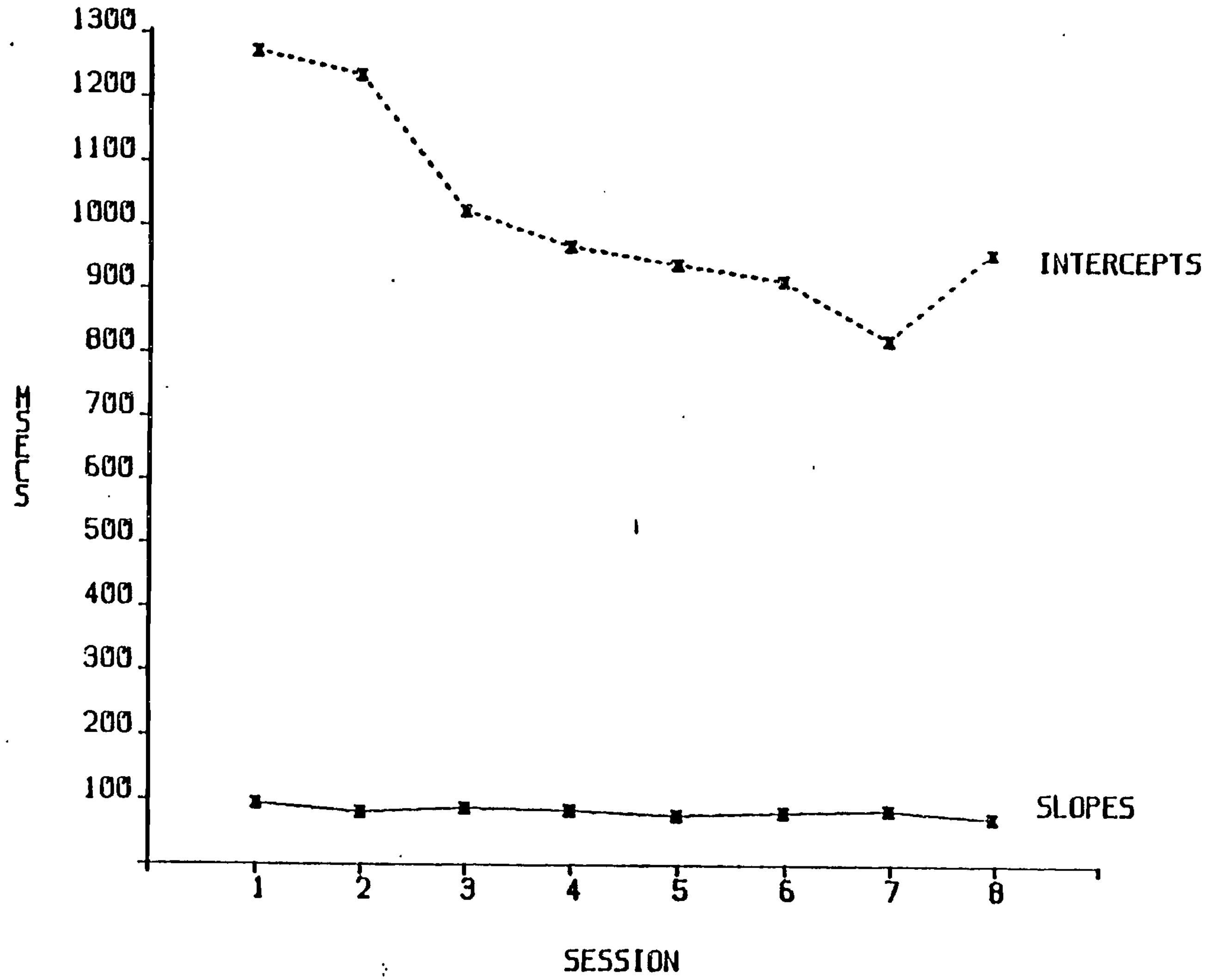


Figure 14. Visual Search I Session Effects for Slopes and Intercepts.

The results obtained in this visual search task were consistent with our expectations. That is, response time was linearly related to target position in the search array. Additionally, we observed improvements in performance over practice which were consistent with a power function. The improvement was moderate and primarily linked to motor response processes.

Semantic Search I. In this task there are two major variables: search type and target position. Our expectations about performances in this task were that in both the member and non-member searches, reaction time should be a linear function of target position. The slope of this function represents encoding, semantic retrieval and comparison time while the intercept reflects choice and motor response processes. Slopes for the member and non-member searches should be identical while the intercept for the non-member search should be higher than the intercept for member search, reflecting additional time for negative final decisions (see e.g., Gitomer, et al., 1983). Components of processing and average reaction time should decrease over sessions for both the member and non-member searches.

Figure 15 presents the group means for member and non-member searches as a function of target position. A linear model provides an extremely good account of both search types. An analysis of variance showed a substantial position effect, $F(5, 310) = 96.64$, $p < .001$. Search type also proved to be highly significant, $F(1, 62) = 226.39$, $p < .001$, which is suggested by the different intercepts of the two functions (1.301 for non-member search but 0.999 for member search). Search type and target position produced a relatively small, $F(5, 310) = 7.83$, $p < .001$, but significant interaction. The source of the interaction can be seen in the slightly steeper slope of the member search function(.146) when compared to the non-member search function (.145).

Not-present trials were not included in the above analysis since they perform the uninteresting function of forcing the subjects to search the array. Briefly, the average latency for not-present trials was expectedly longer than any of the corresponding target position latencies. The non-member not-present latency (M = 2.870) was slightly longer than the member not-present responses (M = 2.793).

Practice effects were analyzed separately for member and non-member search trials and the data are shown in Figure 16. The repeated measures analysis of variance yielded a highly significant practice effect for the member condition, $F(9, 558) = 51.89$, $p < .001$. Member latency dropped an average of 0.647 second between session 1 (M = 2.165) and session 10 (M = 1.518). Non-member latencies also showed a highly significant effect of practice, $F(9, 558) = 27.82$, $p < .001$, with the average latency dropping 0.491 second from 2.379 in session 1 to 1.888 seconds by session 10.

Figure 17 shows the results for the slopes and intercepts of the linear functions relating reaction time to target position for each session and search type. As shown in Figure 17, there was a slight difference in slopes between the member and non-member searches and neither slope value showed any substantial change with practice. The slope parameter represents the time to make a categorical decision for each item in the array. As expected, the time for executing this process is relatively brief with little change over sessions. Figure 17 also shows the results for the intercepts. Consistent

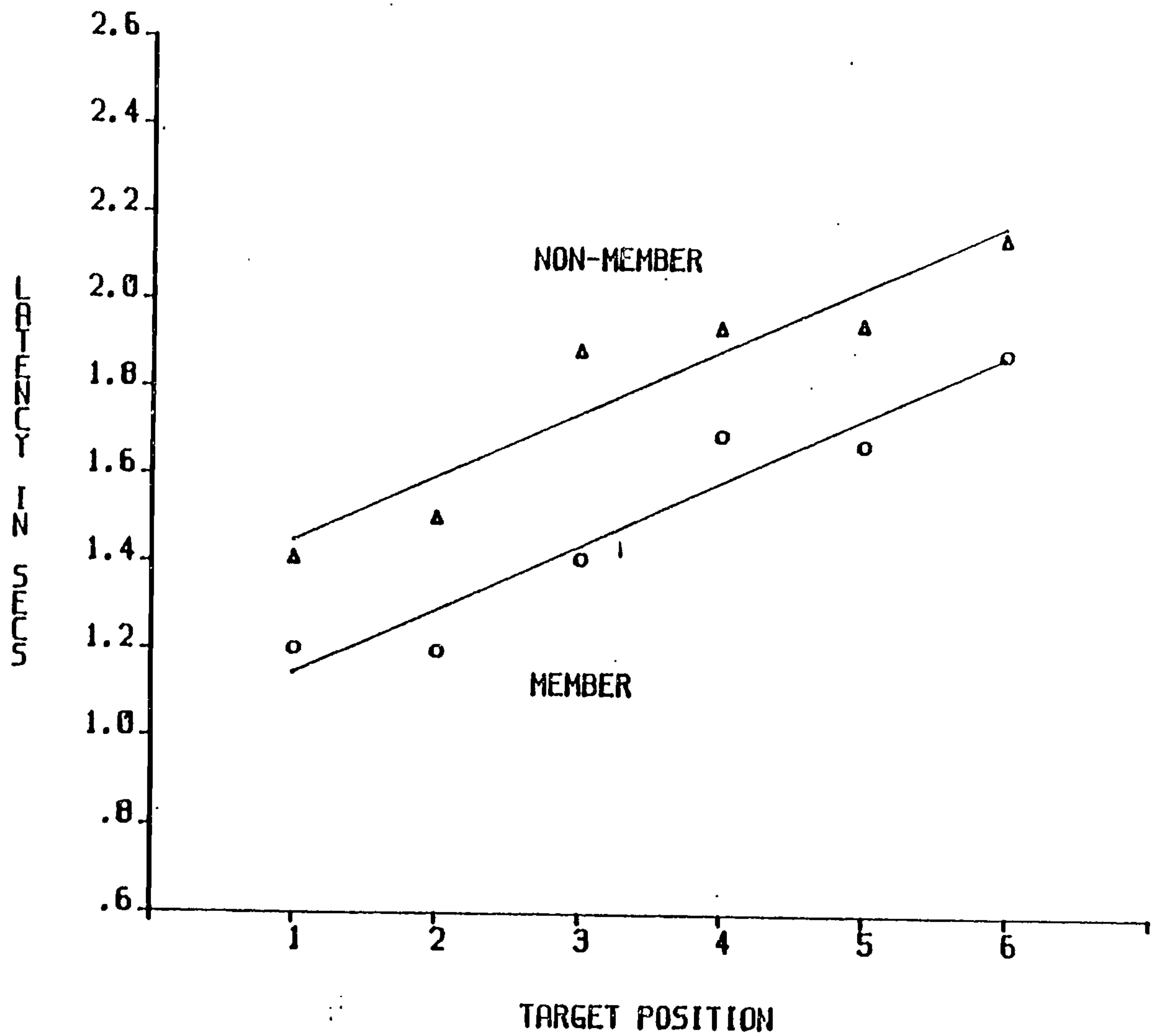


Figure 15. Semantic Search I Mean Latencies as a Function of Target Position for Member and Non-Member Searches.

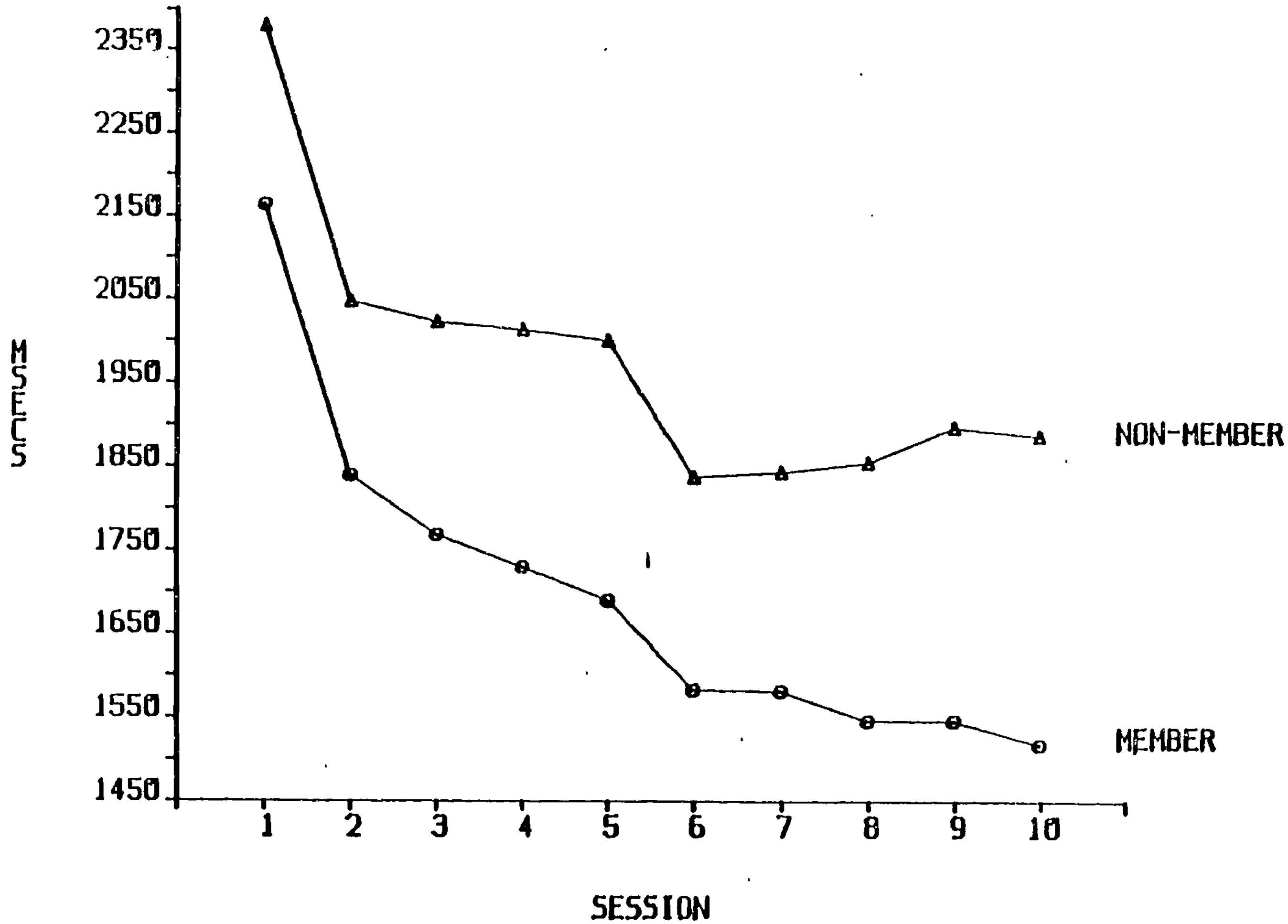


Figure 16. Semantic Search I Session Effects for Member and Non-Member Searches.

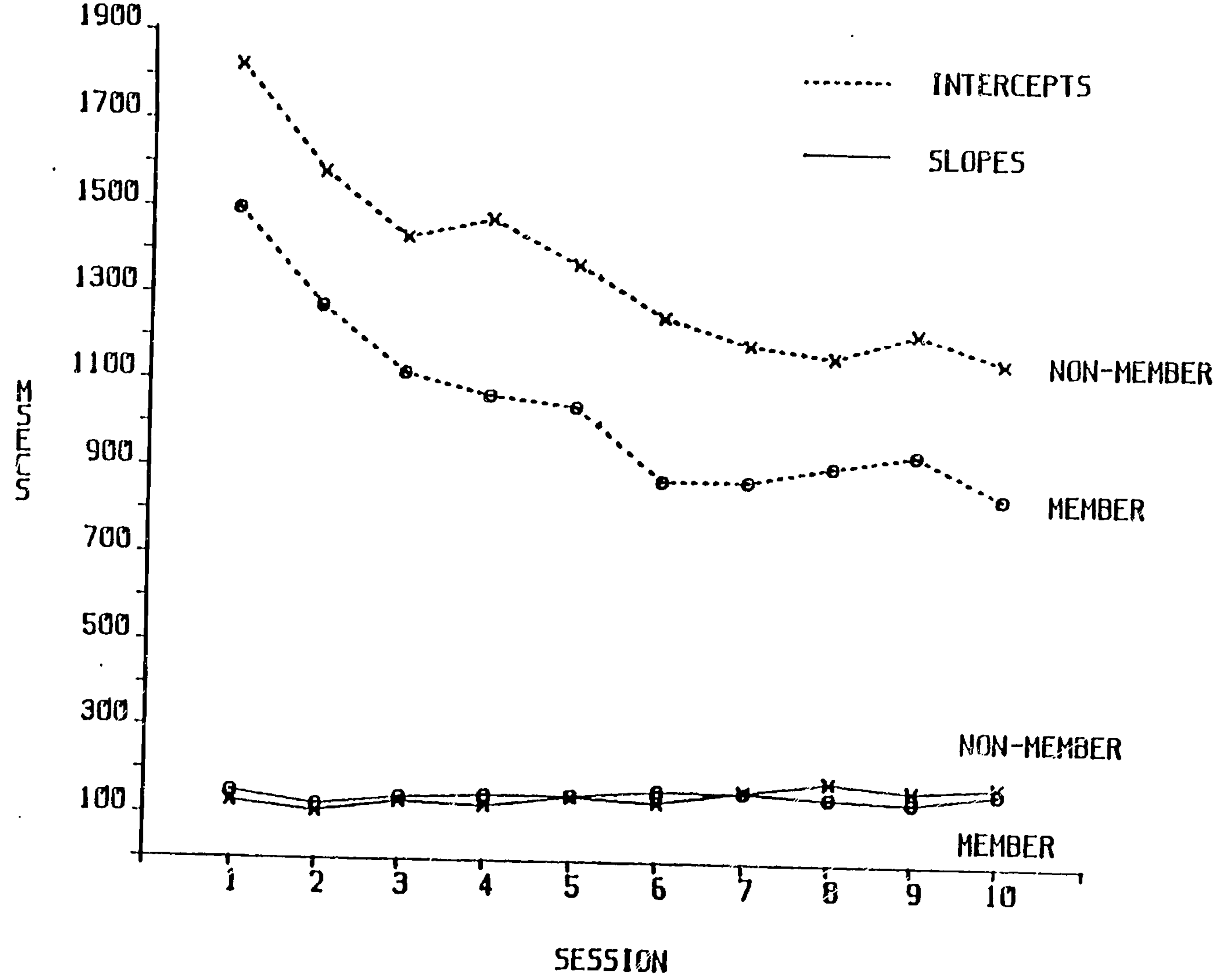


Figure 17. Semantic Search I Session Effects for Slopes and Intercepts of Member and Non-Member Searches.

with the general results shown earlier, the intercept for the non-member search is greater than the intercept for the member search and both show parallel changes over practice. We attribute these changes to improvements in simple motor, perceptual and response choice processes rather than improvements in the speed of making simple categorical decisions.

Taken together these data attest to the internal validity of the task, clearly demonstrating the expected effects. First, varying target position produced linear functions for both member and non-member search conditions. Second, search condition provided a significant effect, with non-member decisions being slower than member decisions. Finally, both search conditions showed strong practice effects although the effect was somewhat more pronounced for member searches. The practice effect was primarily associated with non-semantic processing characteristics of the task.

Summary For Task Battery II. The results obtained for the tasks in this battery are of particular interest relative to those obtained for Task Battery I. First, when a perceptual comparison task involves unfamiliar stimuli of varying complexity, there appears to be a substantial practice effect which is attributable to more than just a simple motor response process. The subjects appear to be learning the stimuli and thus moving from a very analytic mode of processing the stimuli to a more wholistic mode of processing. This suggests that there is skill acquisition in complex perceptual comparisons dealing with unfamiliar stimuli and that part of the acquisition process is learning how to process specific stimuli. This issue is explored further in Task Battery III and Task Battery V using mental rotation and perceptual comparison tasks.

Second, the search task results indicate certain limited changes with practice in these tasks and this was true for both the visual and semantic search tasks. The practice effects seem to have been confined to simple encoding and motor response processes rather than physical comparison or semantic retrieval processes. Thus, it would appear from the results obtained in both Task Battery I and Task Battery II that there is relatively little change in these basic cognitive processes. Adults come to the testing situations with these processing operations at asymptotic performance levels. Simple search tasks, like the simple judgment tasks of Battery I, seem to be excellent measures of current levels of processing efficiency but poor measures of skill acquisition or movement towards automaticity. Given this situation, in Task Battery II we examined performance in two search tasks which allowed for the possibility that subjects could acquire skill in handling multiple comparisons. This was done by using search tasks in which the individual sometimes had to simultaneously search for multiple possible targets. Of concern was whether performance in the multiple-target search would show progress toward parallel processing. The latter is indicated by a multiple-target search speed that does not differ from the search speed obtained when only a single target must be considered.

Task Battery III

Visual Search II. Reaction time in this task should be a linear function of the position of the target. The slope of the one-target search should be less than the slope of the two-target search. This difference reflects a serial mode of target processing and comparison. With practice, differences in slopes and overall mean reaction times should be reduced for the two- versus one-target conditions.

The target position effect obtained in this visual search task was consistent with that obtained in Visual Search I. Decision latency was a linear function of target position for both the 1- and 2- target conditions; the $r(8)$'s were .94 and .99, respectively ($p < .01$, two-tailed). The intercept estimate for the single-target condition was .639, and 1.985 for the two-target condition. Slope estimates for these conditions were .096 and .134. These data are shown in Figure 18. Mean decision time for the single-target condition was shortest when the target appeared in position 2 (M = .819 second) of the search array and then increased linearly to 1.701 seconds for position 10. As in Visual Search I, position 1 (M = .873 second) produced the single anomaly in the data, not fitting a purely linear trend. Decision time in the 2-target condition was shortest for position 2 (M = 1.331 seconds) and then increased linearly to 2.520 seconds for position 10. The inflated decision time observed in the single-target condition at position 1 was attenuated in the 2-target case (M = 1.345 seconds). To provide an integrated picture of these data, they were submitted to a multiple regression analysis with target position and target condition as independent variables. The solution accounted for a highly significant 96.6% of the latency variance, $F(2, 17) = 243.76$, $p < .001$. The beta weights for target condition (beta = .666) and target position (beta = .114) were both highly significant (t's > 15). When collapsed across target position, the search for 1 vs 2 targets produced mean response latencies of 1.325 and 2.086 seconds, respectively. An analysis of variance indicated significant effects of position, $F(9, 513) = 92.97$. $p < .001$; 1 vs 2 targets, $F(1, 57) = 271.94$, $p < .001$; and their interaction, $F(1, 57) = 25.68$, $p < .001$. The longest mean latencies occurred in the not-present condition: M = 2.980 and M = 4.708 for 1 and 2 targets, respectively.

The practice data were partitioned according to target condition (1 vs 2) and subjected to an analysis of variance. These data are shown in Figure 19. The analysis indicated significant effects of session, $F(3, 171) = 70.52$, $p < .001$; target condition, $F(1, 57) = 375.72$, $p < .001$; and their interaction, $F(3, 171) = 17.90$, $p < .001$. A trend analysis on overall latency over sessions indicated highly significant linear, $F(1, 57) = 105.02$, $p < .001$, and quadratic components, $F(1, 57) = 26.15$, $p < .001$. Differences in the slopes of the functions presented in Figure 19 show that asymptotic performance in the single-target condition may occur earlier than in the two-target case. This trend provides some evidence of movement toward parallel processing in the two-target condition.

One of the more interesting aspects of this task is the potential to observe differential changes in the slope of the function relating decision latency to target position for the 1- and 2-target conditions. That is, convergence of the slope in the two-target condition toward that of the one-target condition would strongly suggest a shift to a parallel mode of processing in the two-target case. Figure 20 shows the individual session data for the slopes and intercepts of the linear function relating reaction time to target position for the one- and two-target search conditions. As can be seen in Figure 20, the slope of the two-target condition is greater than the slope of the one-target condition and this difference is consistent over all sessions of practice. Neither slope shows any substantial change with

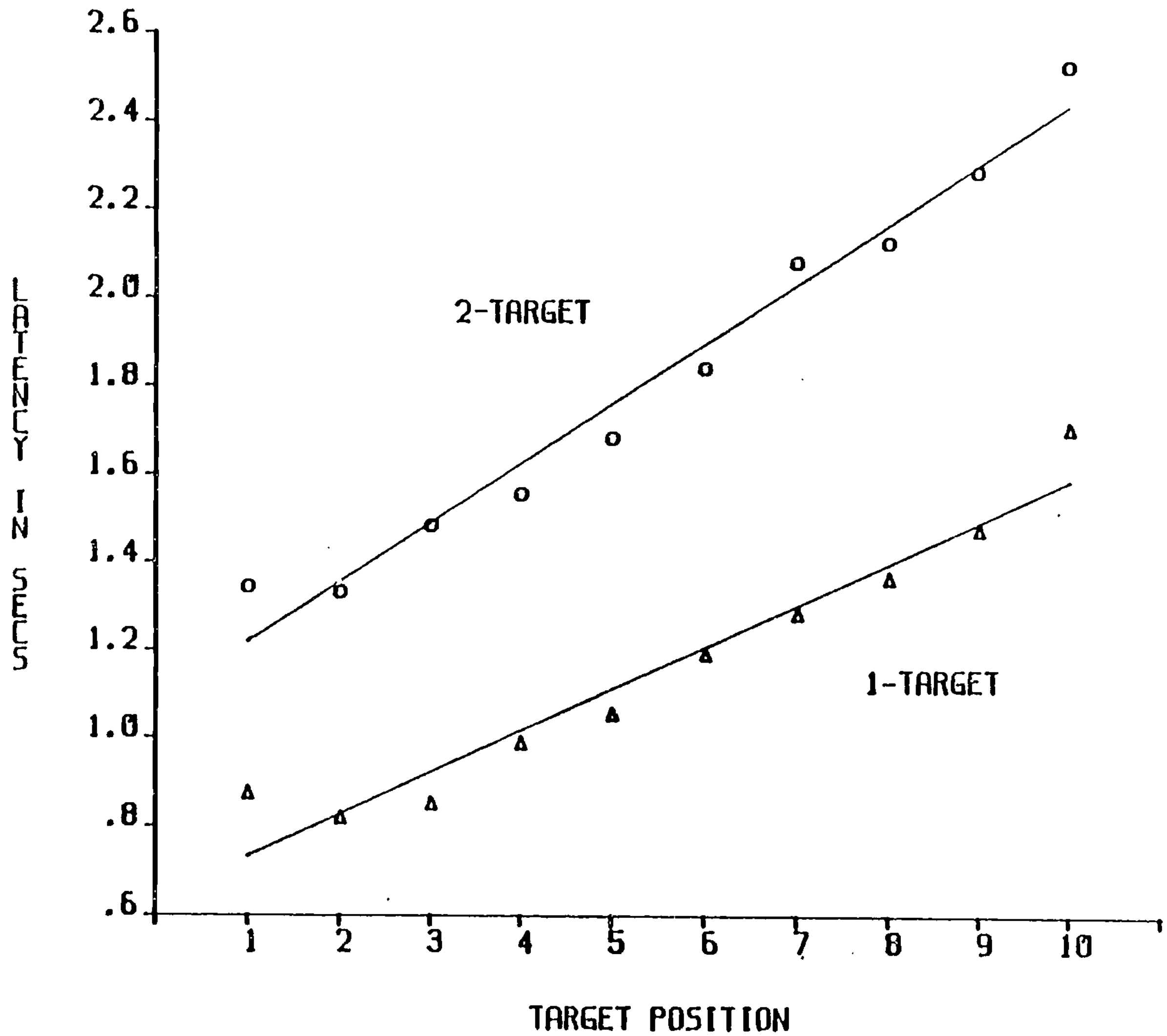


Figure 18. Visual Search II Mean Latencies as a Function of Target Position for 1- and 2-Target Searches.

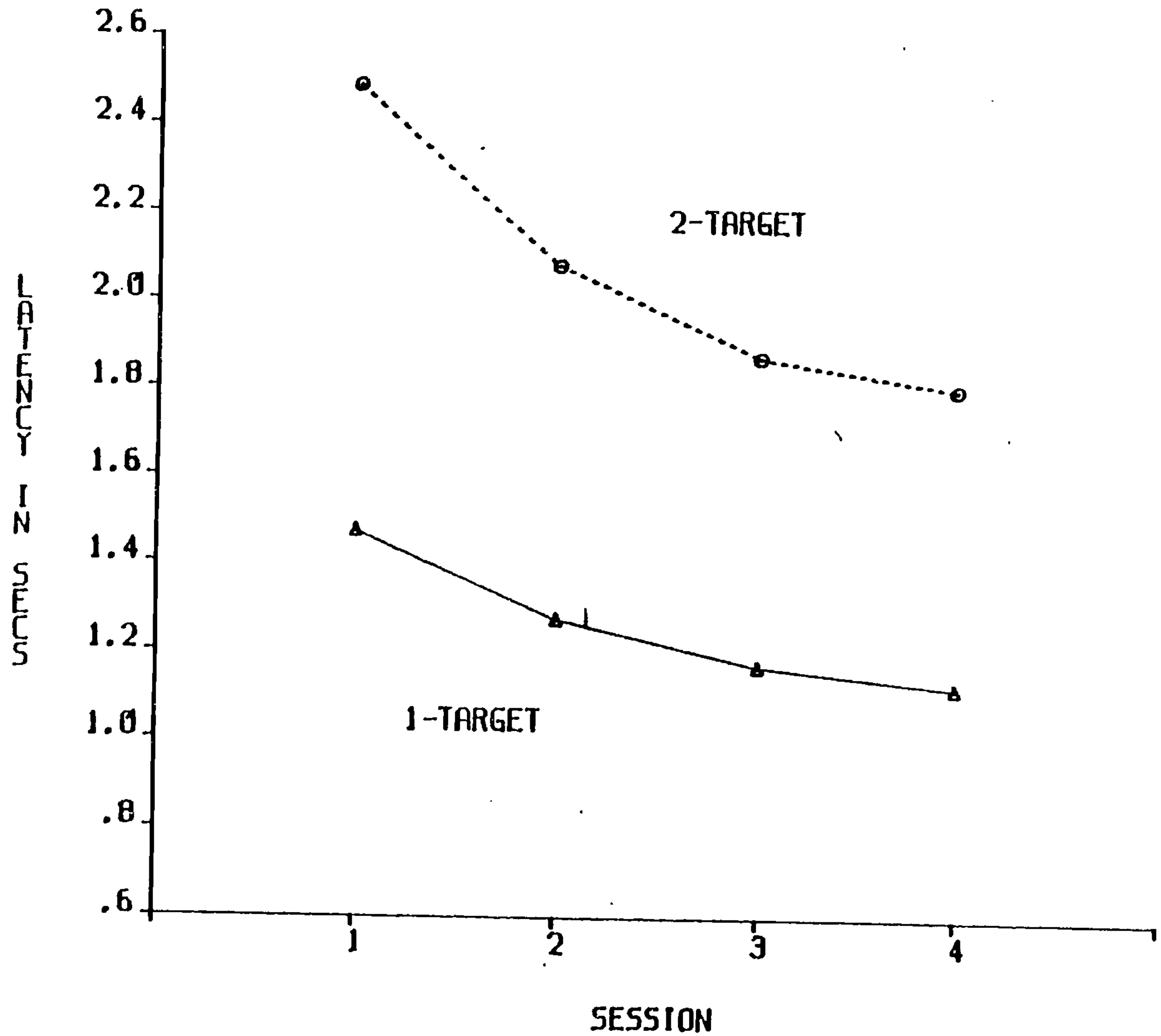


Figure 19. Visual Search II Session Effects for 1- and 2-Target Searches.

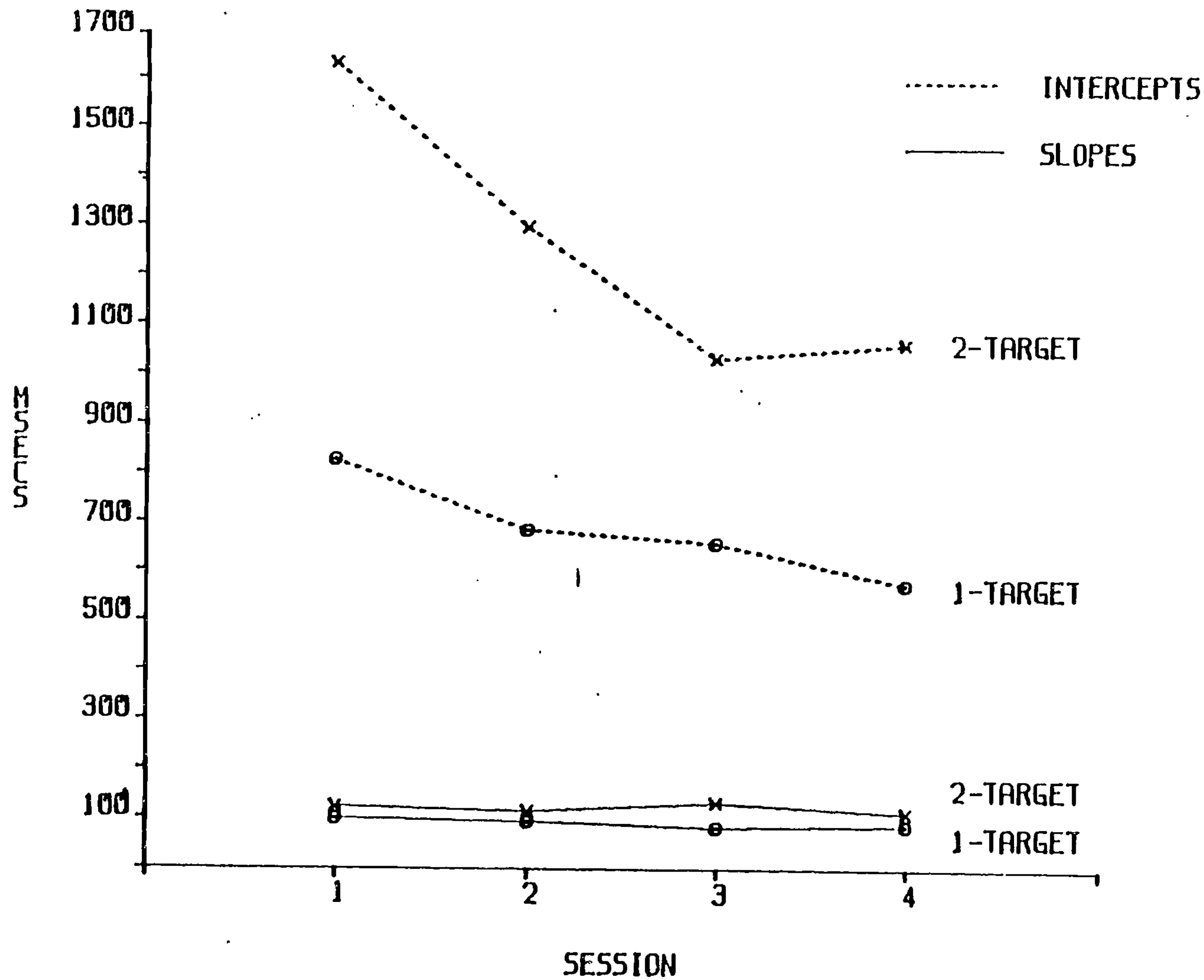


Figure 20. Visual Search II Session Effects for Slopes and Intercepts of 1- and 2-Target Searches.

practice. Thus, the results for the one-target condition are similar to those observed for Visual Search I and the present data reveal little evidence of a convergence of slopes for the multiple- versus single-target visual search conditions. Figure 20 also reveals that both the one- and two-target condition intercepts changed over practice, with the intercept for the two-target condition systematically higher than the intercept for the one-target condition. The change over sessions for the two-target condition is greater than for the one-target condition but the difference between intercepts remains substantial after four sessions of practice. The observed intercept changes can be attributed primarily to motor response and choice processes. Taken together, the slope and intercept results provide little support for movement towards parallel processing in the multiple-target visual search task.

In summary, the analyses of performance in this task support our general expectations regarding processing. In both the 1- and 2-target conditions there are linear search functions, with the slope of the 2-target condition greater than the slope of the 1-target condition. Both search conditions show practice effects and there is a more marked practice effect for the 2-target condition. Decomposition of the practice effect differences in terms of changes in process parameters provided little support for movement towards parallel processing in the multiple-target condition.

Semantic Search II. As in Semantic Search I, it is expected that reaction time in each condition should be a linear function of the position of the target. The slope of the linear function for the 4-target search should be greater than the slope for 2-target search, which in turn should be greater than the slope for 1-target search. Differences in slopes and average reaction times should be reduced over sessions for the different search conditions.

Figure 21 shows the means for each target position for 1-, 2- and 4-target searches. A linear function provided a very good description of each data set; the r's(4) were .997, .996 and .983, respectively ($p < .01$, two-tailed). There was an orderly increase in the intercept estimates for each condition; 0.378, 0721 and 1.001 for 1-, 2- and 4-target categories, respectively. As can be seen in Figure 21, the slopes of the three functions fan out across target positions; the estimates were 0.238, 0.329 and 0.504 for the 1-, 2- and 4-target categories, respectively. To provide an integrated picture of these data, they were submitted to a multiple regression analysis with target position and target condition as independent variables. The solution accounted for 94% of the latency variance, $F(2, 15) = 116.71$, $p < .001$. The beta weights for target condition (beta = 0.508) and target position (beta = 0.357) were both highly significant (t's > 10).

An analysis of variance revealed a highly significant effect of target position, $F(5, 315) = 346.54$, $p < .001$, supporting the strong linear fits and the significant beta weight for target position reported above. The number of target categories also proved to be highly significant, $F(2, 126) = 229.32$, $p < .001$, and confirms the results reported earlier. Finally, the two factors significantly interacted, $F(10, 630) = 35.28$, $p < .001$, a reflection of the fanning of the slopes as seen in Figure 21.

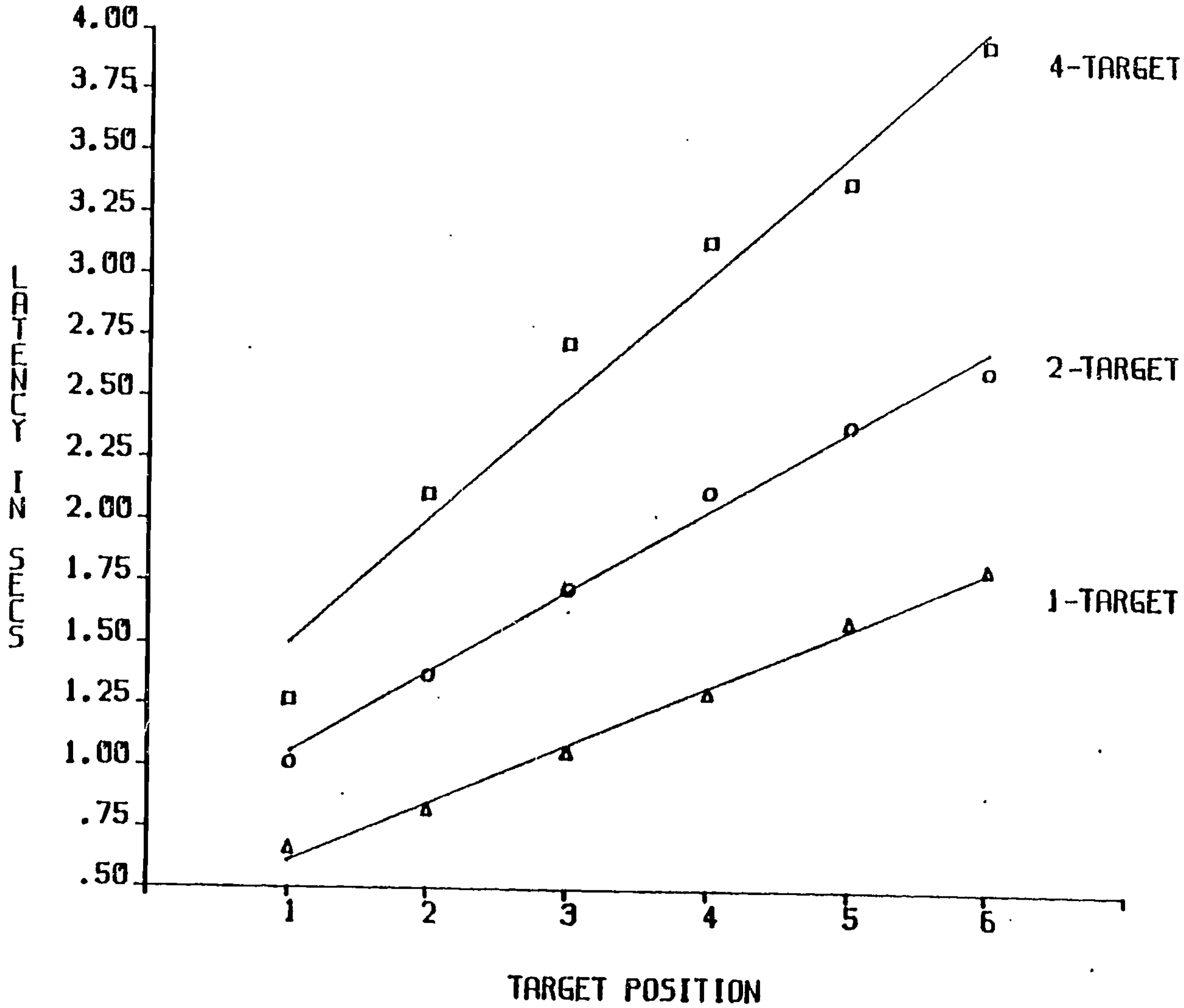


Figure 21. Semantic Search II Mean Latencies as a Function of Target Position for 1-, 2- and 4-Target Searches.

Practice effects for this task are shown in Figure 22. An analysis of variance revealed a substantial effect of session, $F(3, 189) = 42.49$, $p < .001$. The effect of number of targets was also quite substantial, $F(2, 126) = 256.02$, $p < .001$. Most importantly, there was a highly significant interaction of session and number of targets, $F(6, 378) = 15.73$, $p < .001$. The locus of the differential practice effects occurring in the one-, two-, and four-target conditions was examined by determining slopes and intercepts of the linear function relating reaction time to target position for each session for each search condition. Figures 23 and 24 show the session results for the slopes and intercepts. As shown in Figure 23, changes occurred in the slopes for the two- and four-target conditions, with the largest change exhibited in the four-target condition. However, after four sessions of practice, there were still substantial slope differences among the single- and multiple-target search conditions. As shown in Figure 24, intercept differences were apparent for all sessions of practice and the four-target condition showed the most substantial intercept change over sessions. These slope and intercept data suggest that there is evidence of movement towards more efficient parallel processing in the multiple-target search conditions but that more extensive practice may be needed for such effects to occur. This is in contrast to the results obtained in the Visual Search II task.

In summary, the expected results for this task were obtained. Target position produced a linear increase in latency for the 1-, 2- and 4-target search conditions. As the number of target categories increased, trial latency systematically increased. Finally, analyses of practice effects suggest significant overall performance changes, especially in the multiple-target search conditions, with evidence of movement towards parallel processing in these conditions.

Mental Rotation. In all mental rotation tasks it is assumed that reaction time is a linear function of angular disparity between the standard and comparison stimuli in any given trial pair. This is the case whether the pair represents a same or different judgment trial. Analyses of the data showed that such linear functions were obtained for all subjects during all sessions and for all stimulus sets (see Table 9 for average r^2 values). Thus, we derived slope and intercept measures for same and different judgment trials for each stimulus set in each session. Table 9 provides a summary of these data. The general pattern of results was consistent with results from a variety of studies of mental rotation that we have previously done (e.g., Pellegrino & Kail, 1982). As can be seen in Table 9, the slope for different judgments is initially shallower than the slope for same judgments, but by the end of the practice sessions there is no difference in the same versus different judgment slopes. Typically, the intercept for different judgments is greater than the intercept for same judgments and this result was also obtained. This difference in intercepts did not disappear by the end of practice nor would one expect it to since it is attributable to the emission of a negative response which typically adds 50 to 200 msec to response latency.

Our particular concern in this study was the effects of practice on parameters of the mental rotation function. These effects are easier to see in Figures 25 and 26. Figure 25 presents the same judgment intercept data for the different stimulus sets as a function of testing session. Figure 26 is a similar plot of the same judgment slope data. Both figures show the general

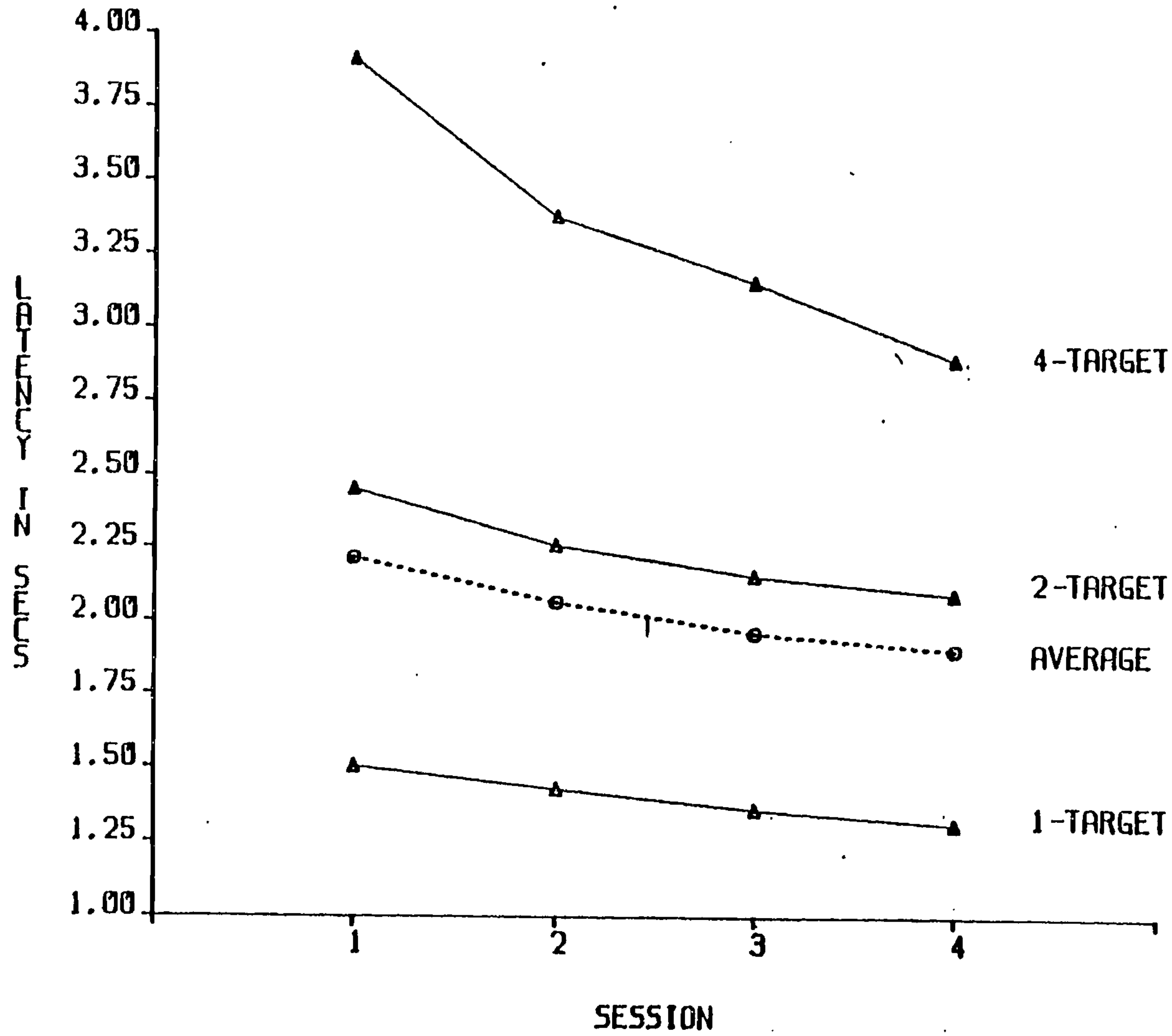
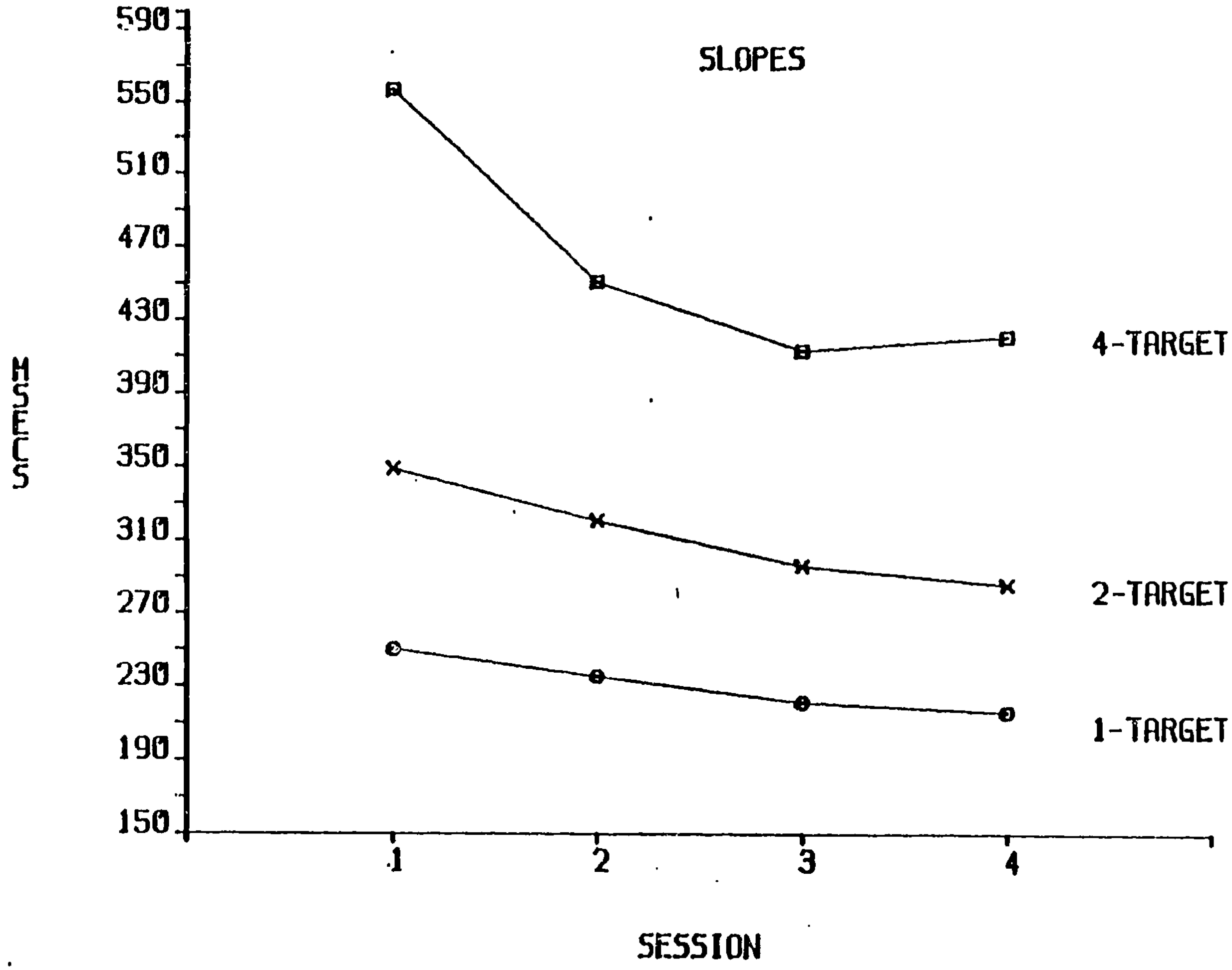


Figure 22. Semantic Search II Session Effects for 1-, 2-, 4- and Average Target Searches.



<u>Figure 23.</u> Semantic Search II Session Effects for Slopes of 1-, 2-, and 4-Target Searches.

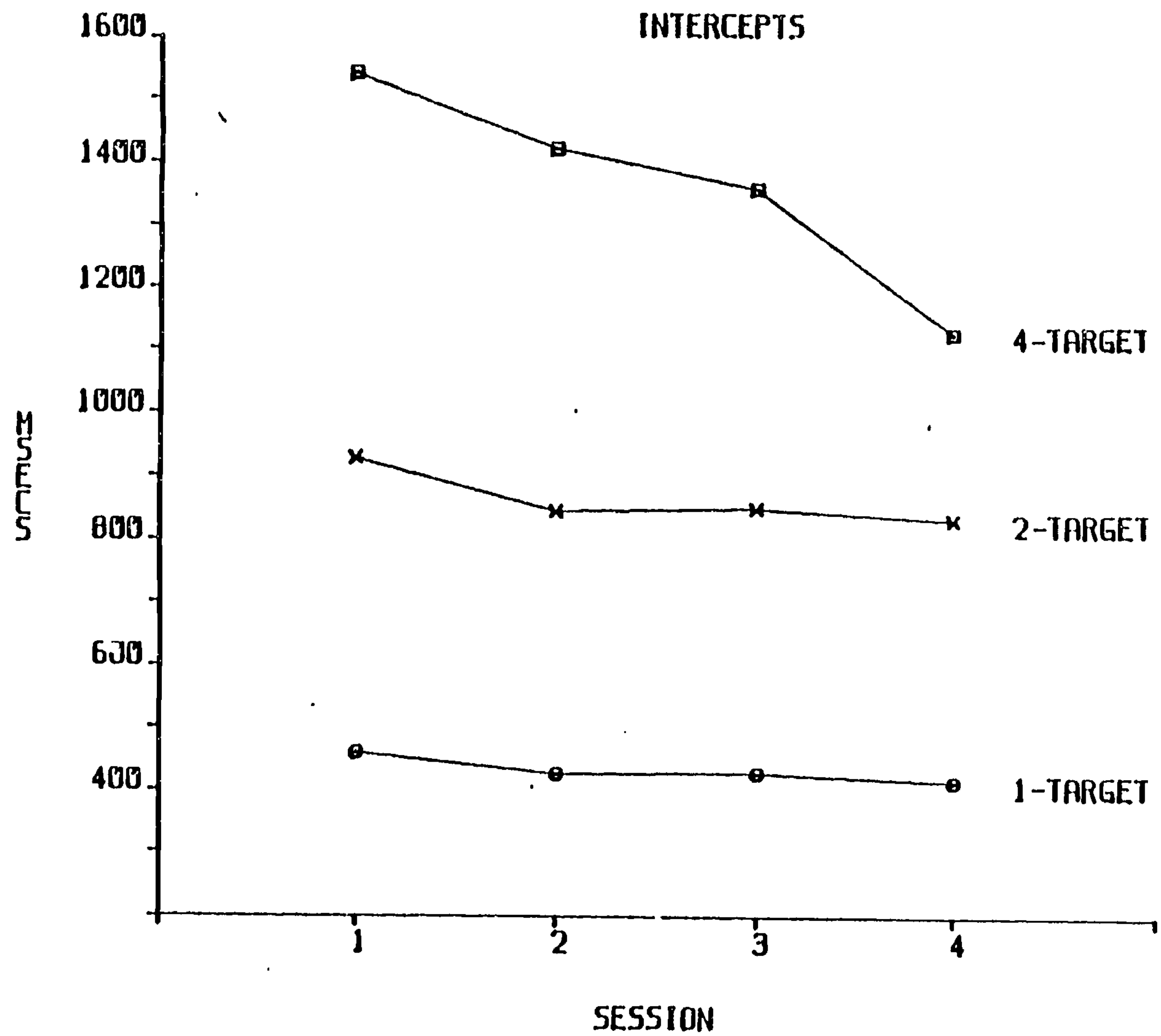


Figure 24. Semantic Search II Session Effects for Intercepts of 1-, 2-, and 4-Target Searches.

Table 9. Mean Rotation Slope, Intercept and r^2 Values by Session and Stimulus Set

Measure	Stimulus set	Session 1	2	3	4	5	6	7
Same slope (sec.)	X	5.96	4.30	3.36	3.13	2.78	2.76	2.60
	Y	6.23	4.88					3.09
	W			4.03	3.54			2.98
	Z					3.99	3.40	2.95
Same intercept (sec.)	X	.883	.694	.656	.608	.624	.598	.604
	Y	.891	.692					.650
	W			.731	.664			.642
	Z					.714	.635	.657
Same r^2	X	.65	.68	.70	.69	.61	.66	.63
	Y	.67	.70					.69
	W			.70	.68			.67
	Z					.67	.62	.61
Different slope (sec.)	X	5.41	4.09	3.49	2.96	3.01	2.86	2.75
	Y	5.18	4.06					3.08
	W			4.30	3.39			3.43
	Z					4.04	3.52	3.01
Different intercept (sec.)	X	1.159	.877	.781	.738	.729	.710	.708
	Y	1.174	.914					.794
	W			.881	.784			.750
	Z					.850	.766	.764
Different r^2	X	.56	.59	.63	.61	.54	.61	.57
	Y	.50	.58					.59
	W			.61	.63			.60
	Z					.55	.62	.62

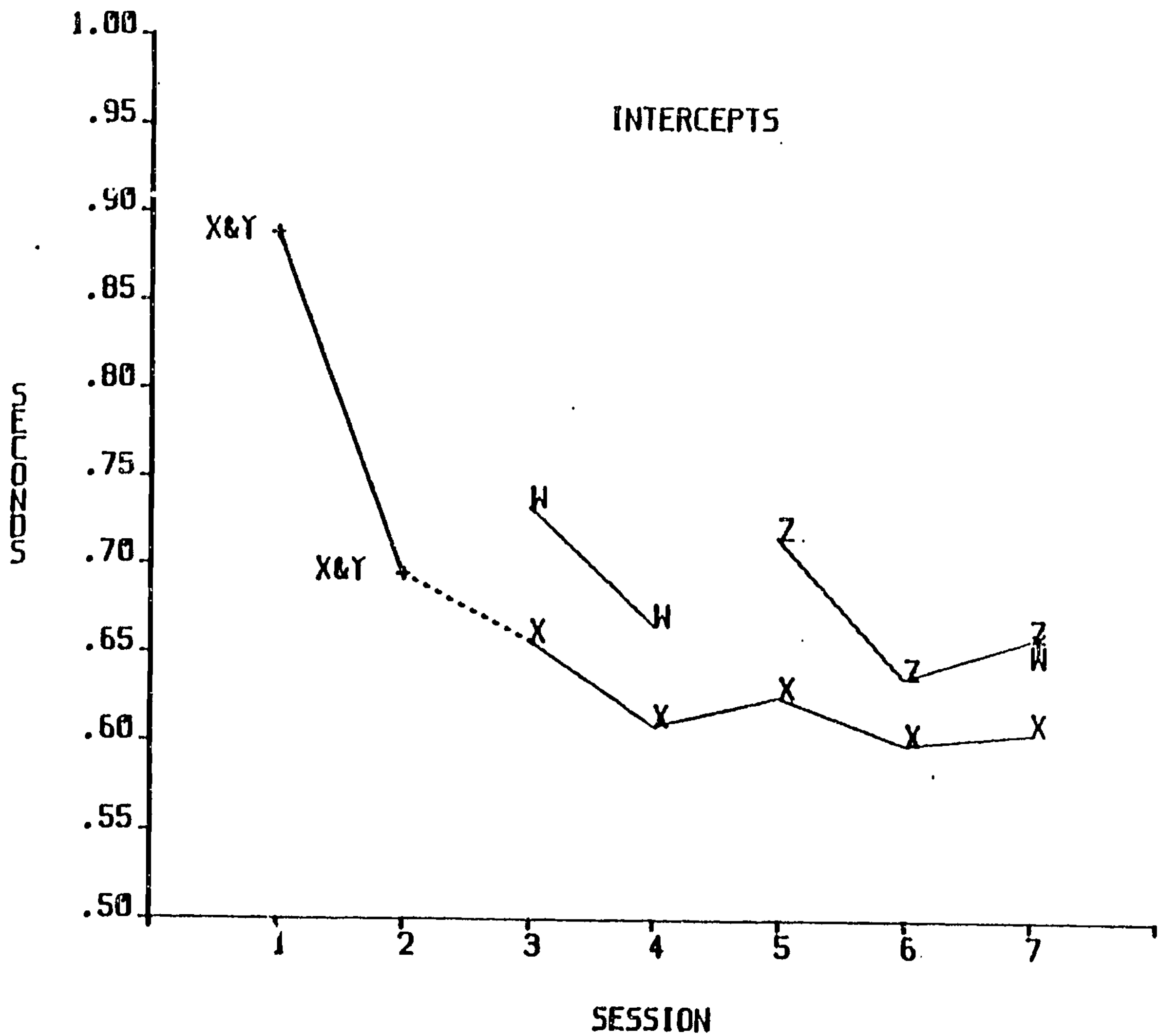


Figure 25. Mental Rotation Intercept Changes by Session for X, X & Y, W, and Z Stimulus Sets.

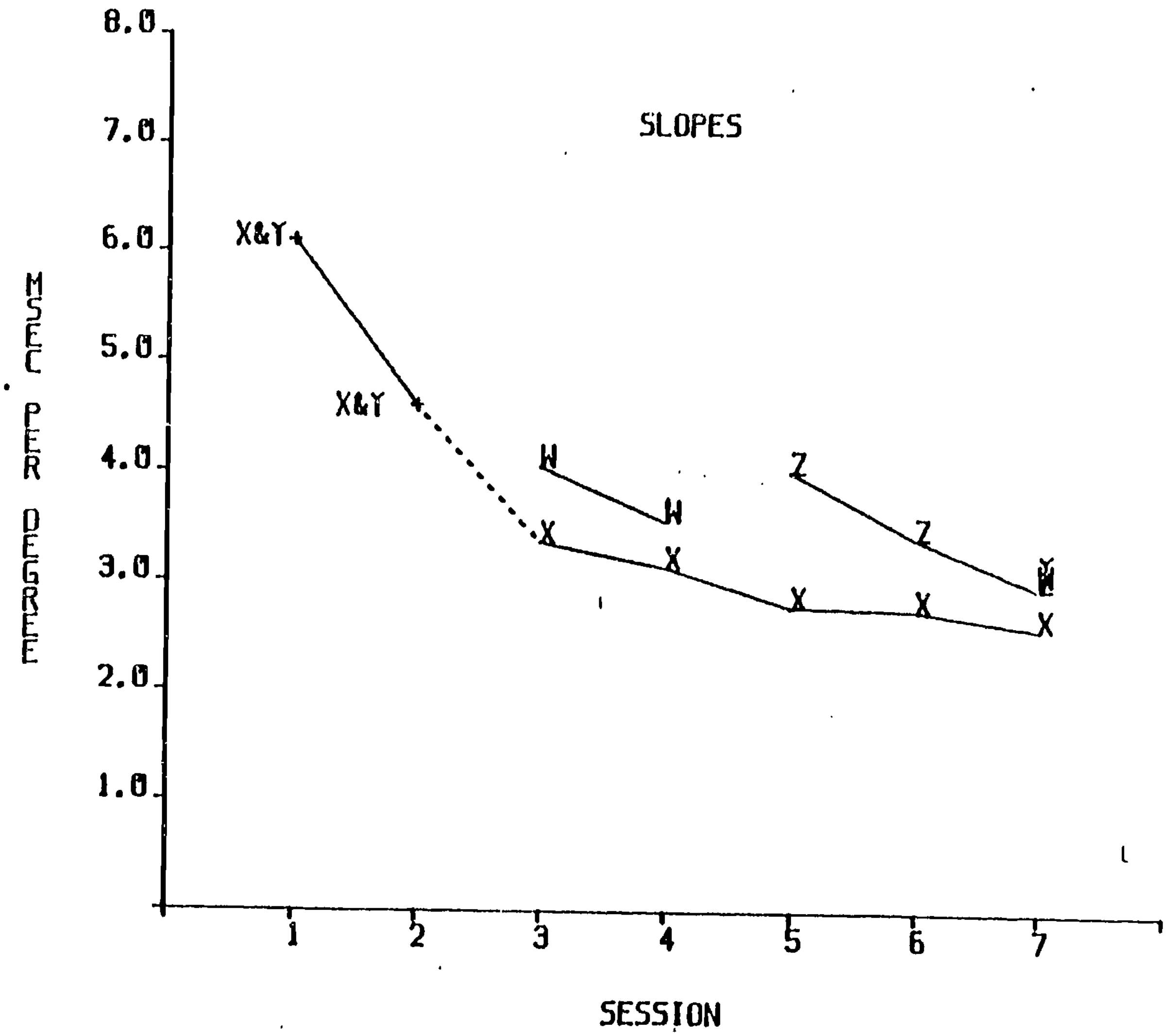


Figure 26. Mental Rotation Slope Changes by Session for X, X & Y, W, and Z Stimulus Sets.

practice effect obtained for the X stimuli over sessions. The time for mental rotation decreases and the time to encode, compare and respond to such stimuli also systematically declines over sessions. Of particular interest are the data for sessions 3, 5, and 7. In both sessions 3 and 5, a new set of stimuli is introduced. These new stimuli show differences relative to the X stimuli with respect to rotation rate and encoding, comparison and response speed. Session 7 contains all four stimulus sets and the data indicate that the X stimuli remain superior to the other three stimulus sets which are equivalent. Of additional interest is performance on the Y and W stimulus sets in session 7. The data suggest that there is generalized transfer to these stimulus sets given their prior performance levels. Thus, our design allows us to separate out item-specific and general practice effects for components of mental rotation, both of which appear to occur over practice in this task.

The other major aspect of this study was the pretest and posttest administration of spatial ability tests. Previous research in our laboratory has shown substantial gains on standardized spatial ability tests after practice on spatial processing tasks. Table 10 contains pretest and posttest scores on the various perceptual and spatial tests administered. As shown in the table, there were substantial practice-related gains in reference test performance for all tests (*t*'s (58) > 3, *p*'s < .05) except the CABP. The latter is a measure of perceptual speed for alphanumeric stimuli whereas all the other tests use figural stimuli. The largest gains were observed for the Cards Rotation Test (CRT), which contains stimuli very similar to those used in the rotation task. Both absolute and relative gains were reduced for the more complex spatial visualization tests (SD and DAT).

The analyses of test score changes suggest that extended practice in spatial processing tasks systematically affects reference ability scores and patterns. The effects are limited to figural-pictorial stimuli. These test score results are also consistent with results obtained for stimulus sets within the rotation task, suggesting both item-specific and general practice effects for component of processing figural stimuli.

Summary For Task Battery III. The results obtained for the three tasks in this battery are particularly interesting in light of issues about changes in processing efficiency with practice. First, the results for the mental rotation task indicate that substantial stimulus-specific learning appears to occur for the processing of unfamiliar stimuli. This is true not only for basic encoding and comparison processes but also for specific transformation processes. In addition to the stimulus-specific skill acquisition effects, there appear to be general processing effects that transfer across stimulus sets and even transfer to reference ability tests. The issue of skill acquisition in processing unfamiliar materials is further examined in Task Battery V.

The results for the two search tasks indicate that searching for multiple targets is a difficult task and that individuals must begin by using a serial, controlled processing mode. With practice, performance improves. In the semantic search task which has constant mapping, there appears to be a shift toward more efficient parallel processing; i.e., the slopes for the 1-, 2- and 4-target search conditions are converging. In the visual search task which has variable mapping, there is less evidence for convergence of slopes. Given the complexity of these search tasks and the limited evidence from the four

Table 10. Pretest and Posttest Reference Test Scores for Subjects Performing the Mental Rotation Task

Point of testing	Perceptual speed: CABP	Perceptual speed: IP	Spatial relations: PMA	Spatial relations: CRT	Spatial visualization: SD	Spatial visualization: DAT
Pretest	60.7	77.8	49.5	130.7	45.9	46.4
Posttest	62.8	87.1	57.5	145.4	53.7	52.0
Absolute change	2.1	9.3	8.0	14.7	7.8	5.6

Spatial aptitude measure

sessions of practice, it was deemed desirable to conduct further tests of both these tasks but under conditions of more practice. Thus, Task Battery IV consists of these two search tasks, both of which were administered for 10 sessions of practice.

Task Battery IV

Visual Search III. This task was identical to Visual Search II, with the exception that subjects performed this task for 10 sessions as opposed to the 4 sessions of practice in Visual Search II. As expected, there was a highly significant effect of number of targets, $F(1, 22) = 33.19$, $p < .001$, which is shown in Figure 27. This figure also shows the significant effect of target position, $F(9, 198) = 87.98$, $p < .001$, and the target position by number of targets interaction, $F(9, 198) = 13.73$, $p < .001$. In both search conditions, reaction time was a linear function of target position and the slope of the linear function was greater in the 2-target search condition. These results are virtually identical to those observed in Visual Search II.

Figure 28 shows the mean reaction times for the 1- and 2-target search conditions for each session of practice. As can be seen in the figure, there was a highly significant session effect, $F(9, 198) = 22.8$, $p < .001$, with both search conditions showing practice effects consistent with power functions. The effect of number of targets was significant, $F(1, 21) = 225.24$, $p < .001$, as was the interaction of number of targets and sessions, $F(9, 198) = 4.33$, $p < .001$. As can be seen in Figure 28, the difference between the 1- and 2-target conditions was greatest during the initial sessions of practice and diminished over sessions. The overall reaction time practice effects shown in Figure 28 were examined in terms of the slopes and intercepts of the linear function relating reaction time to target position in each search condition.

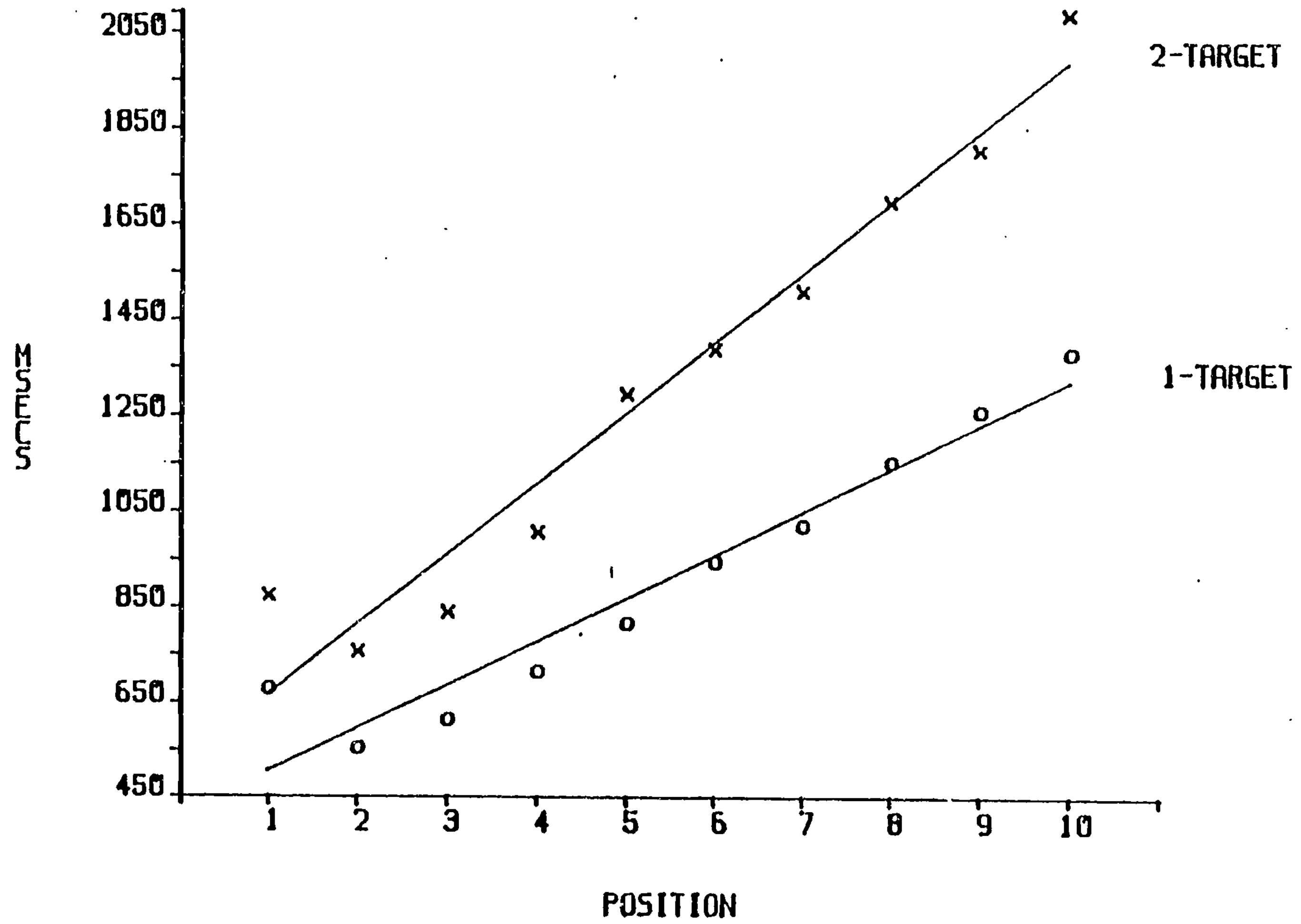


Figure 27. Visual Search III Mean Latencies as a Function of Target Position for 1- and 2-Target Searches.

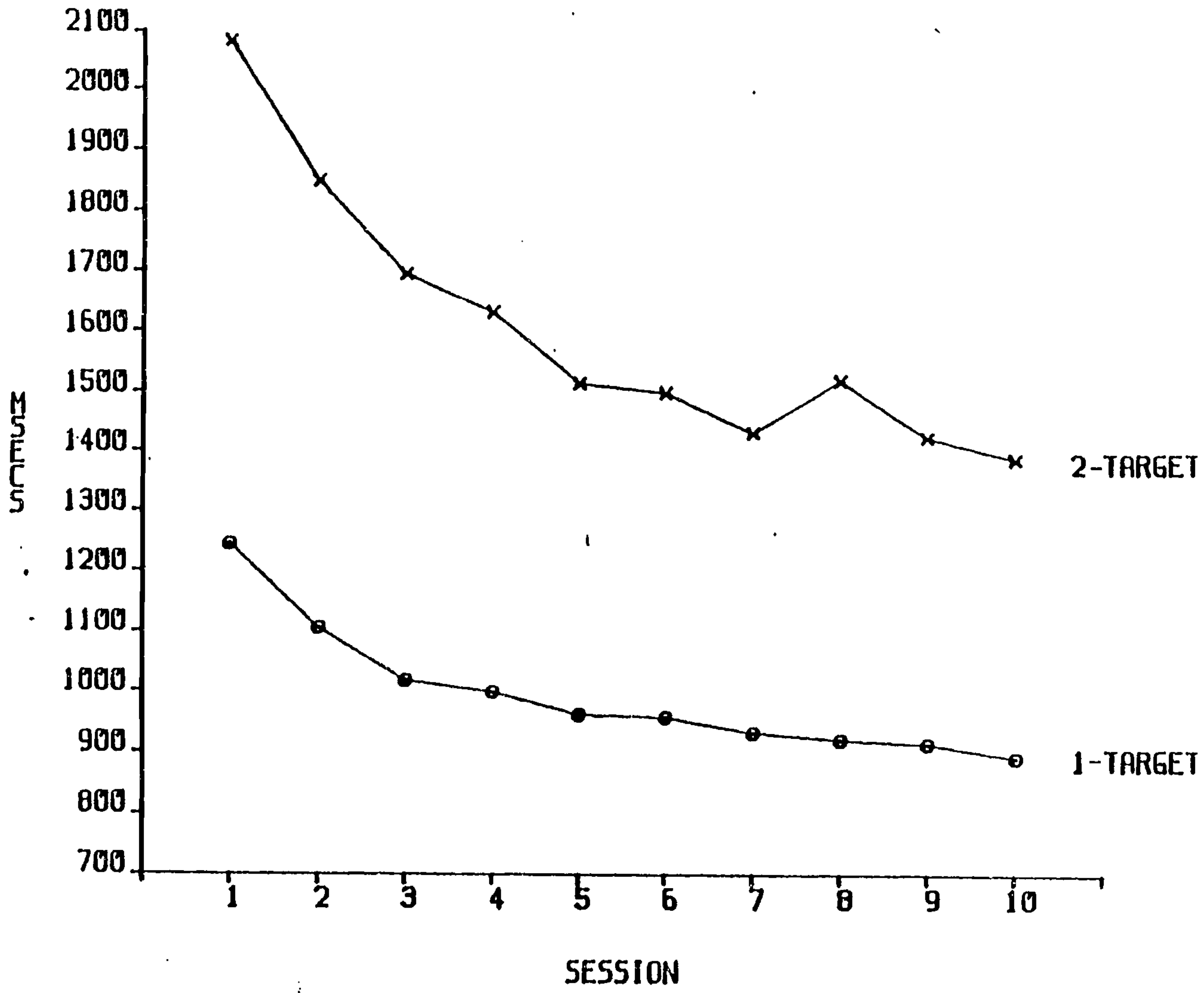


Figure 28. Visual Search III Sessions Effects for 1- and 2-Target Searches.

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Figure 29 shows the results for the slope parameters. As was the case with the Visual Search II task, the slope for the 2-target condition is higher than the slope for the 1-target condition, and neither slope shows any substantial change with practice. Thus, even with more extensive practice, there is little evidence for movement towards parallel processing with regard to matching stimuli against these multiple visual targets. Figure 29 also shows the results for the intercepts and the outcomes are once again similar to those observed for Visual Search II. Both search conditions show improvements in the intercept parameter and these improvements continue over the entire course of practice.

As noted above, the results for this task were completely in accord with those obtained in Visual Search II. The primary purpose of conducting this extension was to determine if more extensive practice would produce evidence of substantially improved performance in the two-target search condition relative to the single-target search condition. The results, however, suggest that there is little evidence of movement towards parallel processing in the multiple-target search conditions even after 10 sessions of practice.

Semantic Search III. This task was identical to Semantic Search II, with the exception that 10 sessions of practice were provided rather than the 4 sessions presented in Semantic Search II. As expected, there was a highly significant effect of number of targets, $F(2, 44) = 134.99$, $p < .001$, and this is shown in Figure 30. Across all three search conditions there was a highly significant linear effect of target position, $F(5, 110) = 560.54$, $p < .001$, and an interaction of target position and number of targets, $F(10, 220) = 45.97$, $p < .001$. The latter reflects the steepening of the slopes of the linear functions relating reaction time to target position as number of targets increases. These results are virtually identical to those obtained in Semantic Search II.

Figure 31 shows the mean reaction times for the different search conditions for each session of practice. As shown in this figure, there were highly significant effects of session, $F(9, 198) = 58.93$, $p < .001$, and number of targets, $F(2, 44) = 151.20$, $p < .001$, as well as a substantial interaction of session and number of targets, $F(18, 396) = 33.95$, $p < .001$. These data reveal a substantial convergence in performance for the different search conditions over sessions. In session 1, the difference between the 1- and 4-target conditions was 2170 msec, whereas the difference was 604 msec by session 10. The multiple-target conditions clearly show the most substantial changes with extended practice.

To examine the general practice effects shown in Figure 31, analyses were performed on the slopes and intercepts of the linear functions relating reaction time to target position for each search condition. The slope results are shown in Figure 32. These data reveal differential changes in the slopes, with minimal change in the 1-target condition (28-msec difference between sessions 1 and 10) and a substantial change in the 4-target condition (270-msec difference between sessions 1 and 10). The change for the 2-target condition was intermediate (81 msec). Figure 33 shows the intercept data, which are similar in pattern to those obtained for the slopes. The largest change over sessions was exhibited in the 4-target condition.

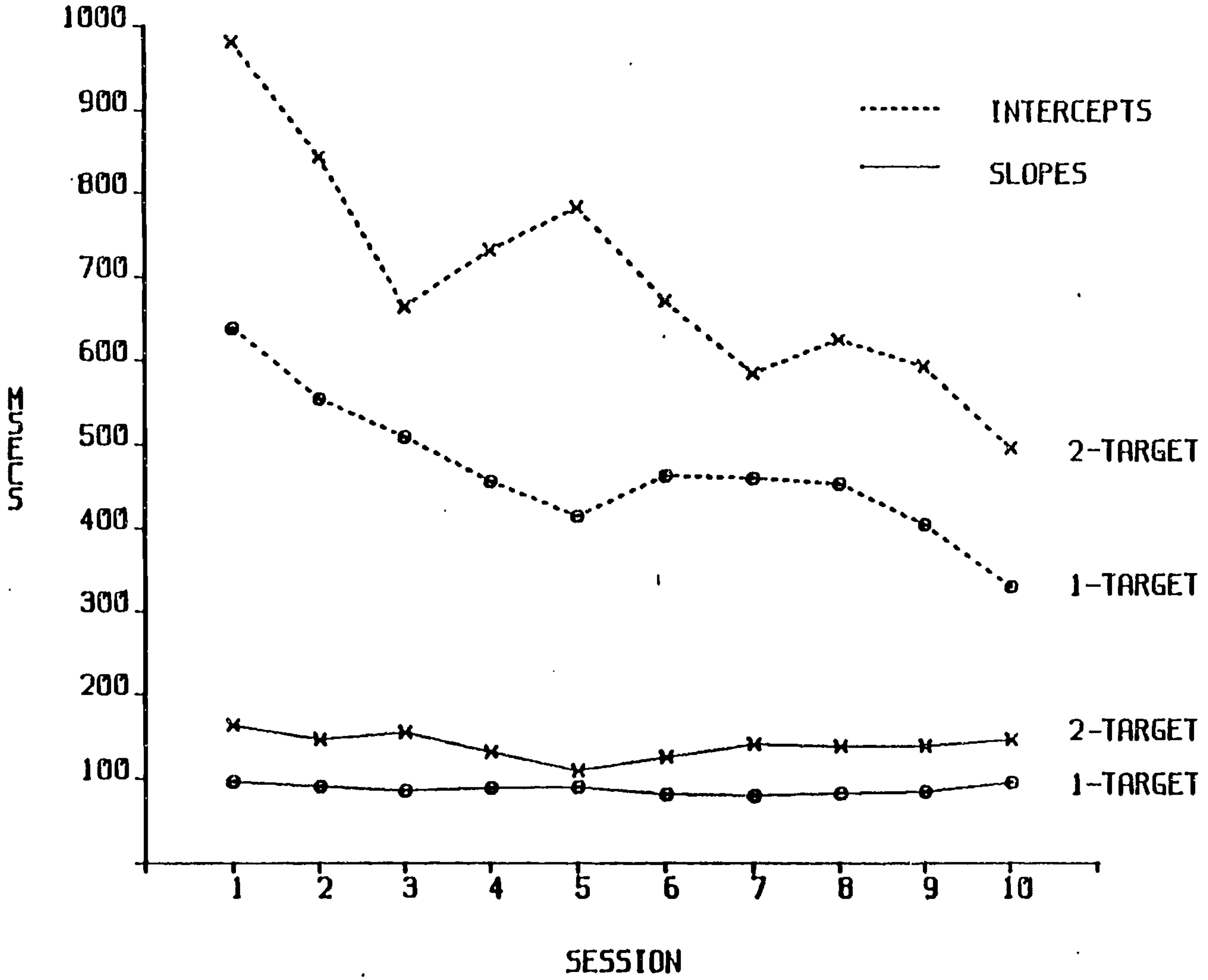

Figure 29. Visual Search III Session Effects for Slopes and Intercepts of 1- and 2-Target Searches.

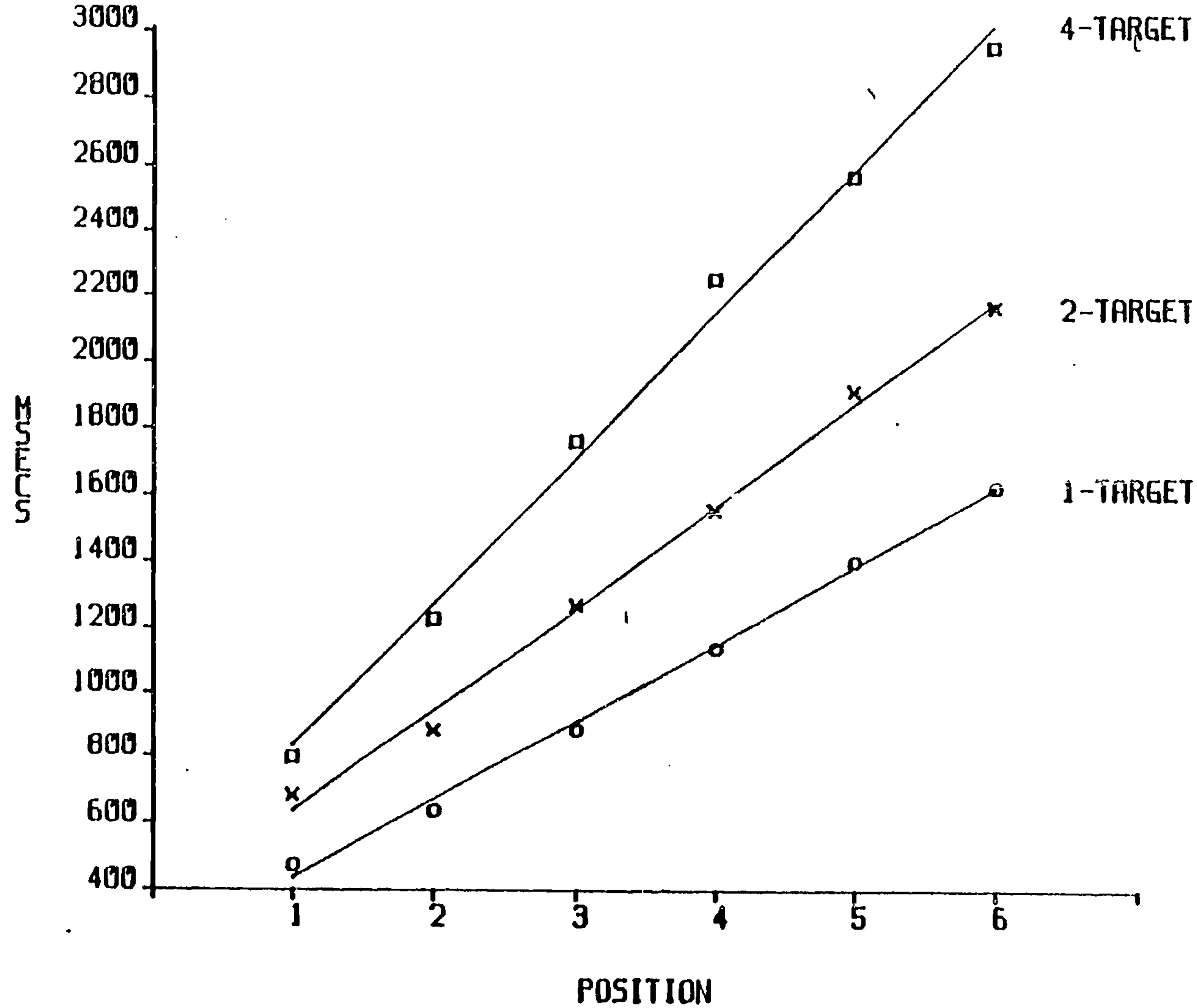

Figure 30. Semantic Search III Mean Latencies as a Function of Target Position of 1-, 2-, and 4-Target Searches.

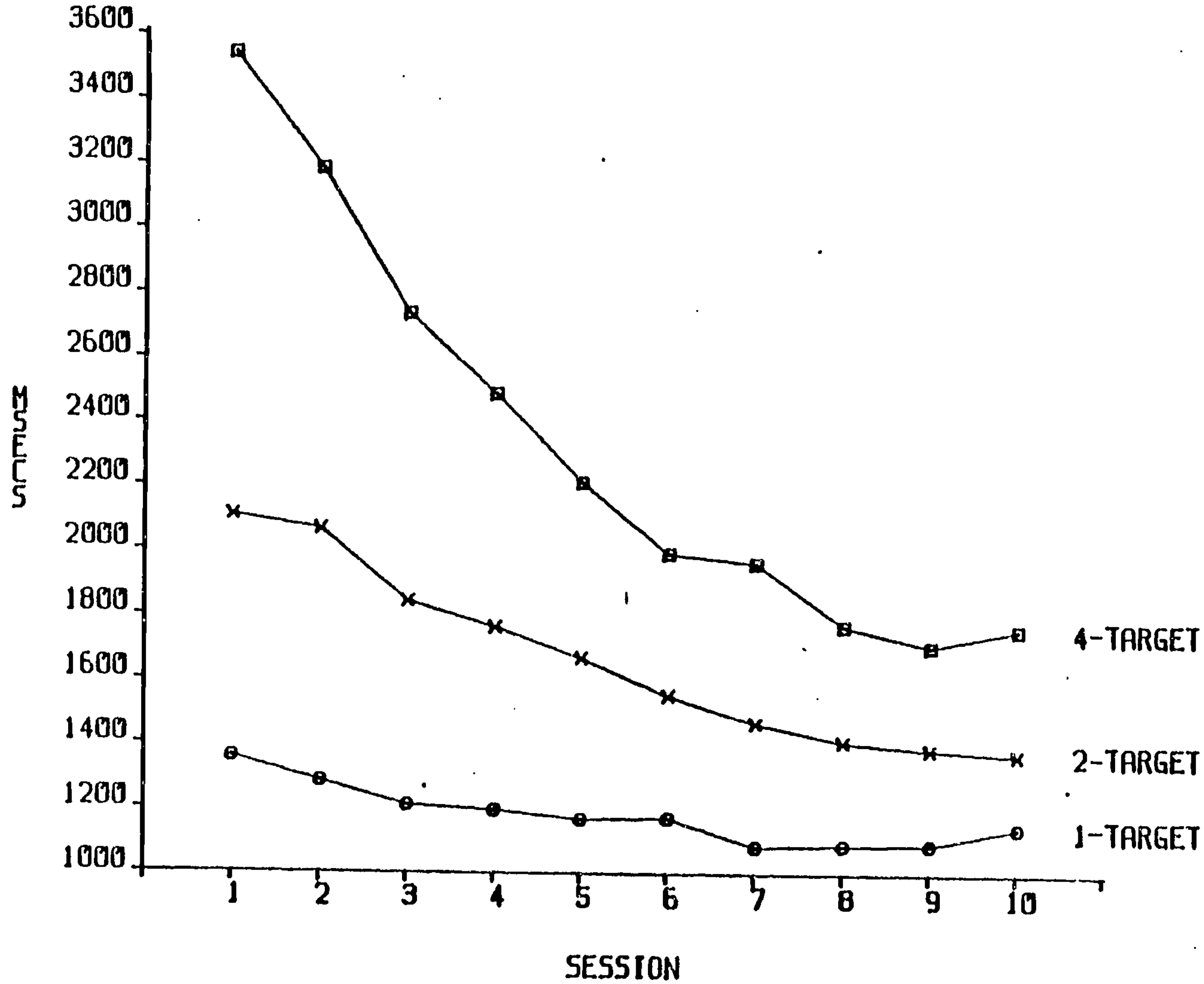

Figure 31. Semantic Search III Session Effects for 1-, 2-, and 4-Target Searches.

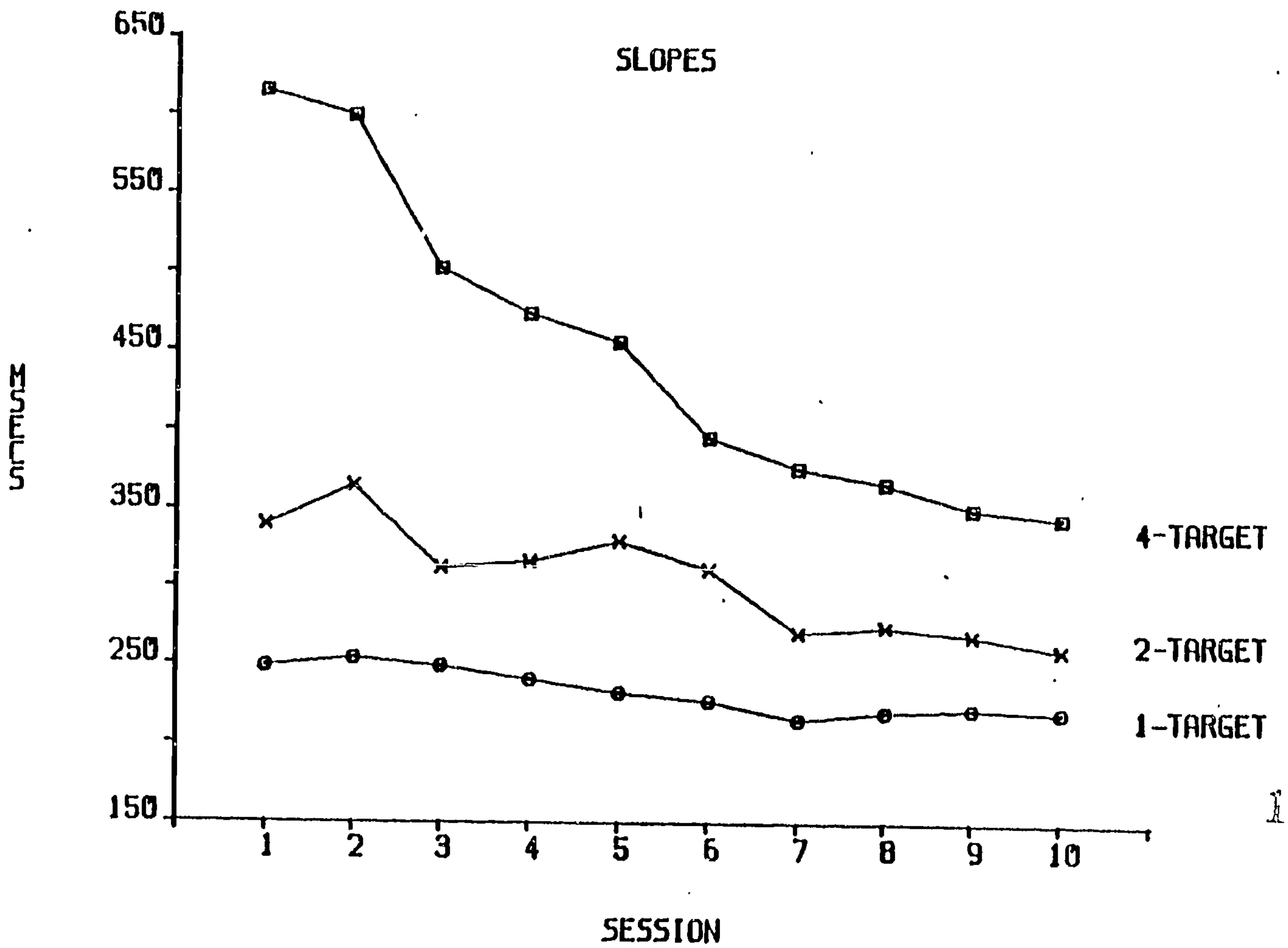

Figure 32. Semantic Search III Session Effects for Slopes of 1-, 2-, and 4-Target Searches.

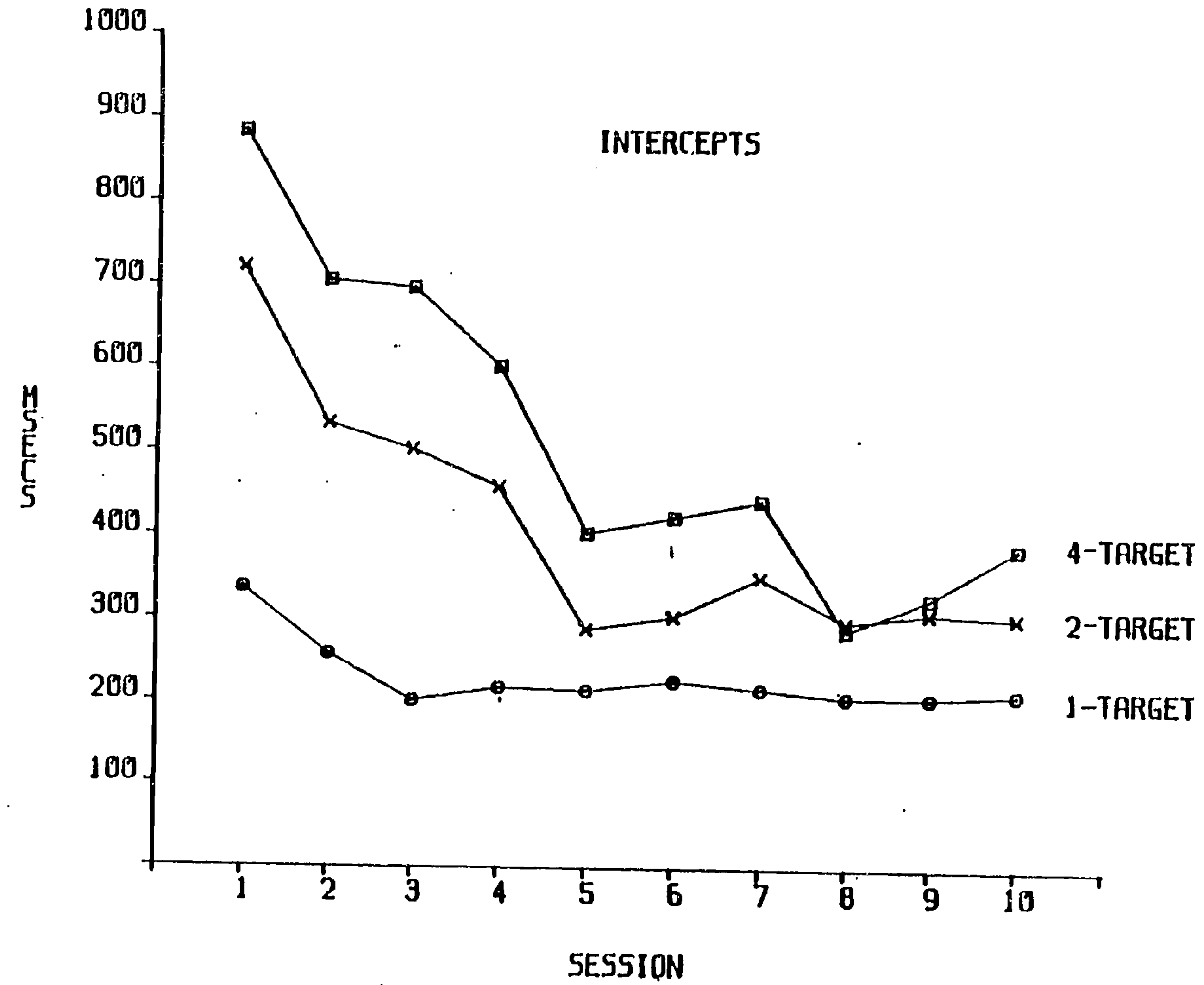

Figure 33. Semantic Search III Session Effects for Intercepts of 1-, 2-, and 4-Target Searches.

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The results for this task are strongly in accord with those obtained in Semantic Search II. Of particular importance is the fact that more extensive practice produces further changes in performance in the multiple-target search conditions. This is in contrast to the results observed in Visual Search III and suggests that in the semantic search task, with its constant mapping of targets and distractions, there is evidence of movement towards a parallel, automated mode of responding.

Summary for Task Battery IV. The results for the two search tasks are quite obvious and support the hypothesis that movement towards a parallel, more efficient mode of processing is possible in multiple-target search tasks only if there is a constant stimulus-response mapping condition. The semantic search task showed a substantial change in the slope for the multiple-target search conditions, with evidence of convergence toward the slope value for the single-target search condition. No such evidence was obtained for the visual search task which involves variable stimulus-response mapping. For these reasons, only the semantic search task was used again in Task Battery V but with a larger sample of subjects. One goal was to see if the practice effects obtained over the multiple sessions would be replicated with the larger subject sample. The second task included in Battery V was a perceptual comparison task which permitted a further examination of practice effects as a function of both stimulus-specific and general contextual variables.

Task Battery V

Semantic Search IV. This task was identical to Semantic Search III and thus the same pattern of results was expected. Figure 34 shows the reaction time results for each search condition as a function of target position. There were highly significant effects of number of targets, $F(2, 80) = 138.21$, $p < .001$, and target position, $F(5, 200) = 496.94$, $p < .001$, as well as a highly significant interaction of number of targets and target position, $F(10, 400) = 27.70$, $p < .001$. Thus, response time linearly increases with target position and the slope of the linear function systematically increases with the number of potential targets. These results are identical to those obtained in Semantic Search II and III.

Figure 35 shows the mean reaction times for each search condition for each session of practice. As can be seen in the figure, there were significant effects of session, $F(9, 360) = 85.79$, $p < .001$, and number of targets, $F(2, 80) = 158.84$, $p < .001$, and an interaction of session and number of targets, $F(18, 720) = 35.93$, $p < .001$. As was the case in Semantic Search III, the 4-target condition shows the most substantial change in performance over sessions, with a lesser change exhibited in the 2-target search condition and the smallest change shown in the 1-target condition.

More refined analyses of the general practice effects shown in Figure 35 were conducted by obtaining slopes and intercepts of the linear function relating reaction time to target position in each search condition for each session. The slope data are shown in Figure 36. As was the case in Semantic Search III, the 1-target condition shows a minimal slope change (16 msec), the 2-target condition has a moderate slope change (63 msec), and the 4-target condition has a substantial change (177 msec). Figure 37 shows the intercept results which again parallel the slope results and those obtained in Semantic Search III. Thus, the data from this replication and extension of Semantic

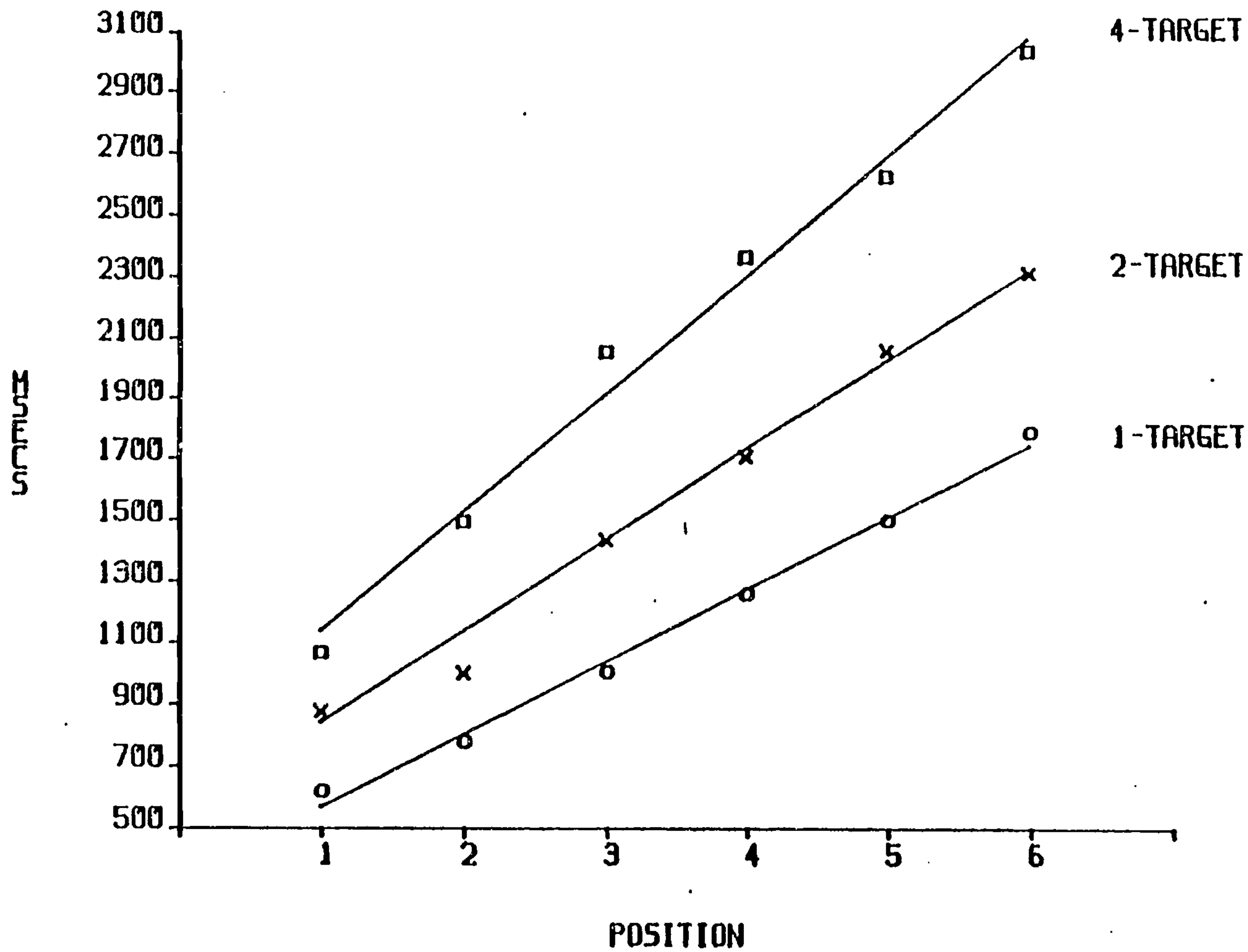

Figure 34. Semantic Search IV Mean Latencies as a Function of Target Position for 1-, 2-, and 4-Target Searches.

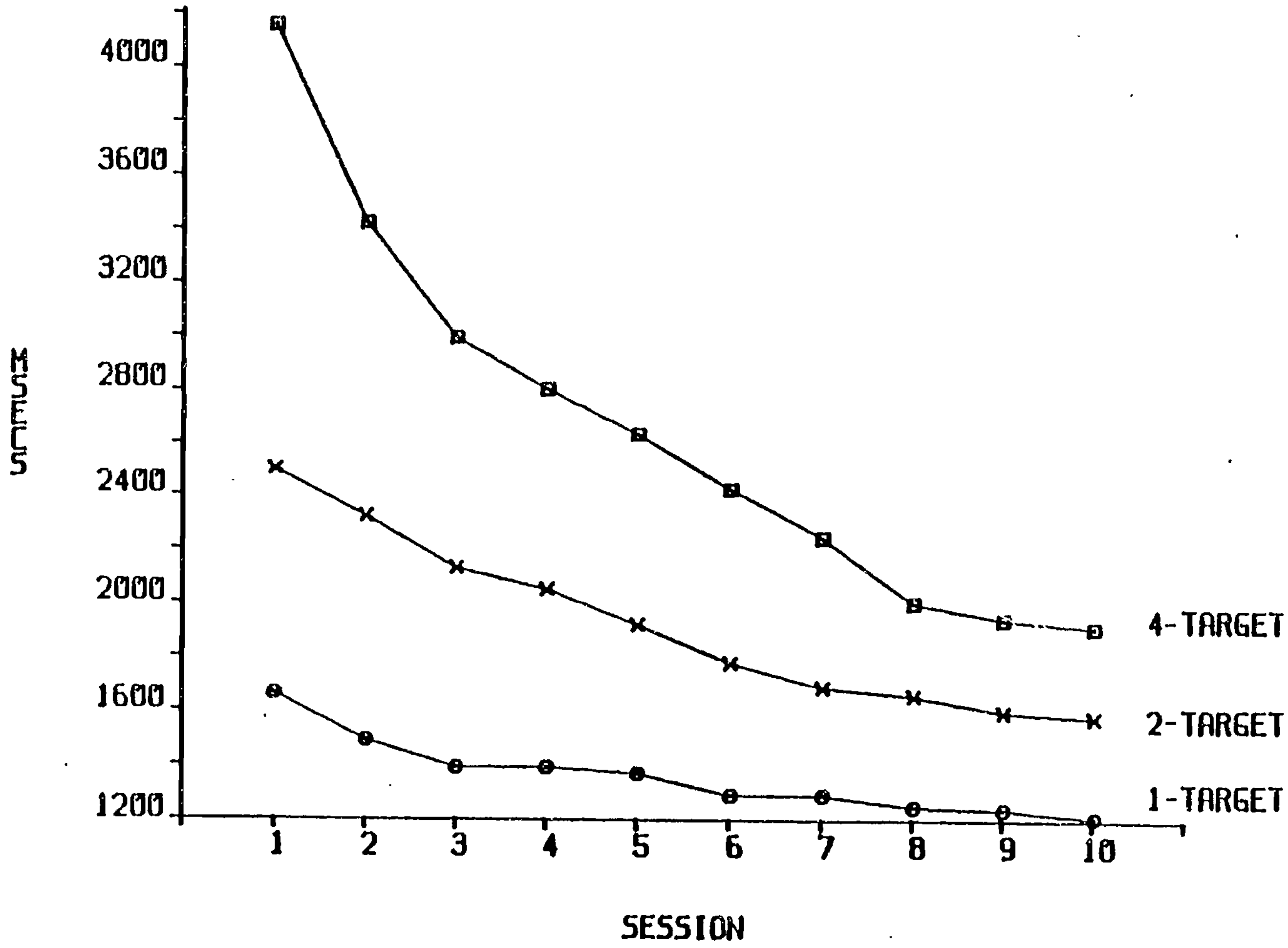

Figure 35. Semantic Search IV Session Effects for 1-, 2-, and 4-Target Searches.

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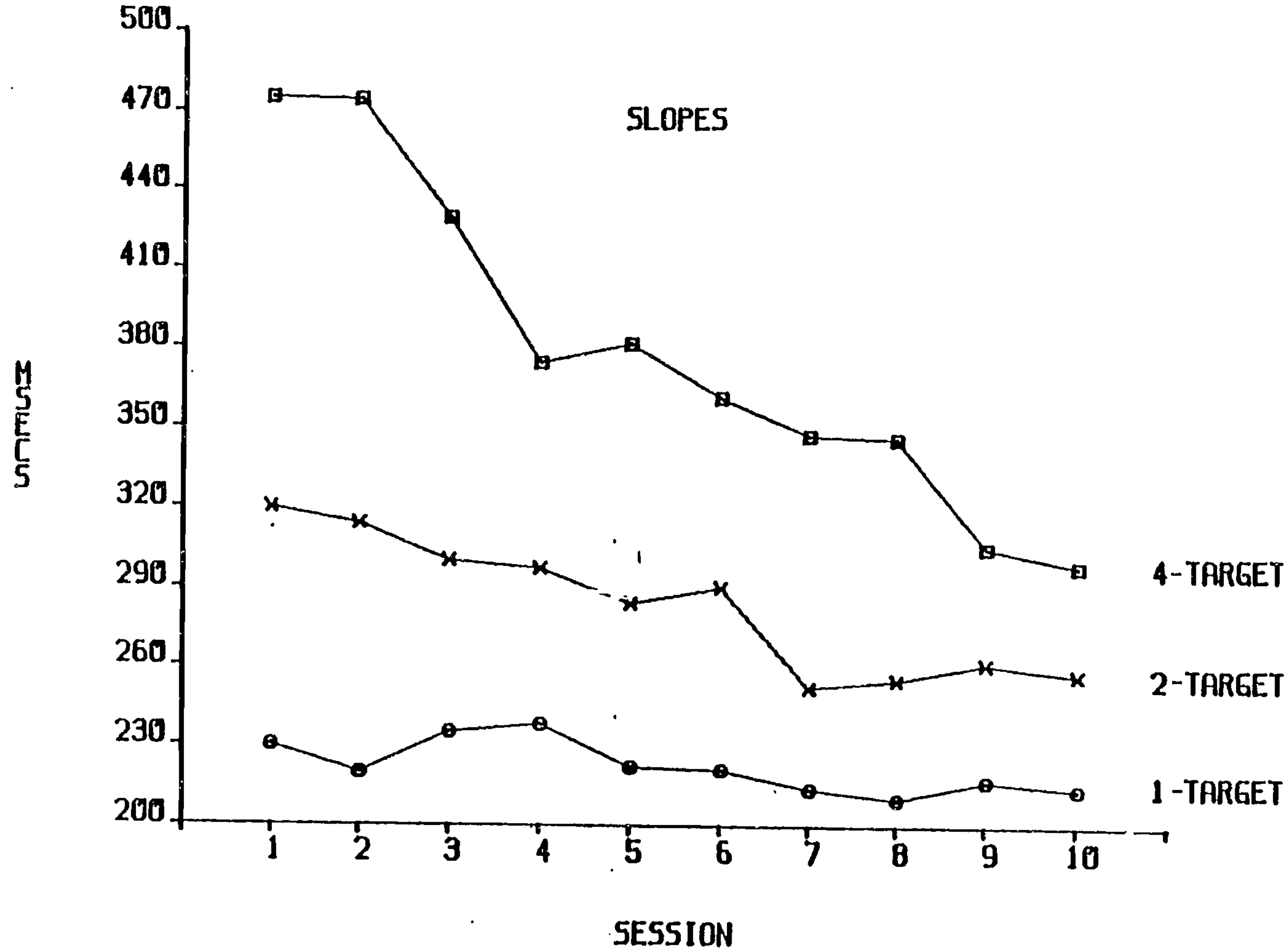

Figure 36. Semantic Search IV Session Effects for Slopes of 1-, 2-, and 4-Target Searches.

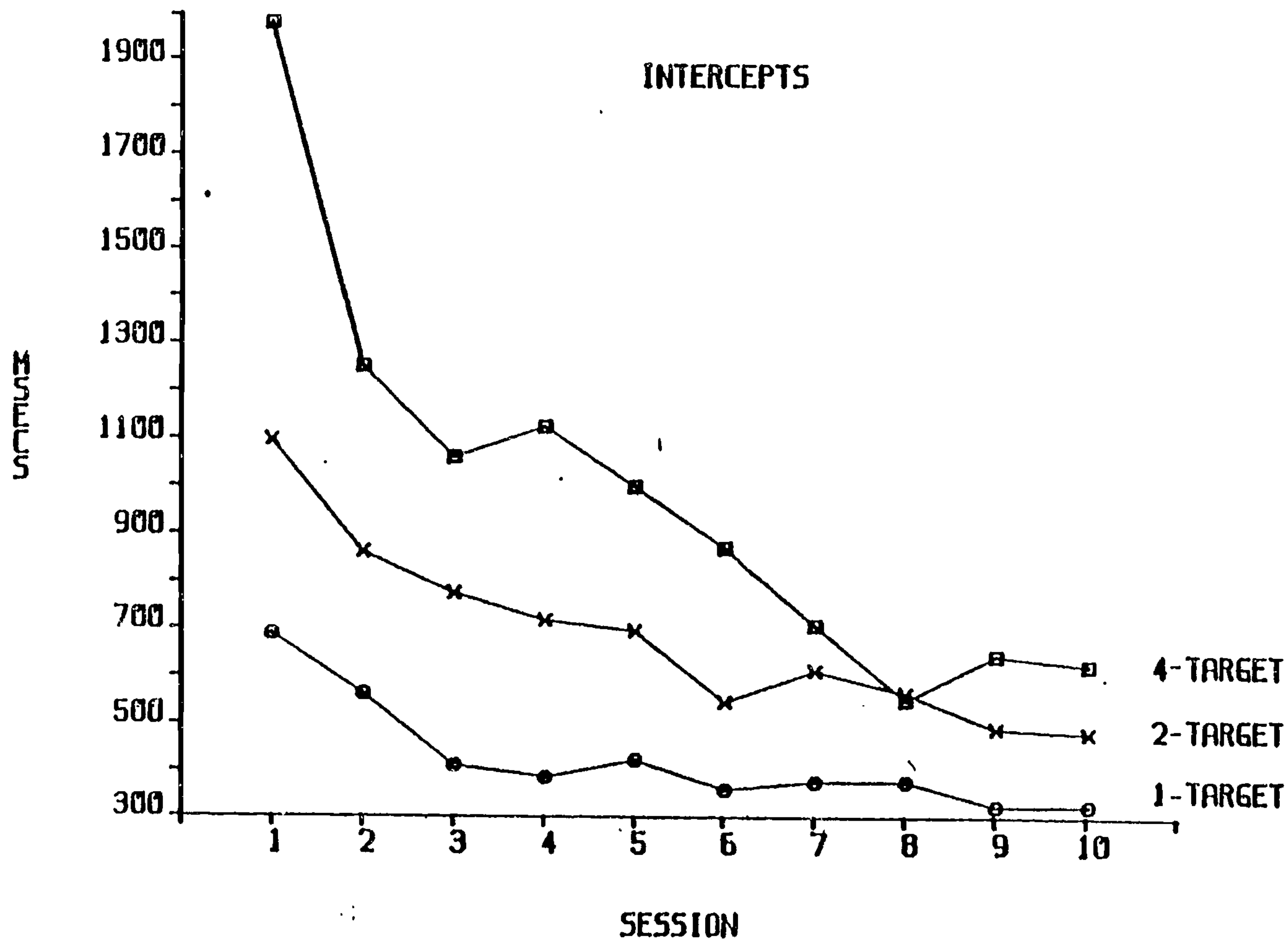

Figure 37. Semantic Search IV Session Effects for Intercepts of 1-, 2-, and 4-Target Searches.

Search III support the conclusion that with extended practice, performance in the multiple-target semantic search conditions improves substantially, with apparent movement towards automatic, parallel processing of multiple targets.

Perceptual Matching III. In this task, subjects were presented pairs of random polygons differing in complexity (number of random points - 6, 8, 12, 16 or 24) and degree of similarity (six levels D1 - D6). All subjects received 16 sessions of practice with the full set of same judgment stimuli. However, one group of subjects, those in the Hard discrimination condition, were presented the different judgment stimuli most similar to the targets (D1 - D3) during the first eight sessions of practice. A second group of subjects, those in the Easy discrimination condition, were presented the different judgment stimuli most dissimilar to the targets (D4 - D6) during the first eight sessions of practice. Both groups of subjects were then presented the full set of different judgment stimuli (D1 - D6) during the last eight sessions of practice. Of particular concern in this study was the effect of discrimination difficulty on performance at varying stages of practice and the effect of introducing new stimuli after several sessions of practice. These issues were examined by separately focusing on measures of performance for the same and different judgment trials.

In the case of same judgment trials, the Hard and Easy discrimination groups received the full stimulus set for all 16 sessions of practice. Thus, an analysis of variance was conducted on the same judgment mean reaction times with Group, Stimulus Complexity, and Session as the primary factors. Figure 38 shows the mean reaction times collapsed over the complexity variable for each group at each session of practice. As shown in this figure, there was a significant effect of Group, $F(1, 39) = 4.42$, $p < .05$; a highly significant session effect, $F(15, 585) = 63.59$, $p < .001$; and a highly significant group by session interaction, $F(15, 585) = 23.7$, $p < .001$. During the first eight sessions of practice, the subjects in the Hard discrimination condition took substantially longer to make same judgments than did the subjects in the Easy discrimination condition. The subjects in the Hard discrimination condition also show a systematic practice effect over the first eight sessions which continues on through the last eight sessions and which is not disrupted by the introduction of new different judgment stimuli in session 9. In contrast, subjects in the Easy discrimination condition show an elevation in same judgment response latency when the new, more similar, different judgment stimuli are introduced at session 9. Their performance thereafter shows relatively little change, and the mean latency in the Easy condition then exceeds the mean latency in the Hard condition.

The mean same judgment reaction times shown in Figure 38 reflect more subtle differences between the groups in reaction times for stimuli of varying complexity. A general expectation for performance on same judgment stimuli is that reaction time should be a linear function of stimulus complexity, as was observed in Perceptual Matching II. The analysis of variance revealed a significant effect of complexity, $F(4, 156) = 43.06$, $p < .001$; a session by complexity interaction, $F(60, 2340) = 3.61$, $p < .01$; and a group by session by complexity interaction, $F(60, 2340) = 1.59$, $p < .01$. Figure 39 depicts the results for stimulus complexity at sessions 1, 8, 9 and 16 for each discrimination group. In the Hard discrimination group there was a substantial stimulus complexity effect which diminished in an orderly fashion over sessions such that by session 16 the effect of stimulus complexity was

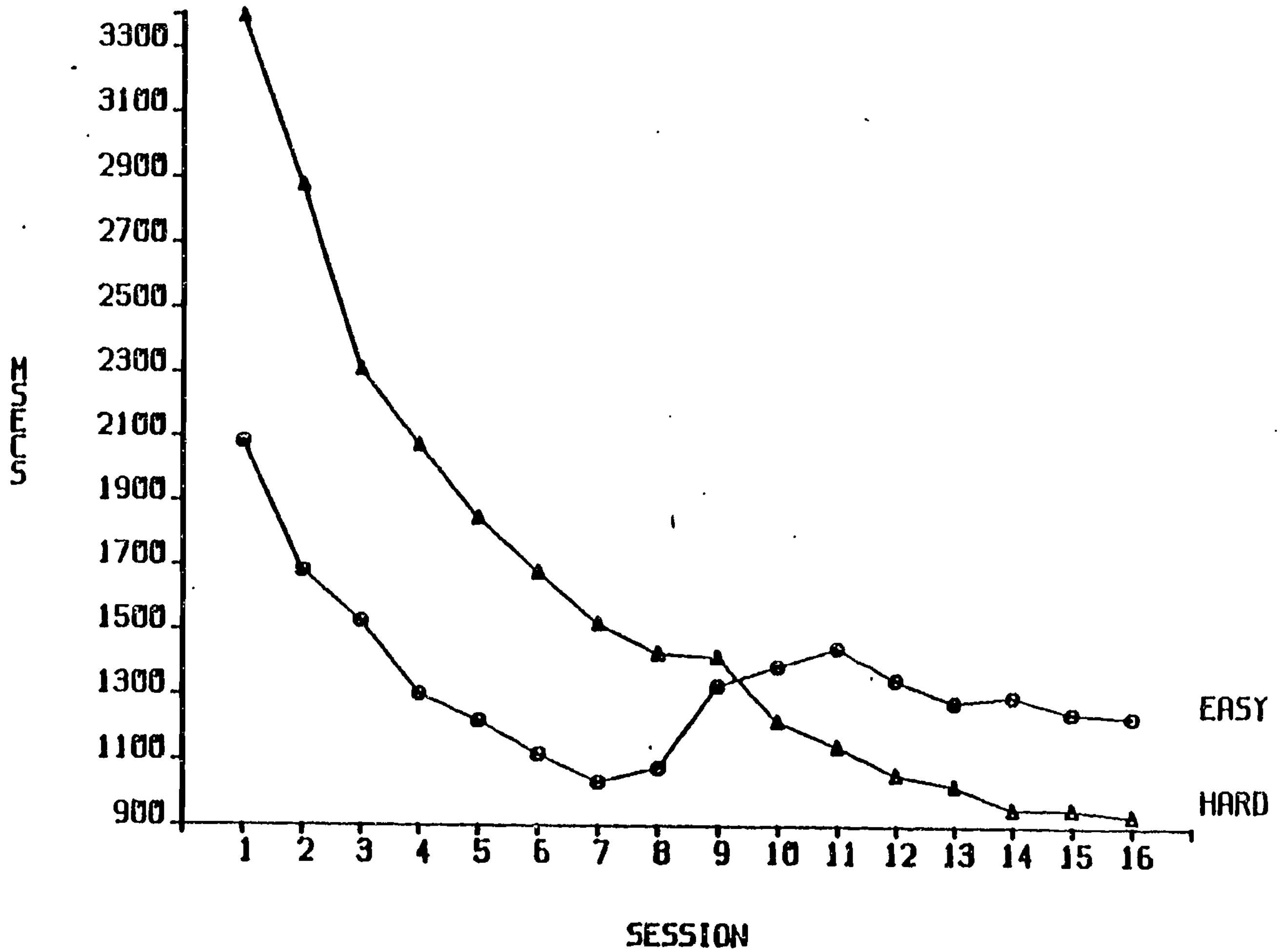

Figure 38. Perceptual Matching III Mean Latencies for Same Judgments as a Function of Discrimination Group and Sessions.

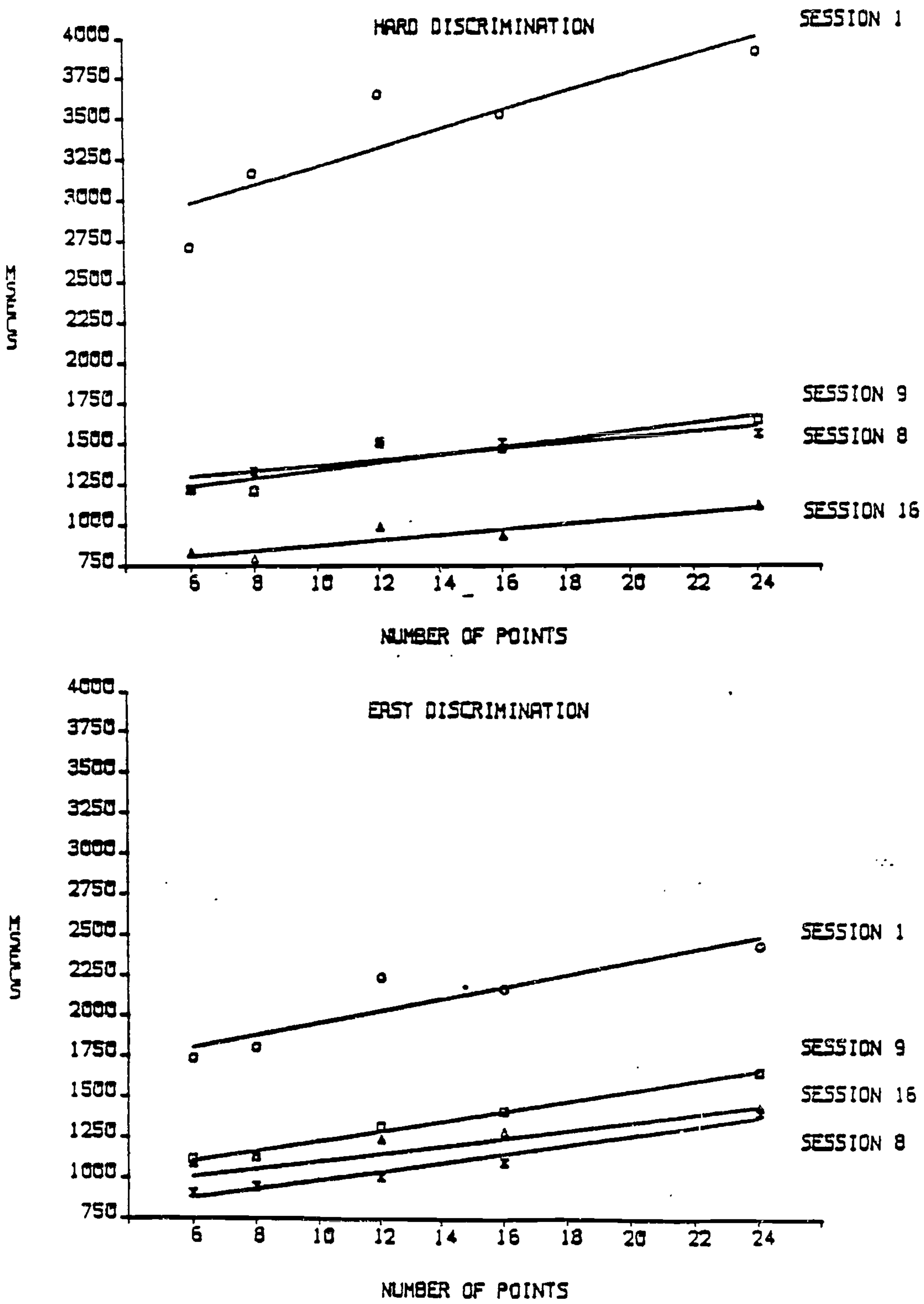

Figure 39. Perceptual Matching III Mean Latencies for Same Judgments as a Function of Stimulus Complexity, Discrimination Group and Sessions 1, 8, 9, and 16.

relatively small. In the Easy discrimination group the effect of stimulus complexity was much less substantial during session 1 and showed a small decline over the remaining 15 sessions.

A more detailed analysis was done of the differential reaction time patterns exhibited by the Hard and Easy discrimination groups over sessions for same judgments. Slopes and intercepts of the linear function relating reaction time to stimulus complexity were derived for each group at each session of practice. The slope data are shown in Figure 40. As can be seen in this figure, the change in slopes for the Hard discrimination condition was substantial and orderly over the entire 16 sessions of practice. The Easy discrimination group showed a much smaller initial slope value and a much attenuated change in slopes over sessions, with an elevation in slope at session 9. In addition, the Hard discrimination condition shows shallower slopes than the Easy discrimination condition over the last eight sessions of practice. Figure 41 shows the results for the intercepts. As was the case for the slopes, the Hard discrimination group showed a substantial and orderly practice effect over sessions. In the Easy discrimination group the change in intercepts was also orderly over the first eight sessions and the intercepts were lower than those obtained in the Hard discrimination group. At session 9, however, there was an increase in the intercept, with relatively little change thereafter. In addition, the intercept for the Hard discrimination group was lower than the intercept of the Easy discrimination group over the last six sessions of testing.

Analyses were also conducted of the different judgment performance over the last eight sessions of practice since the Easy and Hard discrimination groups were equivalent with respect to the different judgment stimuli presented; this was not the case for the first eight sessions of practice. Figure 42 shows the mean latencies for different judgments for the Easy and Hard discrimination groups. The Hard discrimination group shows a substantial decrease in mean latency over sessions 9 through 16 and a lower mean reaction time than the Easy discrimination group. For the latter group there is much less of a performance change.

A more refined analysis of the different judgment reaction times was conducted by determining slopes and intercepts of the functions relating reaction time to degree of target-distractor similarity. Figure 43 shows the slope data while Figure 44 shows the intercept data. With respect to the slopes, the Hard discrimination group shows a pattern over sessions very similar to that shown in Figure 42 for mean different judgment reaction time. There is a systematic decline in the sensitivity of subjects in the Hard discrimination group to degree of target-distractor similarity. The slope values are also considerably less than those obtained for subjects in the Easy discrimination group. The latter group shows an unsystematic, slight decline in the slope value for difference detection.

For the intercept data, the Hard discrimination group again shows an orderly decline in the estimated time for a final decision and motor response. The intercept latencies are 50 to 100 msec longer than those estimated for the Easy discrimination group. Of particular interest is the unsystematic, slight overall decline in intercept values for the Easy discrimination group. The peaks and troughs of the intercept graph are opposite to those shown for the slopes for this subject group. This pattern reflects the negative correlation

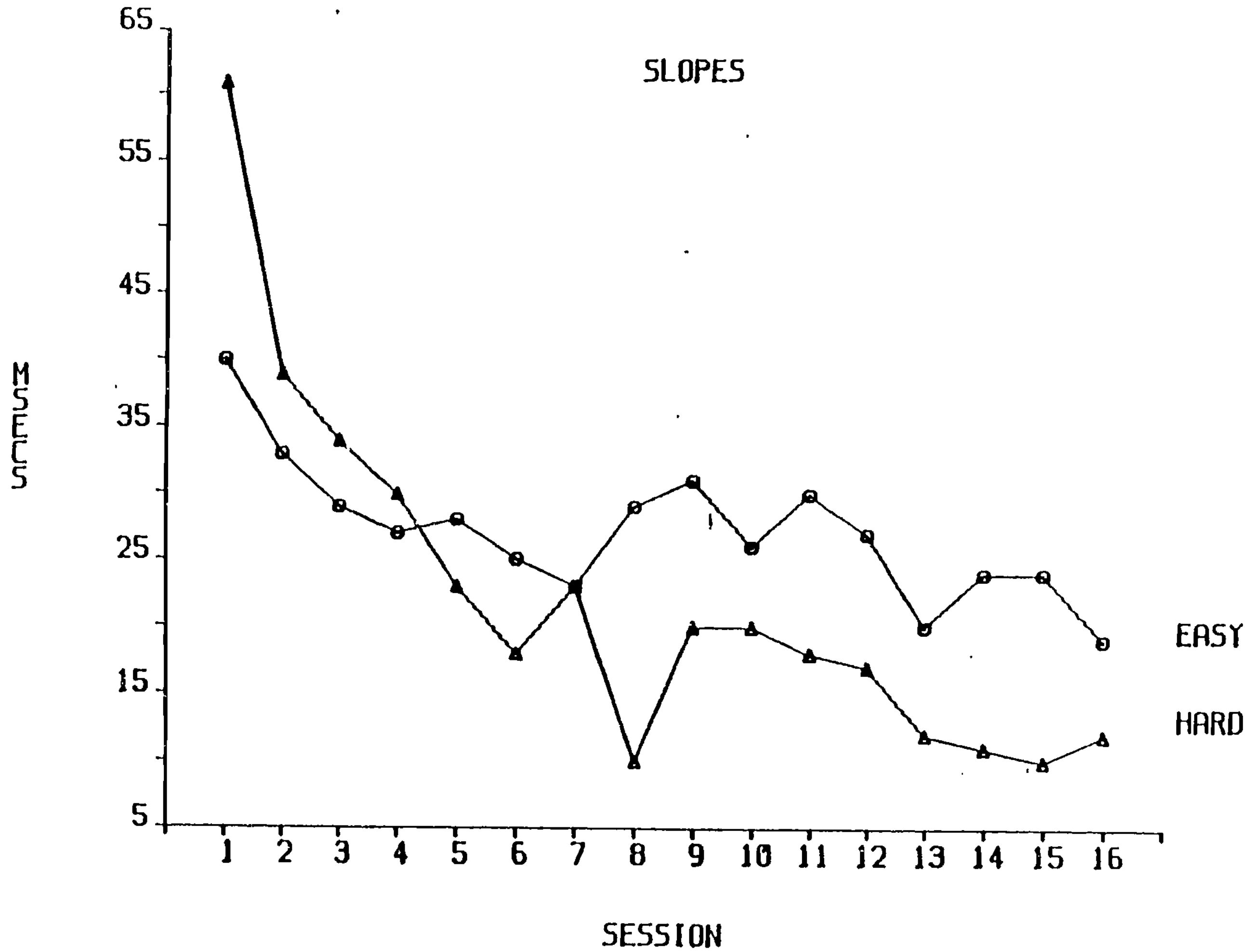

Figure 40. Perceptual Matching III Session Effects for Same Judgment Slopes as a Function of Discrimination Group.

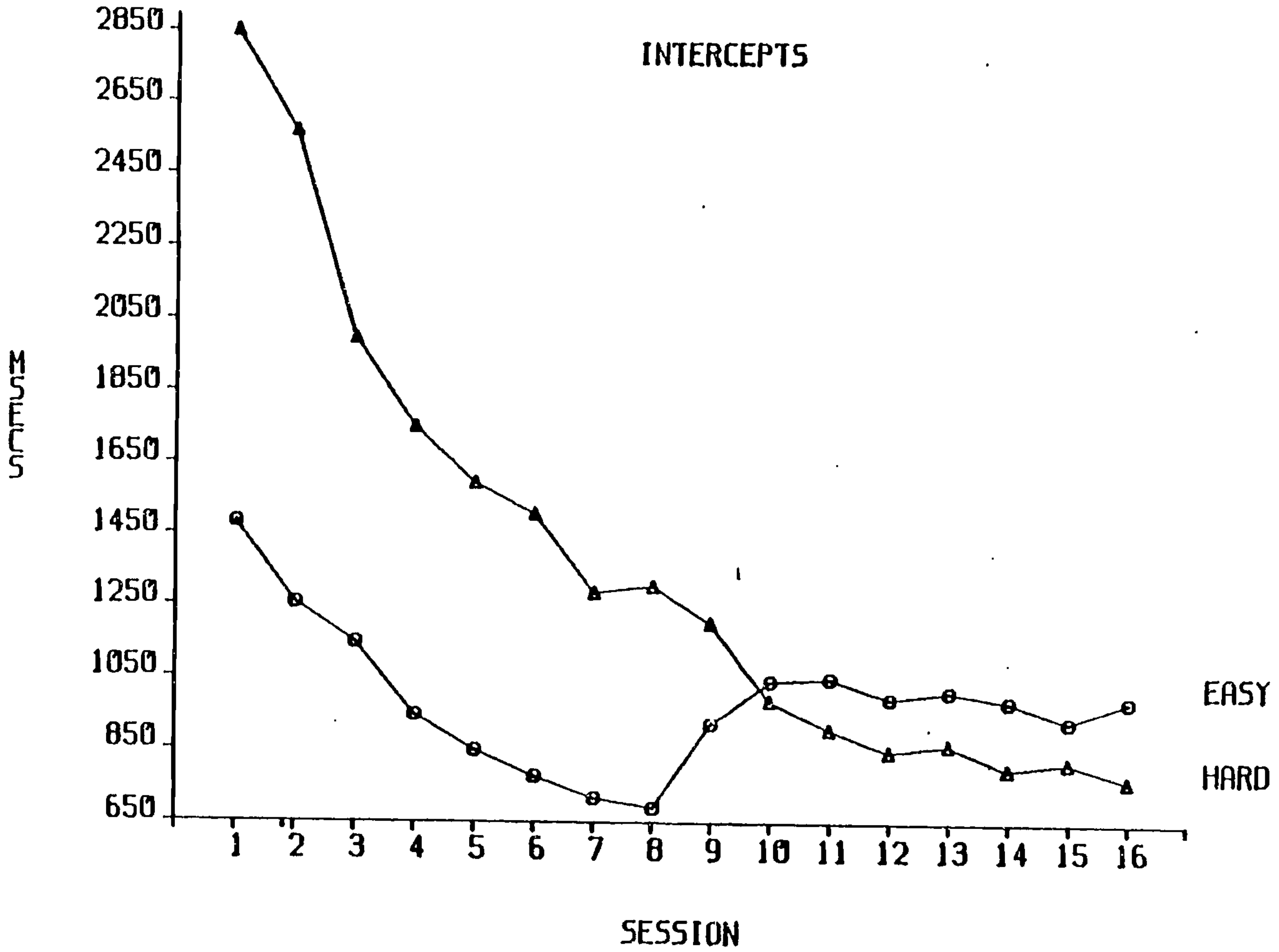

Figure 41. Perceptual Matching III Session Effects for Same Judgment Intercepts as a Function of Discrimination Group.

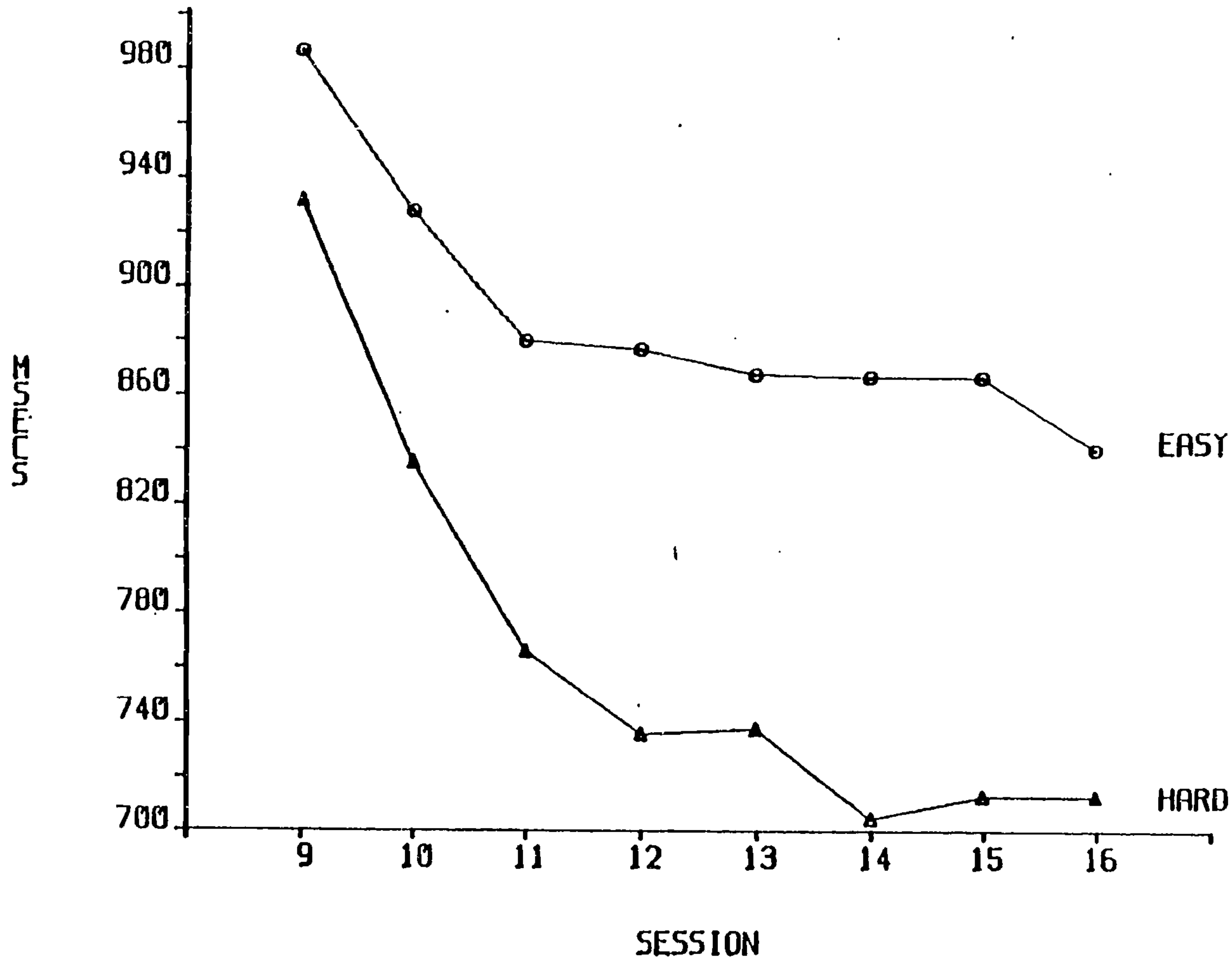

Figure 42. Perceptual Matching III Mean Latencies for Different Judgments as a Function of Discrimination Group and Sessions 9 - 16.

141 142

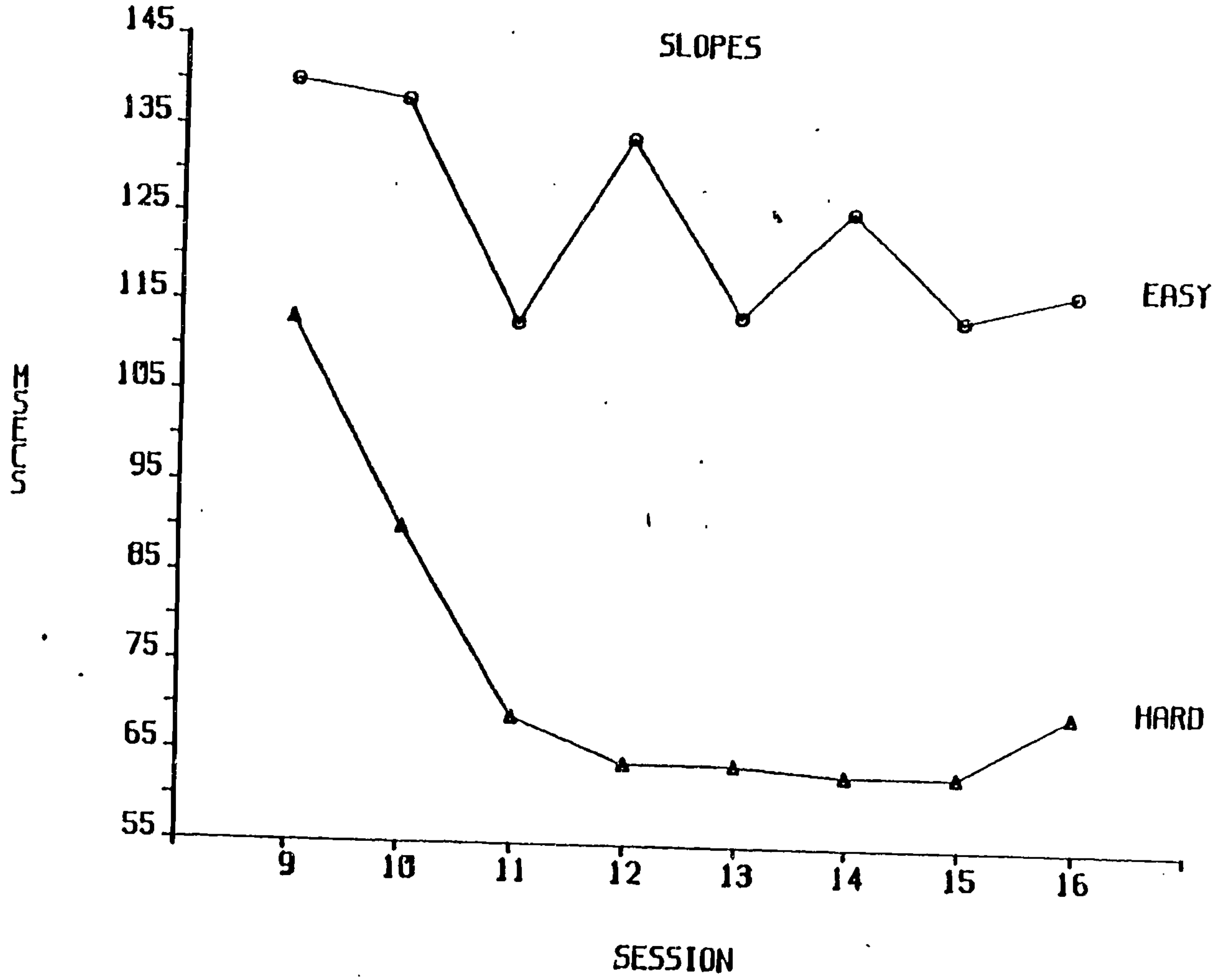

Figure 43. Perceptual Matching III Session Effects for Different Judgment Slopes as a Function of Discrimination Group.

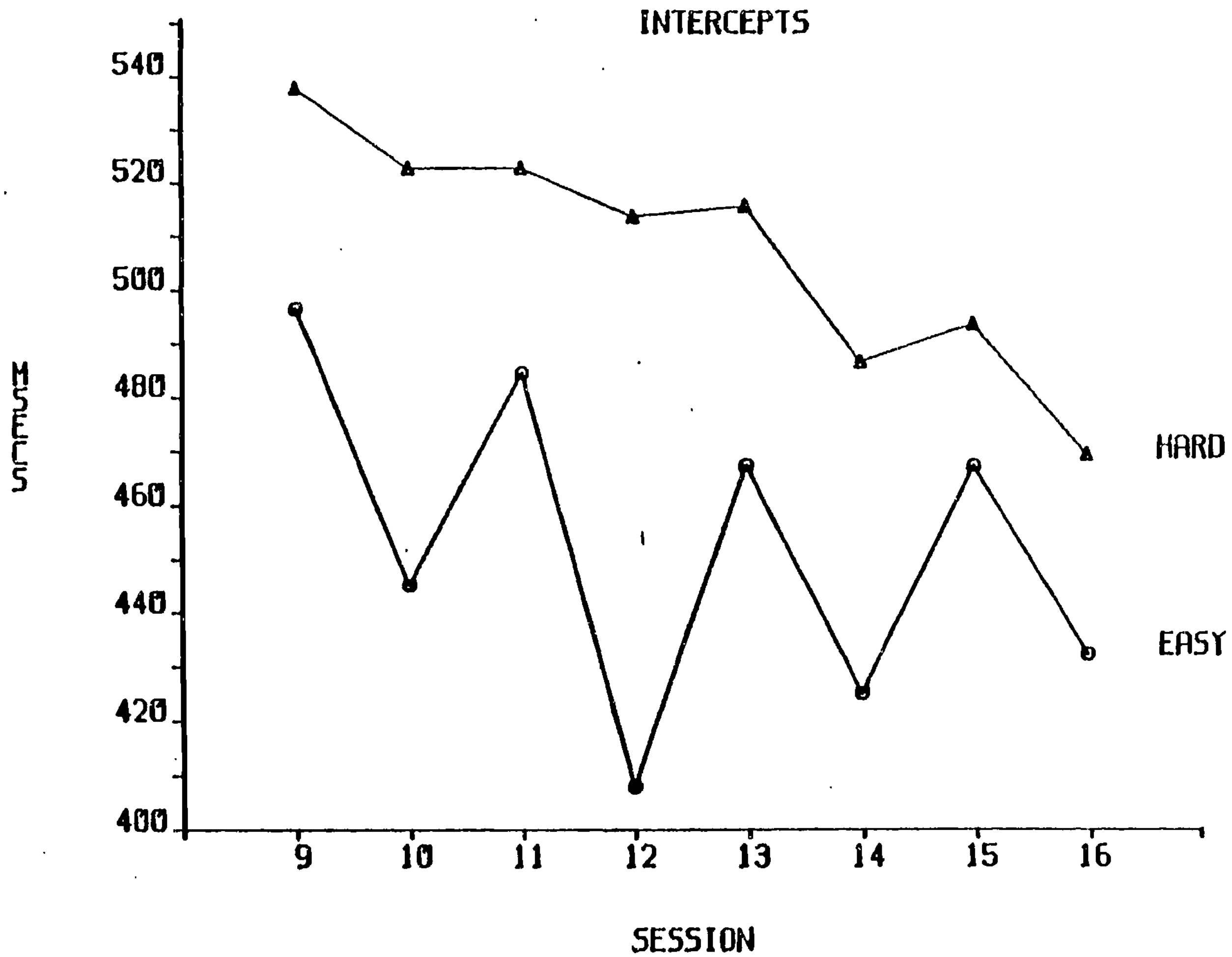

Figure 44. Perceptual Matching III Session Effects for Different Judgment Intercepts as a Function of Discrimination Group.

between slopes and intercepts when performance is unsystematic. Apparently, the performance of subjects in the Easy discrimination group was significantly disrupted by the introduction of the more similar distractor stimuli, thus producing an unsystematic pattern of response latencies across different judgment problem types. The apparent net result was that improvements in performance on these stimuli were inhibited. No such disruption occurred for the Hard discrimination group when the less similar distractor stimuli were introduced. Instead, these subjects showed an orderly and consistent pattern of performance across all stimuli, with substantial improvements in performance over sessions.

In summary, this study has provided substantial evidence that improvements in performance in a perceptual judgment task with unfamiliar stimuli of varying complexity are not solely a function of the amount of practice provided in responding to particular stimuli. The context in which responses are elicited is equally important, particularly with respect to continued performance improvements, transfer to new stimuli, and performance disruption when task demands change. Subjects who initially practiced under the most difficult discrimination conditions took substantially longer to respond but they showed orderly acquisition effects that continued when new stimuli were introduced into the task, albeit stimuli of greater discriminability than those originally presented. Their performance improvements were such that eventually they responded faster than subjects presented an easier discrimination task when both groups were responding to the full stimulus set. In contrast, subjects in the easier discrimination task had fast responses during the initial stages of task performance but an elevation in response time when the task context changed. This occurred even though both groups of subjects had identical exposure frequencies for the matching stimulus pairs of varying complexity. Stimulus complexity was obviously less important in making judgments when target-distractor similarity was low. Thus, the mental representations acquired by subjects in the Easy discrimination group may have lacked sufficient precision to be of substantial benefit when criteria for making decisions became globally more precise. Not only do subjects apparently acquire general processing skill with extended practice in making perceptual judgments but they also apparently acquire stimulus-specific knowledge and memory representations that reduce stimulus complexity and unfamiliarity effects.

Summary For Task Battery V. The results obtained for the semantic search task provide a clear replication of the results obtained earlier for this task in Battery IV. With multiple sessions of practice there is a substantial improvement in performance in the multiple-target search conditions. Of particular significance is the fact that the slopes for the 1-, 2- and 4-target searches tend to converge, indicating movement toward a parallel, more efficient mode of stimulus processing. It must be emphasized again that this search task involves a constant stimulus-response mapping design and thus, the results support arguments in the literature that a parallel "automatic" mode of processing can be approached when constant mapping is present.

The results obtained for the perceptual comparison task raise other interesting issues about stimulus-specific practice effects. As illustrated earlier in Task Battery II, there were substantial practice effects in this task indicating stimulus-specific learning. However, the nature of the learning that occurred was not simply a matter of the frequency of exposure nor the mapping of a given stimulus onto a specific response. Rather, the need for stimulus-specific learning and/or the nature of that learning changed as a function of the larger experimental context. It would appear that context significantly influences the nature of knowledge and skill acquisition that occurs over practice and this can be critical in determining flexibility and ease of transfer to new situations.

General Summary

In the preceding five sections we have presented group-level results for 13 tasks. The results demonstrate that it is feasible to assess an individual's current level of information processing efficiency for a variety of basic processes. All of the microcomputer-administered tasks had a high level of internal validity as demonstrated by fits of models to group mean data. All the tasks also demonstrated practice effects over the time course of testing (2 to 5 hours). The practice effects were consistent with general power functions and varied in magnitude as a function of task complexity and stimulus familiarity. Practice effects were small for highly speeded simple decision tasks with familiar content. More substantial practice effects occurred in tasks involving unfamiliar stimuli and/or the simultaneous processing of multiple targets. These general results will be discussed in more detail subsequently. In the next section we consider relationships between reference ability measures and measures of information processing efficiency derived from our different tasks.

V. INDIVIDUAL DIFFERENCES IN PROCESS EXECUTION SPEED

In the preceding section we considered characteristics of performance in each of the 13 information processing tasks. In all cases, group performance showed that the tasks behaved as expected. Model fits for group mean data were typically excellent and in accord with a priori assumptions about internal task performance. The same models for task performance were also fit to the data for each individual subject in each task. In this section we consider the process measures derived in each task for each subject, their distributional characteristics and reliabilities. We then consider how these process measures were correlated with scores derived from the reference ability battery.

Descriptive Statistics and Reliabilities

Table 11 contains summary data for the process measures derived for the tasks in Battery I. In Perceptual Matching I, we derived three measures of performance: (a) time to execute a single Encoding + Comparison of alphanumerics, (b) the additional time to respond different, and (c) a Motor Response constant. As shown in Table 11, each of these three measures had reasonable mean values and variance. The split-half reliabilities for these measures were acceptable, with the least reliable measure being the additional time to respond different.

In the Attribute Comparison task, we derived four measures of processing: (a) the time for Encoding, physical Comparison + Motor Response, (b) the additional time to retrieve and compare Name information, (c) the additional

Table 11. Means, Standard Deviations, and Reliabilities of Task Battery I Process Parameters

Task	Process measure	Mean (msec)	SD (msec)	Reliability
Perceptual matching	E + C[a]	220	50	.92
	Different	360	140	.61
	Motor response	400	200	.78
Attribute comparison	E + C + R	720	220	.99
	Name retrieval	130	80	.83
	Category retrieval	240	120	.57
	Respond different	70	80	.89
Addition	Slope	26	13	.78
	E + C + R	510	140	.85
Subtraction	Slope	21	16	.25
	E + C + R	660	170	.89
Multiplication	Slope	7	5	.60
	E + C + R	520	270	.66
Division	Slope	27	17	.74
	E + C + R	750	210	.95

[a]E = encode, C = compare, R = respond.

time to retrieve and compare Category information, and (d) the additional time to respond different. All four of these measures had reasonable means and variances and three of the four had substantial split-half reliabilities. The least reliable measure was the additional time to retrieve and compare Category information. Fewer data points contributed to the estimate of this process measure and thus its lower reliability is not unexpected.

In the Fact Retrieval tasks, we derived two measures for each of the four fact types. The slope measures provide an index of the efficiency of retrieval of fact information as the sum, difference, product or quotient increases. Shallow slopes indicate highly efficient retrieval. The intercept measures reflect the time to Encode the problem, Compare the answer to the correct one retrieved from memory, and execute a Response. As shown in Table 11, the E + C + R measures are consistent over tasks, with reasonable variances and reliabilities. The slope measures for the two incrementing tasks (addition and multiplication) are similar and shorter than the slope measures for the two decrementing tasks (subtraction and division) and this reflects a difference in the range of values used in the regression. The slope measures have reasonable variances but the reliabilities are not as high as the E + C + R measures. The slope for the subtraction task has a very low reliability and we are uncertain as to what is responsible for this.

Table 12 contains the summary data for process measures obtained in Task Battery II. In Perceptual Matching II, we derived four measures of performance: (a) a slope measure for Stimulus Complexity, which reflects the additional time to match stimuli that have more points (features); (b) a slope measure for Difference Detection, which reflects the additional time to recognize a mismatch as stimuli become more similar to the standard; (c) an intercept measure which reflects Encoding + Comparison + motor Response time for simple positive matches; and (d) an intercept measure which reflects Encoding + Comparison + Motor Response time for very dissimilar negative matches. Each of these measures had reasonable means and variances and very high reliabilities.

In the Visual Search I task, we derived two measures of processing: (a) a slope measure reflecting the time for Encoding + Comparing a single graphic stimulus, and (b) a Motor Response constant. Means and variances were reasonable for these measures and both had very high reliabilities.

Table 12. Means, Standard Deviations, and Reliabilities of Task Battery II Process Parameters

Task	Process measures	Mean (msec)	SD (msec)	Reliability
Perceptual Matching II	Stimulus complexity	60	60	.96
	E + C + R (Positive)[a]	1110	840	.97
	Difference detection	150	60	.89
	E + C + R (Negative)	500	160	.87
Visual Search I	E + C	120	40	.97
	M.R.	550	180	.97
Semantic Search I	E + C + Retrieval (member)	190	60	.88
	M.R.	760	340	.94
	E + C + Retrieval (nonmember)	220	50	.91
	M.R.	970	450	.96

[a]E = encode, C = compare, R = respond, M.R. = motor response.

The Semantic Search I task produced four process measures: (a) a slope measure reflecting the time to Encode a word, Retrieve semantic category information and Compare it to the target category in member searches; (b) a similar slope measure for non-member searches; (c) an intercept measure reflecting Motor Response and final decision time for member searches; and (d) a similar intercept measure for non-member searches. As shown in Table 12, the E + C + R measures for member and non-member search were virtually identical as expected, and the MR constants differed in the expected direction. All four measures had reasonable means and variances and high reliabilities.

Table 13 contains summary data for process measures for two of the three tasks in Battery III. In Visual Search II, we derived four process measures: (a) a slope measure reflecting Encoding + Comparison of a single graphic stimulus in the 1-target condition, (b) a similar measure for the 2-target condition, (c) a Motor Response and final decision constant for 1-target searches, and (d) a similar measure for 2-target searches. As shown in Table 13, the slope measure for 2-target searches was longer than the corresponding measure for 1-target searches, which was expected. Similarly, the MR measure for 2-target searches is greater than the MR measure for 1-target searches, which was also expected. All four measures had reasonable means and variances and high reliabilities.

Table 13. Means, Standard Deviations, and Reliabilities of Task Battery III Process Parameters

Task	Process measures	Mean (msec)	SD (msec)	Reliability
Visual Search II	E + C (1 target)[a]	110	40	.91
	E + C (2 targets)	180	70	.85
	M.R. (1 target)	510	220	.91
	M.R. (2 targets)	800	430	.86
Semantic Search II	E + C (1 target)	240	60	.89
	E + C (2 targets)	340	100	.81
	E + C (4 targets)	600	230	.89
	M.R. (1 target)	380	190	.80
	M.R. (2 targets)	680	320	.77
	M.R. (4 targets)	710	330	.86

[a]E = encode, C = compare, R = respond, M.R. = motor response.

In the Semantic Search II task, we derived six measures of performance. Three of the measures reflect search slopes. These search slopes represent the time to Encode + Compare the semantic features of a single word against the category target(s). As shown in Table 13, the E + C measures systematically increase as one goes from 1- to 2- to 4-target search conditions. The remaining three measures reflect Motor Response and final decision constants in the three search conditions. There is an increase in these constants as one goes from 1- to 2-target searches, with little additional increase for the 4-target searches. All six measures had reasonable means and variances and all but one had a reliability of .80 or above.

The means and standard deviations of process parameters for tasks in Batteries IV and V are shown in Table 14. Reliabilities were not computed for two reasons: first, because of the smaller subject sample size and second, because there was no reason to expect a decline in reliability given the results obtained earlier for these search tasks, particularly since more total trials were now presented for these tasks, producing an even larger base for computing process measures. For the Visual Search III task, we derived the same process parameters as for Visual Search II. These included the encoding and comparison times (slopes) for the 1- and 2-target searches. As shown in Table 14, the encoding and comparison time for 2-target searches was longer than the encoding and comparison time for 1-target searches, as expected. The intercepts of the search functions reflect motor response and final comparison processes and these too differed for the 1- and 2-target search conditions, as expected. The values obtained for all four parameters are lower than those obtained in the Visual Search II task and this is attributable to the more extensive practice that subjects received in Visual Search III.

Table 14. Means and Standard Deviations of Task Battery IV and V Process Parameters

Task	Process measures	Mean (msec)	SD (msec)
Visual Search III	E + C (1 target)[a]	96	26
	E + C (2 targets)	176	65
	M.R. (1 target)	382	127
	M.R. (2 targets)	436	219
Semantic Search III	E + C (1 target)	236	30
	E + C (2 targets)	311	71
	E + C (4 targets)	435	120
	M.R. (1 target)	198	83
	M.R. (2 targets)	306	135
	M.R. (4 targets)	395	229
Semantic Search IV	E + C (1 target)	233	40
	E + C (2 targets)	297	69
	E + C (4 targets)	403	140
	M.R. (1 target)	337	166
	M.R. (2 targets)	542	276
	M.R. (4 targets)	693	345

[a]E = encode, C = compare, R = respond, M.R. = motor response.

For the Semantic Search III and IV tasks, we derived the same process parameters as for Semantic Search II. These included encoding and semantic comparison times (slopes) for 1-, 2- and 4-target searches. As shown in Table 14, the encoding and semantic comparison time increased with the number of potential target categories, as expected. The values obtained for these process parameters were highly similar in Semantic Search III and IV. The intercepts of the search functions reflect motor response and final comparison processes and, as was true for Semantic Search II, these increased with the number of potential target categories. The pattern of results for all six process parameters is highly similar across all three multiple-target semantic search tasks, II, III and IV.

Reference Ability Correlations

To examine the relationship between process measures derived from each task and reference ability scores, we derived factor scores for each subject on the three major factors described earlier in Section II. The three factor score measures were: (a) Fluid ability (Gf), (b) Crystallized ability (Gc), and (c) Perceptual-Spatial ability. The three factor scores were derived by weighting individual test scores in accordance with factor weights from the full sample factor analysis. The process parameters derived for each subject for each task were then correlated with each of the reference ability factor scores. Both simple and multiple regression analyses were pursued. In the multiple regression analyses, all process parameters for a given task were entered. Tables 16 through 26 contain the individual task results for both the simple and multiple regressions, with results reported separately for each reference ability factor. (Caution should be observed in examining the results in Tables 24 and 25 for the Visual Search III and Semantic Search III tasks, respectively, since the sample size for these tasks was small, N = 24.) With respect to the simple correlations of process parameters with reference ability scores, the majority of the correlations were non-significant. Those that were significant were in the range of .25 to .50 and typify results previously reported in the literature attempting to relate measures of information processing speed to measures of general and specific cognitive abilities. Those correlations that were significant tended to be with the Perceptual-Spatial ability factor. The significant correlations were negative, indicating that individuals of higher ability are faster at executing certain cognitive processes; typically, basic encoding and comparison processes and/or motor response and choice processes.

Of greater interest are the multiple regression results which are summarized in Table 15. This table contains the multiple R's obtained when all process parameters for a given task were simultaneously regressed against each separate reference ability factor score (no multiple regression results are reported for the Visual Search III and Semantic Search III tasks due to the small sample size). Thus, it is possible to ascertain the general relationship between performance on a specific information processing task and standardized measures of cognitive abilities. The results for the tasks in Battery I, Perceptual Matching I, Attribute Comparison, and Fact Retrieval, are very clear. For all these tasks and subtasks, the highest multiple R's are obtained for the Perceptual-Spatial ability factor. The multiple R's are all of similar magnitude. Furthermore, none of the tasks or subtasks shows any substantial relationship to the Crystallized ability factor. Relationships with the Fluid ability factor are moderate with two exceptions,

Table 15. Summary of Multiple Regression Values Obtained for Process Measures and Ability Factors

Task battery	Task	Gf	Gc	Perceptual-spatial
		Ability factor		
I	Perceptual Matching I	.319	.200	.657***
	Attribute comparison	.364	.239	.624***
	Fact retrieval			
	Addition	.307*	.076	.625***
	Subtraction	.481***	.113	.629***
	Multiplication	.299*	.124	.557***
	Division	.455***	.239	.583***
II	Perceptual Matching II	.294	.326	.306
	Visual Search I	.057	.292*	.382**
	Semantic Search I	.275	.282	.210
III	Visual Search II	.430**	.316	.335
	Semantic Search II	.433*	.456*	.603***
V	Semantic Search IV	.540*	.607***	.503

$*p < .10$.
$**p < .05$.
$***p < .01$.

Table 16. Perceptual Matching I Simple Correlations and Multiple Regression Results for Process Parameters

Ability factor	Statistic	Encode & compare	Respond different	Motor response
Gf	r	-.21	-.23*	-.10
	B[a]	-1.61	-6.28	-3.98
	t	-0.23	-2.07**	-1.84*
R = .319				
Gc	r	-.17	-.25*	-.12
	B	-1.89	-2.52	.03
	t	-0.33	-1.03	.02
R = .200				
Perceptual spatial	r	-.48***	-.21	-.34**
	B	-8.53	-5.05	-4.46
	t	-2.59**	-3.59***	-4.45***
R = .657***				

[a]unstandardized regression coefficient.
*p < .10.
**p < .05.
***p < .01.

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Table 17. Attribute Comparison Simple Correlations and Multiple Regression Results for Process Parameters

Ability factor	Statistic	E+C+R	Name retrieval	Category retrieval	Respond different
Gf	r	-.19	-.20	-.01	-.20
	B[a]	1.738	-6.494	1.908	-11.406
	t	.787	-1.529	.549	-2.288**
R = .364					
Gc	r	-.03	-.15	-.03	.03
	B	2.442	-5.032	-2.006	-2.641
	t	1.319	-1.414	-.689	-.632
R = .239					
Perceptual spatial	r	-.57***	-.48***	-.29**	-.53***
	B	-2.362	-5.685	-.295	-3.461
	t	-2.238**	-2.803***	.781	-1.454
R = .624***					

[a]unstandardized regression coefficient.
*p < .10.
**p < .05.
***p < .01.

Table 18. Fact Retrieval Simple Correlation and Multiple Regression Results for Process Parameters

Task	Ability factor	Statistic	Intercept	Slope
Addition	Gf	r	-.21	-.25*
		B[a]	-4.53	-.44
		t	-1.74*	-1.52
	R = .307*			
	Gc	r	-.07	-.09
		B	1.14	-.03
		t	.54	-.14
	R = .076			
	Perceptual spatial	r	-.58***	-.26*
		B	-6.52	-.32
		t	-5.26***	-2.3**
	R = .625***			
Subtraction	Gf	r	-.18	-.48***
		B	-1.45	-.73
		t	-1.23	-3.95***
	R = .481***			
	Gc	r	-.12	-.08
		B	-.16	-.14
		t	-.16	-.82
	R = .113			
	Perceptual spatial	r	-.61***	-.42***
		B	-3.11	-.36
		t	-5.13***	-3.70***
	R = .629***			

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Table 18 (Concluded)

Task	Ability factor	Statistic	Intercept	Slope
Multiplication	Gf	r	-.02	-.08
		B	-1.107	-1.536
		t	-.727	-2.182**
	R = .299*			
	Gc	r	-.08	-.19
		B	-.060	.404
		t	-.049	.707
	R = .124			
	Perceptual spatial	r	-.20	-.18
		B	-2.879	-1.686
		t	-3.733***	-4.733***
	R = .557***			
Division	Gf	r	-.07	-.43***
		B	-1.243	-.695
		t	-.818	-3.603***
	R = .445***			
	Gc	r	-.19	-.01
		B	-2.286	-.077
		t	-1.779*	-.476
	R = .239			
	Perceptual spatial	r	-.34**	-.53***
		B	-2.057	-.424
		t	-2.565**	-4.172***
	R = .583***			

[a]unstandardized regression coefficient.
*p < .10.
**p < .05.
***p < .01.

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Table 19. Perceptual Matching II Simple Correlations and Multiple Regression Results for Process Parameters

Ability factor	Statistic	Stimulus complexity	E+C+R positive	Difference detection	E+C+R negative
Gf	r	.18	-.13	-.18	.09
	B[a]	11.823	.044	-8.422	-.158
	t	1.674*	.091	-1.420	-.079
R = .294					
Gc	r	.32**	-.12	-.05	-.00
	B	12.328	-.019	-.545	.093
	t	2.242**	-.053	-.122	.060
R = .326					
Perceptual spatial	r	-.11	-.19	-.22*	-.03
	B	-4.012	-.343	-4.974	-1.074
	t	-.807	-1.015	-1.234	-.762
R = .306					

[a]unstandardized regression coefficient.
*p < .10.
**p < .05.
***p < .01.

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Table 20. Visual Search I Simple Correlations and Multiple Regression Results for Process Parameters

Ability factor	Statistic	Encode + compare	Motor response
Gf	r	-.07	.05
	B[a]	-2.451	-.042
	t	-.282	-.036
R = .057			
Gc	r	.26**	-.16
	B	12.746	.737
	t	1.942*	.852
R = .292*			
Perceptual Spatial	r	-.26**	.05
	B	-17.785	-1.749
	t	-3.124***	-2.333**
R = .382**			

[a]unstandardized regression coefficient.
*p < .10.
**p < .05.
***p < .01.

Table 21. Semantic Search I Simple Correlations and Multiple Regression Results for Process Parameters

Ability factor	Statistic	E+C+Retrieval member	M. R. member	E+C+Retrieval non-member	M. R. non-member
Gf	r	.00	-.14	.00	-.15
	B[a]	11.029	2.062	-15.203	-3.142
	t	1.072	.772	-1.580	-1.387*
R = .275					
Gc	r	-.04	-.08	.03	-.15
	B	5.028	2.886	-7.394	-3.068
	t	.622	1.375	-.978	-1.723*
R = .282					
Perceptual spatial	r	-.01	-.10	.00	-.10
	B	2.833	-.391	-5.761	-.506
	t	.383	-.204	-.833	-.311
R = .210					

[a]unstandardized regression coefficient.
*p < .10.
**p < .05.
***p < .01.

Table 22. Visual Search II Simple Correlations and Multiple Regression Results for Process Parameters

Ability factor	Statistic	1 Target slope	1 Target intercept	2 Targets slope	2 Targets intercept
Gf	r	.12	-.31**	.03	-.23*
	B[a]	7.166	-2.950	-15.319	-.897
	t	.416	-1.264	-1.681*	-.756
R = .430**					
Gc	r	.30**	-.28**	.24*	-.17
	B	8.479	-1.451	.249	.435
	t	.521	.657	.029	.388
R = .316					
Perceptual spatial	r	.09	.26**	.07	-.18
	B	-8.505	-2.542	-.043	.369
	t	-.872	-1.922*	-.008	.548
R = .336					

[a] unstandardized regression coefficient.
*p < .10.
**p < .05.
***p < .01.

Table 23. Semantic Search II Simple Correlations and Multiple Regression Results for Process Parameters

Ability factor	Statistic	1 Target slope	1 Target intercept	2 Targets slope	2 Targets intercept	4 Targets slope	4 Targets intercept
Gf	r	-.08	-.01	-.07	-.04	.19	-.10
	B[a]	14.577	-3.606	-19.921	-4.149	7.781	1.138
	t	1.215	.947	-2.464**	-1.842*	3.334***	1.668
R = .433*							
Gc	r	-.14	-.10	-.14	.03	.21*	-.15
	B	-8.307	-3.982	-6.142	.534	4.582	.429
	t	-.779	-1.176	-.854	.267	2.183**	.707
R = .456*							
Perceptual spatial	r	-.30**	-.21*	-.31**	-.27**	-.04	-.30**
	B	7.447	3.088	-11.866	-3.539	2.745	-.025
	t	1.291	1.686*	-3.052***	-3.267***	2.419**	-.079
R = .603***							

[a]unstandardized regression coefficient.
*p < .10.
**p < .05.
***p < .01.

Table 24. Visual Search III Simple Correlations and Multiple Regression Results for Process Parameters

Ability factor	Statistic	1 Target slope	1 Target intercept	2 Targets slope	2 Targets intercept
Gf	r	.06	-.26	-.05	-.09
	B[a]	-61.933	-21.562	46.904	7.919
	t	-.815	-1.237	.545	.858
R = .349					
Gc	r	-.02	-.37*	-.36	.05
	B	-49.659	-13.957	5.500	4.911
	t	-1.120	-1.373	.304	.912
R = .519					
Perceptual spatial	r	.06	-.42*	-.25	-.06
	B	9.648	-9.311	-11.482	1.667
	t	.311	-1.308	-.907	.442
R = .593					

[a]unstandardized regression coefficient.
*$p < .10$.
**$p < .05$.
***$p < .01$.

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Table 25. Semantic Search III Simple Correlations and Multiple Regression Results for Process Parameters

Ability factor	Statistic	1 Target slope	1 Target intercept	2 Targets slope	2 Targets intercept	4 Targets slope	4 Targets intercept
Gf	r	-.24	-.25	-.37*	.39*	-.10	.07
	B[a]	29.118	-4.026	-21.189	11.707	3.313	-3.130
	t	.742	-.276	-.882	.945	.394	-.706
R = .552							
Gc	r	-.47**	.11	-.46**	.26	-.20	-.19
	B	-33.847	-7.541	16.632	17.460	-6.341	-7.669
	t	-1.427	-.856	1.146	2.333**	-1.248	-2.864**
R = .726**							
Perceptual spatial	r	.04	-.11	-.12	-.19	-.11	-.41**
	B	16.242	2.936	-4.304	1.389	-3.060	-4.178
	t	.853	.415	-.369	.231	-.750	-1.944*
R = .564							

[a]unstandardized regression coefficient.
*p < .10.
**p < .05.
***p < .01.

Table 26. Semantic Search IV Simple Correlations and Multiple Regression Results for Process Parameters

Ability factor	Statistic	1 Target slope	1 Target intercept	2 Targets slope	2 Targets intercept	4 Targets slope	4 Targets intercept
Gf	r	.16	-.23	.05	-.21	.16	-.07
	B[a]	32.945	9.297	-47.510	-15.317	14.801	5.699
	t	1.367	1.550	-2.929***	-3.185***	3.088***	2.684**
R = .540*							
Gc	r	-.19	.03	-.01	-.13	.20	-.04
	B	10.954	12.018	-27.635	-9.647	13.248	3.076
	t	.471	2.077**	-1.766*	-2.080**	2.866***	1.502
R = .607***							
Perceptual spatial	r	-.05	-.07	-.07	-.08	-.04	-.09
	B	-29.739	-5.638	-3.898	-1.547	4.326	2.185
	t	-1.902	-1.448	-.370	-.496	1.391	1.586
R = .503							

[a]unstandardized regression coefficient.
*$p < .10$.
**$p < .05$.
***$p < .01$.

subtraction and division fact retrieval. The results for the latter two tasks are of particular interest since these two tasks involve quantitative decrementing and both can be solved by making use of highly overlearned quantitative incrementing facts. We hypothesize that solution of such problems requires retrieval of addition or multiplication facts and then mapping such facts onto the given subtraction or division problem. Thus, the involvement of Fluid ability may be in the conversion or mapping process where solution depends on rapid transformation of one form of information into a form suitable for problem solution. This would be manifest in the slope of the function relating reaction time to the size of the difference or quotient. Both of these slopes were substantially correlated with the Fluid ability factor and account for the size of the multiple R.

The full set of results for the tasks in Battery I strongly support the general prediction that simple, highly speeded information processing tasks, with familiar content, require similar basic cognitive processes for task execution and these processes are most highly associated with a Perceptual-Spatial ability factor. Relationships with a Fluid ability factor appear only when the tasks also include some degree of "novelty," perhaps in the form of transforming available information into a task usable form.

The results for the tasks in Battery II, Perceptual Matching II, Visual Search I, and Semantic Search I, are of interest when contrasted with the results obtained for tasks in Battery I and the more complex search tasks. For all three tasks in Battery II, the highest multiple R's are not necessarily obtained with the Perceptual-Spatial ability factor. Furthermore, none of the simple or multiple correlations is of substantial magnitude. The reduced correlations with the Perceptual-Spatial ability factor may be due to the use of unfamiliar visual stimuli in two of the tasks and/or the multiple, sequential comparison process required in the two search tasks. Both the nature of the stimuli and the nature of the task demands make these tasks less similar to the type of tasks loading on the Perceptual-Spatial ability factor. In the one task where familiar stimuli were involved, the task requires decisions based on semantic category information rather than perceptual information. The lack of any substantial correlation with the Fluid and Crystallized ability factors is not surprising since none of the three tasks had any level of processing complexity nor did any of the tasks require transformation of familiar information for task performance.

The results for the more complex search tasks, Visual Search II, Semantic Search II and IV, are especially interesting in light of the results for the tasks in Battery I and II. These two search tasks involve single-target searches, as was the case for Visual Search I and Semantic Search I, but these were intermingled with more complex search trials involving two or four active targets as the basis for the search. The results in Table 15 indicate that these tasks maintain some degree of relationship with the Perceptual-Spatial ability factor but also show multiple R's of similar, and in some cases greater, magnitude with the general ability factors, particularly Fluid ability. For the complex Visual Search task, the highest multiple R is for the Fluid ability factor. The complex Semantic Search tasks show similar multiple R's for the Fluid ability factor but differ from the Visual Search task with respect to the size of the multiple R's for the Crystallized ability factor. This factor is of significance only when semantic processing of multiple targets is required. Thus, it appears that increases in task and processing complexity, whereby individuals must deal with multiple targets sequentially or in parallel, require processing abilities more closely related to those tapped by measures of general cognitive abilities. These tasks also involve perceptual processing and motor response processes that are related to more specific Perceptual-Spatial abilities.

Finally, it should be noted that as task complexity increased, there was a tendency towards non-significant simple correlations of process parameters with reference ability scores. It appears that the patterning and relationships among the process parameters within a given task are important in predicting the ability factors, rather than the process parameters in isolation. Part of this may be due to the fact that in the search tasks the various slopes and intercepts were intercorrelated. Table 27 contains the results for the within-task correlations of the process parameters. For example, in the Semantic Search tasks the slopes for 1-, 2-, and 4-target searches were significantly correlated, as were the intercepts; and within each type of target search, the slopes and intercepts were negatively correlated, as often occurs in these tasks. Thus, the relationship of task performance to ability factors becomes apparent only by examining the pattern of multiple $\underline{R}$'s.

In summary, the results of our analyses of the relationships between individual task process parameters and reference ability scores support the fact that both simple and more complex cognitive tasks tap very basic encoding, comparison and motor response processes associated with a relatively specific Perceptual-Spatial ability factor. Cognitive tasks with greater complexity, or which introduce some form of processing "novelty," tap processes of information coordination and/or transformation that appear to be associated with more general ability factors, particularly Fluid ability.

VI. INDIVIDUAL DIFFERENCES IN PRACTICE PARAMETERS

In Section IV, we considered general practice effects within each of the 13 information processing tasks. In all cases, the group mean data indicated significant practice effects consistent with a general power function (see e.g., Newell & Rosenbloom, 1981). For each subject we derived median latencies for each session or subsession of each task. A simple power function was then fit to these data for each subject. The parameters of the power function were Beta, which corresponds to an intercept or initial value at the start of practice, and Alpha, which corresponds to a slope or rate of change value over sessions. First we will consider descriptive statistics for these measures in all five Task Batteries. Then we will consider how these measures correlate with reference ability scores. Finally, we will consider how the measures correlate with each other within and across tasks within a battery.

Descriptive Statistics

Table 28 contains summary statistics for the Beta and Alpha parameters for the tasks in Battery I. In the Perceptual Matching I task, we derived these measures for same and different judgment data combined and separately. In the Fact Retrieval tasks, we derived these measures for each of the the four fact

Table 27. Within-Task Correlations of Process Measures

Task battery	Task	Measures correlated	r Value
I	Perceptual Matching I	Encode & Compare - Respond Different	.16
		Encode & Compare - Motor Response	.12
		Respond Different - Motor Response	-.58***
	Attribute Comparison	Encode, Compare & Respond - Name Retrieval	.21
		Encode, Compare & Respond - Category Retrieval	.62***
		Encode, Compare & Respond - Respond Different	.79***
		Name Retrieval - Category Retrieval	.13
		Name Retrieval - Respond Different	.16
		Category Retrieval - Respond Different	.44***
	Addition Fact Retrieval	Intercept - Slope	.07
	Subtraction Fact Retrieval	Intercept - Slope	.28*
	Multiplication Fact Retrieval	Intercept - Slope	-.60***
	Division Fact Retrieval	Intercept - Slope	.15
II	Perceptual Matching II	Stimulus Comparison - E + C + R Positive	-.32**
		Stimulus Comparison - Difference Detection	.25*
		Stimulus Comparison - E + C + R Negative	-.06
		E + C + R Positive - Difference Detection	.26*
		E + C + R Positive - E + C + R Negative	.13
		Difference Detection - E + C + R Negative	-.46***
	Visual Search I	Encoding + Comparison - Motor Response	-.82***
	Semantic Search I	E + C + R Member - MR Member	-.68***
		E + C + R Member - E + C + R NonMember	.84***
		E + C + R Member - MR NonMember	-.57***
		MR Member - E + C + R NonMember	-.69***
		MR Member - MR NonMember	.92***
		E + C + R NonMember - MR NonMember	-.76***

Table 27 (Continued)

Task battery	Task	Measures correlated	r Value
III	Visual Search II	1 Target Slope - 1 Target Intercept	-.78***
		1 Target Slope - 2 Target Slope	.84***
		1 Target Slope - 2 Target Intercept	-.57***
		1 Target Intercept - 2 Target Slope	-.72***
		1 Target Intercept - 2 Target Intercept	.82***
		2 Target Slope - 2 Target Intercept	-.75***
IV	Semantic Search II	1 Target Slope - 1 Target Intercept	-.25
		1 Target Slope - 2 Target Slope	.73***
		1 Target Slope - 2 Target Intercept	-.01
		1 Target Slope - 4 Target Slope	.32**
		1 Target Slope - 4 Target Intercept	.11
		1 Target Intercept - 2 Target Slope	-.06
		1 Target Intercept - 2 Target Intercept	.73***
		1 Target Intercept - 4 Target Slope	.04
		1 Target Intercept - 4 Target Intercept	.41***
		2 Target Slope - 2 Target Intercept	-.20
		2 Target Slope - 4 Target Slope	.59***
		2 Target Slope - 4 Target Intercept	-.04
		2 Target Intercept - 4 Target Slope	.08
		2 Target Intercept - 4 Target Intercept	.41***
		4 Target Slope - 4 Target Intercept	-.42***
V	Semantic Search IV	1 Target Slope - 1 Target Intercept	-.71***
		1 Target Slope - 2 Target Slope	.54***
		1 Target Slope - 2 Target Intercept	-.21
		1 Target Slope - 4 Target Slope	.43***
		1 Target Slope - 4 Target Intercept	-.04
		1 Target Intercept - 2 Target Slope	-.39**
		1 Target Intercept - 2 Target Intercept	.58***
		1 Target Intercept - 4 Target Slope	-.36**
		1 Target Intercept - 4 Target Intercept	.49***

Table 27 (Concluded)

Task battery	Task	Measures correlated	r Value
		2 Target Slope - 2 Target Intercept	-.68***
		2 Target Slope - 4 Target Slope	.63***
		2 Target Slope - 4 Target Intercept	-.34**
		2 Target Intercept - 4 Target Slope	-.31*
		2 Target Intercept - 4 Target Intercept	.73***
		4 Target Slope - 4 Target Intercept	-.46***

*$p < .10$.
**$p < .05$.
***$p < .01$.

types. As shown in Table 28, the Beta parameters varied across tasks and all had substantial variance. Within the Fact Retrieval tasks, the Beta parameters were all similar. The Alpha parameters are summarized in the rightmost portion of Table 28. All had reasonable variance but the mean values for this parameter were relatively low, indicating small changes over sessions. The one exception was in the Attribute Comparison task, which had a moderate Alpha parameter.

Table 28. Means and Standard Deviations for Task Battery I Practice Parameters

Task	Beta parameter Mean (msec)	Beta parameter SD (msec)	Alpha parameter Mean	Alpha parameter SD
Perceptual Matching I				
Same and different	1555	353	.067	.061
Same	2024	503	.080	.071
Different	1221	2[illegible]	.061	.053
Attribute Comparison	1311	484	.197	.115
Fact Retrieval				
Addition	904	239	.093	.060
Subtraction	890	345	.090	.077
Multiplication	925	261	.096	.087
Division	1074	349	.123	.121

Table 29 summarizes the results for the Beta and Alpha parameters for the tasks in Battery II. In the Perceptual Matching II task, these parameters were derived for both same and different judgment trials. In the Semantic Search II task, they were derived for both the member and non-member search conditions. The Beta parameters for all three tasks in Battery II were substantial and all had reasonable variance. The Alpha parameters for the Perceptual Matching II task were moderate and had reasonable variance. The Alpha parameters for the Visual Search I and Semantic Search I tasks were low, although there was reasonable variance.

Tables 30 and 31 summarize the results for the Beta and Alpha parameters for the tasks in Batteries III - V. In the Visual Search II and Visual Search III tasks, these parameters were derived for both the 1- and 2-target search conditions. In the Semantic Search II, III and IV tasks, these parameters were derived for the 1-, 2- and 4-target search conditions. In all tasks, for all search conditions, the Beta parameters were substantial and all had reasonable variance. As expected from results presented earlier in Section IV, the Beta parameters were larger for the multiple-target search conditions and there was more substantial variance in these parameters. A similar

Table 29. Means and Standard Deviations for Task Battery II Practice Parameters

Task	Beta parameter Mean (msec)	Beta parameter SD (msec)	Alpha parameter Mean	Alpha parameter SD
Perceptual Matching II				
Same	3451	1347	.290	.174
Different	1542	347	.238	.087
Visual Search I	2196	516	.126	.100
Semantic Search I				
Member	2121	497	.148	.078
Non-Member	2320	597	.093	.083

Table 30. Means and Standard Deviations for Task Battery III Practice Parameters

Task	Beta parameter Mean (msec)	Beta parameter SD (msec)	Alpha parameter Mean	Alpha parameter SD
Visual Search II				
One target	1457	317	.186	.120
Two targets	2432	631	.218	.166
Semantic Search II				
One target	1509	373	.093	.095
Two targets	2432	658	.112	.115
Four targets	3736	1327	.167	.224

Table 31. Means and Standard Deviations for Task Battery IV and V Practice Parameters

Task	Beta parameter Mean (msec)	Beta parameter SD (msec)	Alpha parameter Mean	Alpha parameter SD
Visual Search III				
One target	1220	239	.137	.100
Two targets	2045	532	.169	.132
Semantic Search III				
One target	1367	198	.103	.059
Two targets	2228	545	.210	.101
Four targets	3689	1042	.318	.083
Semantic Search IV				
One target	1638	298	.128	.078
Two targets	2558	561	.207	.103
Four targets	4297	1203	.332	.159

pattern occurred for the Alpha parameters. The mean rate of change was considerably less in the 1-target search condition than in the 2- or 4-target search conditions. Thus, there was also more variance in the Alpha parameters derived for the multiple-target search conditions. The Alpha parameters were also higher for the multiple-target search conditions in the Semantic Search tasks with more total sessions (Semantic Search III and IV), when contrasted with the comparable estimates for the Semantic Search task with fewer total sessions (Semantic Search II). This would be expected given general practice effect data reported for Semantic Search tasks in Section IV. Further practice in the Visual Search task did not significantly impact the Alpha parameters for the single- or multiple-target search conditions.

Correlations With Reference Abilities

The Beta and Alpha parameters derived for each task were correlated with reference ability factor scores. The reference ability scores were derived in the same way as discussed in Section V. Table 32 summarizes the correlations obtained for the Beta parameters in all five Task Batteries. As shown in the table, the Beta parameters for all tasks in Battery I were significantly correlated with the measure of Perceptual-Spatial ability. Correlations with other reference abilities were minimal and only one exceeded the $p < .05$ level. In Task Battery II, significant correlations were again obtained for the Beta parameter with the Perceptual-Spatial ability scores. The exception to this was the Semantic Search I task. Also, the Beta parameters did not correlate with any other reference ability scores. Thus, it appears that measures of Perceptual-Spatial ability predict the overall mean response

Table 32. Correlations of Beta Practice Parameters with Reference Factors

Task	Ability factor		
	Gf	Gc	Perceptual-spatial
Task Battery I			
Perceptual Matching I			
Same and different	-.31**	-.17	-.63***
Same	-.18	-.12	-.51***
Different	-.26*	-.08	-.63***
Attribute comparison	-.20	-.09	-.35***
Fact retrieval			
Addition	-.21	.11	-.51***
Subtraction	-.22	.15	-.65***
Multiplication	.01	.14	-.38***
Division	-.12	.16	-.36***
Task Battery II			
Perceptual Matching II			
Same	.08	.11	-.27**
Different	-.17	-.17	-.27**
Visual Search I	-.11	.18	-.46***
Semantic Search I			
Member	-.20	-.19	-.20
Non-member	-.29**	-.20	-.20
Task Battery III			
Visual Search II			
One target	-.41***	-.05	-.29**
Two targets	-.27**	.00	-.10
Semantic Search II			
One target	-.03	-.14	-.36***
Two targets	-.12	-.02	-.40***
Four targets	-.06	.15	-.33***

Table 32 (Concluded)

Task	Ability factor		
	Gf	Gc	Perceptual-spatial
Task Battery IV			
Visual Search III			
One target	-.09	-.30	-.19
Two targets	-.07	-.28	-.21
Semantic Search III			
One target	-.13	-.38*	-.13
Two targets	-.12	-.29	-.16
Four targets	.14	-.21	-.12
Task Battery V			
Semantic Search IV			
One target	-.08	-.29**	-.25*
Two targets	-.08	-.33**	-.01
Four targets	-.05	-.33**	-.06

*$p < .10$.
**$p < .05$.
***$p < .01$.

latency during the first session of performance on several cognitive tasks, particularly those that involve perceptual-visual comparisons and/or the retrieval of highly overlearned math facts. Initial latencies in simple verbal-semantic processing tasks are not well predicted by any reference ability measures.

In Task Battery III, the Beta parameters for four of five search conditions were correlated with the Perceptual-Spatial ability factor. In addition, there were significant correlations with the Fluid ability factor for the Beta parameters in the Visual Search II task. No significant results were obtained for the tasks in Battery IV and this is probably attributable to the small sample size. For the Semantic Search IV task in Battery V, there was one significant correlation with the Perceptual-Spatial ability factor. However, all three Beta parameters were correlated with the Crystallized ability factor. Thus, it appears that the more complex search tasks maintain significant correlations between the Beta parameters and the Perceptual-Spatial ability factor, although the correlations are of lesser magnitude when compared to those obtained for the simpler cognitive tasks in

Task Battery I. In addition, initial performance levels in the more complex search tasks, as reflected in the value of the Beta parameter, are also related to general cognitive abilities. For the Visual Search II task, the relationship is with Fluid ability. For one sample of subjects, those in Semantic Search IV, the relationship is with Crystallized ability.

Table 33 contains the correlation results for the Alpha parameters derived from the tasks in all five batteries. As is obvious, the Alpha parameters have minimal relationships with reference ability scores. No meaningful pattern can be discerned for the few correlations that exceed the $p < .05$ level. The one possible exception involves the significant correlations with Crystallized ability for all search conditions in Semantic Search IV.

Correlations of Practice Parameters Within and Across Tasks

The preceding section indicated that correlations with reference abilities are obtained for the Beta parameters but not for the Alpha parameters. One possible reason for this pattern is that the Beta parameters are correlated with each other, since all may involve components of Perceptual-Spatial ability. In contrast, the Alpha parameters may be uncorrelated across tasks. Table 34 shows the results for correlations of the practice parameters within and across tasks in Battery I. Tables 35 through 38 are similar summaries for the tasks in Batteries II-V. The data in Table 34 for the Beta parameter indicate moderate correlations for this measure across tasks and higher correlations for this parameter across conditions within a task. A similar pattern in shown in Tables 35 through 38 for the Beta parameter. Tables 34 through 38 indicate that the Alpha parameters have minimal correspondence across tasks. The only significant correlations for this parameter of practice were obtained for conditions within the same task.

Examination of the between-task and within-task correlational patterns for the Beta and Alpha parameters can also contribute to understanding whether the low or non-existent correlations of practice parameters with reference abilities might be due to unreliability of these measures. Split-half reliability scores were not derived for the practice parameters and thus, it could be argued that the low correlations with reference ability scores are uninterpretable in the absence of such data. While one could debate such a conclusion, given the large number of data points contributing to individual session reaction time means, there are other aspects of the data that actually permit an even stronger form of reliability assessment for the practice parameters derived for the majority of the information processing tasks. One can treat certain aspects of the data presented in Tables 34 through 38 as measures of alternate forms reliability since practice parameters were derived for closely related conditions within the same task. Examples include same versus different judgments in perceptual matching, member versus non-member searches, and one versus two target searches.

If we focus first on the Beta parameter, we find that the average within-task correlation for this parameter is quite high, with a mean of .71 based on 20 separate values obtained from 9 of the 11 tasks presented in Tables 34 through 38. If a stringent selection criterion is used to compute the average within-task correlation (eliminating the four subtasks of the Fact Retrieval task and correlations between 1- and 4-target searches in the Semantic Search tasks), then the mean value is .77 based on 11 separate values

Table 33. Correlations of Alpha Practice Parameters with Reference Factors

Task	Ability factor		
	Gf	Gc	Perceptual-spatial
Task Battery I			
Perceptual Matching I	-.05	-.06	-.07
Same and different	-.03	-.12	-.11
Same	-.09	-.13	-.16
Different			
Attribute comparison	-.09	-.14	-.18
Fact retrieval			
Addition	.09	-.11	.07
Subtraction	-.05	.31**	-.26**
Multiplication	-.11	-.12	.04
Division	.02	.25*	-.05
Task Battery II			
Perceptual Matching II			
Same	.05	-.05	-.03
Different	-.09	-.23*	-.04
Visual Search I	-.13	.01	-.12
Semantic Search I			
Member	.00	-.17	-.07
Non-member	-.18	-.06	-.16
Task Battery III			
Visual Search II			
One target	-.19	-.05	-.01
Two targets	-.04	-.01	.15
Semantic Search II			
One target	.19	.06	.15
Two targets	-.02	.10	.16
Four targets	-.14	.13	-.06

Table 33 (Concluded)

Task	Ability factor		
	Gf	Gc	Perceptual-spatial
Task Battery IV			
Visual Search III			
One target	-.05	-.08	.10
Two targets	-.15	-.12	.08
Semantic Search III			
One target	.01	-.08	.12
Two targets	.20	.18	.01
Four targets	.30	.16	.30
Task Battery V			
Semantic Search IV			
One target	.02	-.28*	-.25
Two targets	-.15	-.46***	-.15
Four targets	-.08	-.35*	-.02

*p < .10.
**p < .05.
***p < .01.

Table 34. Correlations of Task Battery I Beta and Alpha Parameters Within and Between Tasks

Parameter	Task	Perceptual matching	Attribute comparison	Fact retrieval			
		Diff.		Add.	Sub.	Mult.	Div.
Beta	Perceptual Matching I						
	Same	.82***	.13	.40***	.42***	.44***	.39***
	Different		.30**	.60***	.63***	.52***	.36**
	Attribute comparison			.32*	.33*	.34**	.25**
	Fact retrieval						
	Addition				.82***	.62***	.68***
	Subtraction					.73***	.60***
	Multiplication						.63***
Alpha	Perceptual Matching I						
	Same	.66***	.02	.02	-.08	.04	.10
	Different		.23*	.11	.04	.04	-.02
	Attribute comparison			.24*	.12	.20	.03
	Fact retrieval						
	Addition				.19	-.05	.29*
	Subtraction					.16	.06
	Multiplication						.08

*p < .10.
**p < .05.
***p < .01.

Table 35. Correlations of Task Battery II Beta and Alpha Parameters Within and Between Tasks

Parameter	Task	Perceptual Matching II	Visual Search I	Semantic Search I	
		Different		Member	Non-member
Beta	Perceptual Matching II				
	Same	.49***	.16	.23*	.18
	Different		.25*	.38***	.34***
	Visual Search I			.14	.18
	Semantic Search I				
	Member				.87***
Alpha	Perceptual Matching II				
	Same	.59***	.06	.18	.02
	Different		-.12	.17	-.06
	Visual Search I			-.04	-.01
	Semantic Search I				
	Member				.63***

*$p < .10$.
**$p < .05$.
***$p < .01$.

Table 36. Correlations of Task Battery III Beta and Alpha Parameters Within and Between Tasks

		Visual Search II	Semantic Search II		
Parameter	Task	Two targets	One target	Two targets	Four targets
Beta	Visual Search II				
	One target	.78***	.38***	.52***	.46***
	Two targets		.45***	.56***	.60***
	Semantic Search II				
	One target			.87***	.55***
	Two targets				.74***
Alpha	Visual Search II				
	One target	.48***	.16	.28**	.23*
	Two targets		.43***	.19	.18
	Semantic Search II				
	One target			.51***	.08
	Two targets				.44***

*p < .10.
**p < .05.
***p < .01.

Table 37. Correlations of Task Battery IV Beta and Alpha Parameters Within and Between Tasks

Parameter	Task	Visual Search III	Semantic Search III		
		Two targets	One target	Two targets	Four targets
Beta	Visual Search III				
	One target	.81***	.36*	.40**	.46**
	Two targets		.21	.36*	.45**
	Semantic Search III				
	One target			.68***	.42**
	Two targets				.80***
Alpha	Visual Search III				
	One target	.73***	.05	-.09	.30
	Two targets		.03	-.35*	-.03
	Semantic Search III				
	One target			.24	.25
	Two targets				.45**

*p < .10.
**p < .05.
***p < .01.

Table 38. Correlations of Task Battery V Beta and Alpha Parameters

Parameter	Task	Semantic Search IV	
		Two targets	Four targets
Beta	Semantic Search IV		
	One target	.87***	.60***
	Two targets		.75***
Alpha	Semantic Search IV		
	One target	.72***	.40***
	Two targets		.64***

*p < .10.
**p < .05.
***p < .01.

derived from 8 of the 11 tasks. Thus, it would appear that the Beta parameter has substantial alternate forms reliability. This is also not surprising since the Beta parameter typically is a close approximation to the mean latency obtained for the first session of practice. Given that this latency is based on many trials, one would expect it to have high reliability. The present data indicate that this performance parameter does in fact have substantial consistency across task conditions for the Alpha parameter.

A similar analysis can be conducted for the Alpha parameter. If we consider the stringent inclusion criterion, then the mean value is .55, which is clearly lower than the value obtained for the Beta parameter. However, this is not surprising since some of the conditions correlated were previously shown to have either very small or different rates of change. Thus, we consider the value of .55 to be an underestimate of the alternate forms reliability and a substantial underestimate of the split-half reliability, again because of the large numbers of latency trials contributing to the individual session means used in estimating the practice parameters. What we consider far more important is the fact that while the Alpha parameters may be substantially correlated across conditions within a task, they are clearly not correlated across speeded processing tasks. This is the case even when the tasks are highly similar in form (e.g., search tasks). Thus, it would appear to be the case that the failure to obtain correlations between rate of change practice parameters (Alpha) and reference ability scores is not due to simple issues of unreliability but to other conceptual problems with such measures as discussed in the next section.

Reference Ability - Task Performance Correlations at Different Stages of Practice

Recently, Ackerman (in press) has discussed classic problems in assessing changes in task performance as related to measures of cognitive ability. The particular problems relate to rate-of-change parameters, including their instability and positive correlation with initial levels of task performance. Individuals of lower ability may perform more poorly than high ability individuals during initial phases of task performance, as shown in the present studies, but they may also show greater absolute and relative rates of change over sessions than high ability subjects who have less room for improvement. Thus, the rate-of-change scores (Alpha parameters) are derived from a mixture of possible situations, with the net result of minimal correlations with reference ability scores and with each other across tasks. This was certainly true for the present studies.

Ackerman (in press) has suggested an alternate mode of analysis to examine relationships between reference abilities and task performance at different stages of practice. This involves correlating individual session performance scores with reference ability factor scores and examining the trends in the correlations over sessions of practice. Furthermore, this type of analysis is most useful for consistent and varied mapping tasks which have sufficient levels of complexity such that correlation patterns may change for general and specific ability factors. Our previously reported analyses of process parameters and Beta practice parameters suggest that such analyses may be useful for the more complex visual and semantic search tasks. Thus, correlational analyses were conducted using mean response times at each session of practice for the different search conditions in Visual Search II, Semantic Search II, and Semantic Search IV.

Before presenting the results of these analyses, it is useful to present some general predictions from Ackerman's (1986) theory. He has argued that at the beginning stages of practice on any task, there is a degree of novelty and thus initial performance on the task should be a function of several factors: specific skills, content abilities, specialized knowledge, and general ability. However, during training there are differential effects depending on whether a task has consistently mapped or inconsistently (varied) mapped components. In the former case, automatic processing should be approached and general abilities should no longer determine performance differences among individuals. The argument is that such tasks move from being resource limited to data limited and ability measures provide an index of available resources. In the case of an inconsistently mapped task, controlled processing will continue throughout practice, the task will remain resource limited and thus general and specific abilities will continue to predict performance scores.

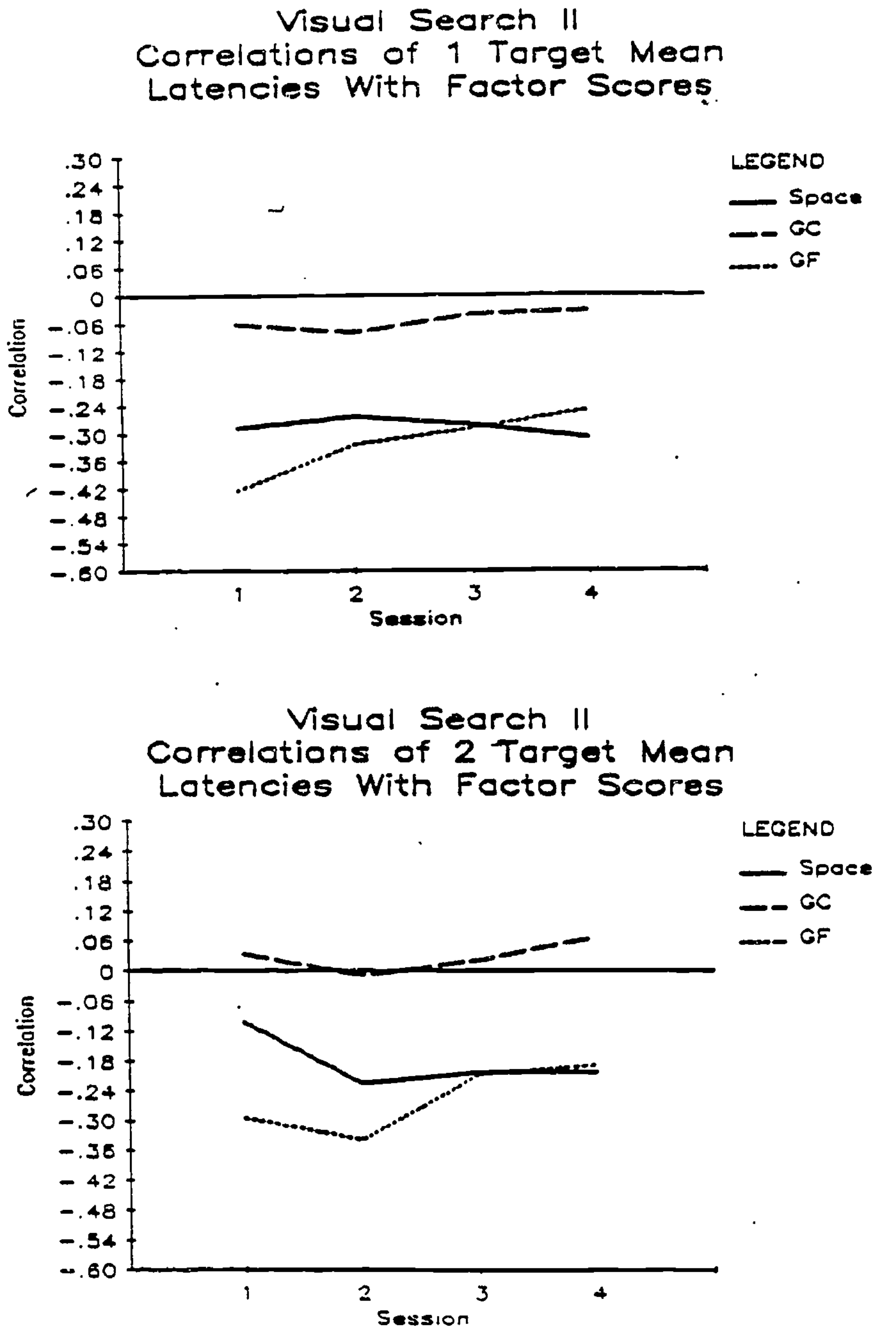
Given Ackerman's theory, there are differential predictions to be made for the visual search and semantic search tasks. For the visual search task, which has varied mapping, it would be predicted that one or both measures of general ability would be correlated with performance and that the magnitude of the correlations should remain relatively constant over practice sessions. It would also be predicted that the perceptual-spatial factor would also correlate with performance and that the magnitude of the correlation would remain stable over practice.

For the semantic search task, which has consistent mapping, the predictions would be that any general ability relationships that exist will be present only early in practice. These will decline over practice, while specific ability relationships might actually increase over practice.

For both the visual search and semantic search tasks, it would also be expected that the magnitude of any relationship observed between performance and ability factors should also be a function of task demands. Thus, stronger relationships would be expected in multiple-target search conditions which place greater demands on memory and attentional resources.

The results for Visual Search II are shown in Figure 45. For both the 1- and 2-target search conditions, there were moderate correlations between mean reaction time and the Perceptual-Spatial ability and Fluid ability factors and no correlations with the Crystallized ability factor. The initial session correlations are higher for the Fluid ability factor, with a convergence of Fluid and Perceptual-Spatial ability by session 3. These patterns occurred for both the 1- and 2-target search conditions. Generally, these results are consistent with predictions from Ackerman's theory and the correlations obtained between reference ability factor scores and both process and Beta practice parameters for this task.

The results for Semantic Search II are shown in Figure 46. First, consistent with reference ability correlations obtained for both process and Beta practice parameters, there are correlations with the Perceptual-Spatial ability factor. These occur in all three target search conditions and are maintained throughout all four sessions of practice. This is generally



<u>Figure 45.</u> Correlations of Visual Search II Mean Session Latencies with Reference Ability Factors.

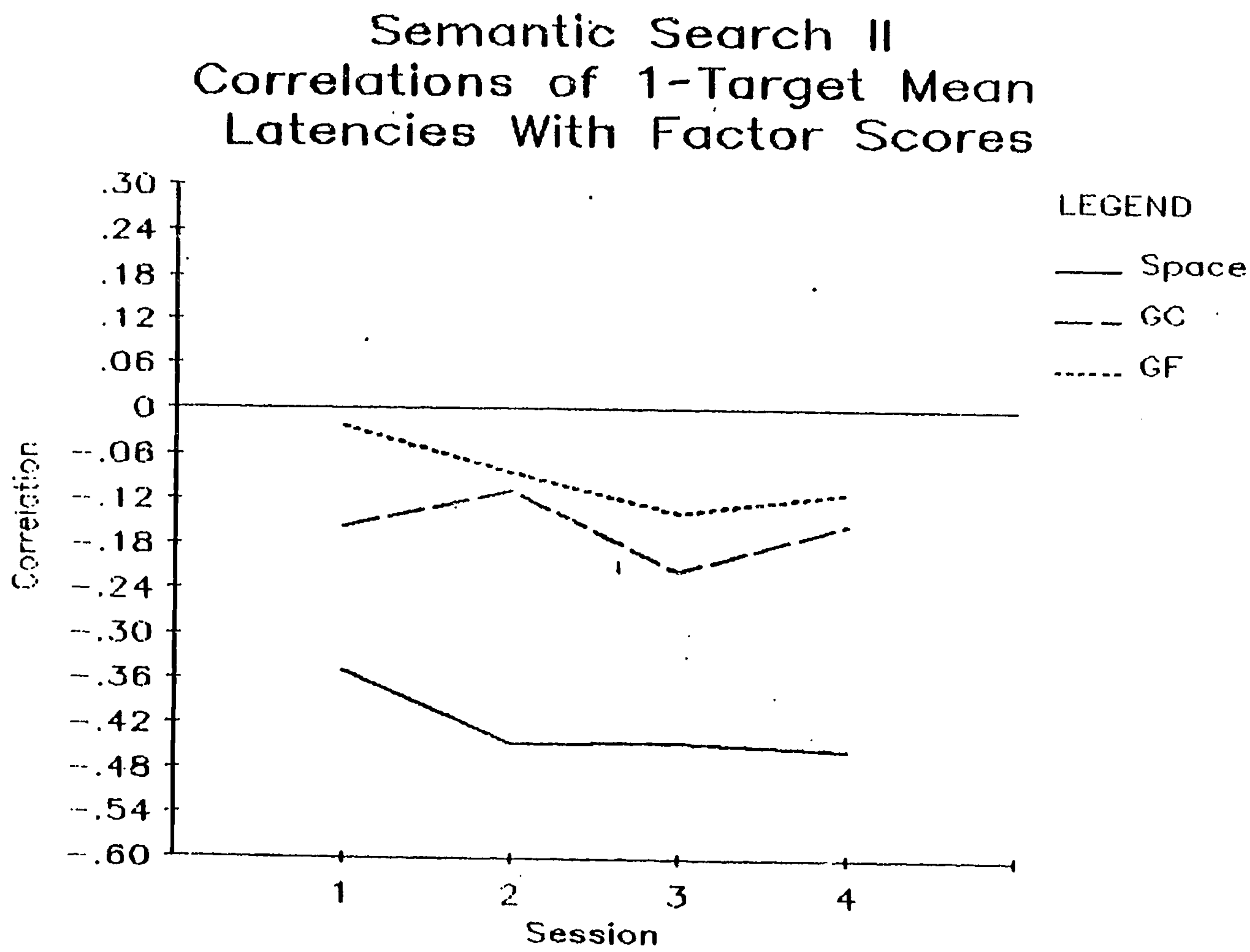


Figure 46. Correlations of Semantic Search II Mean Session Latencies with Reference Ability Factors.

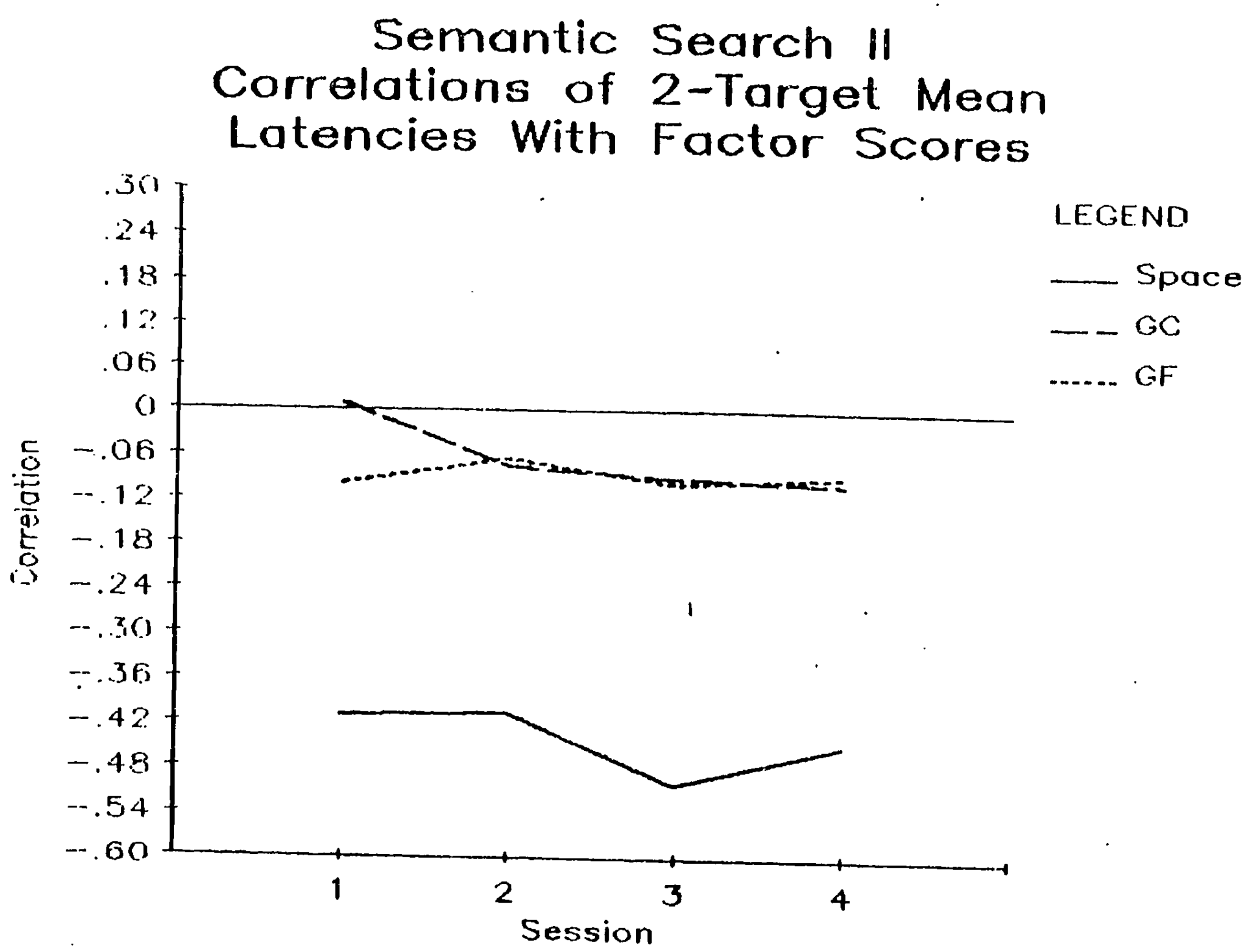


Figure 46 (Continued)

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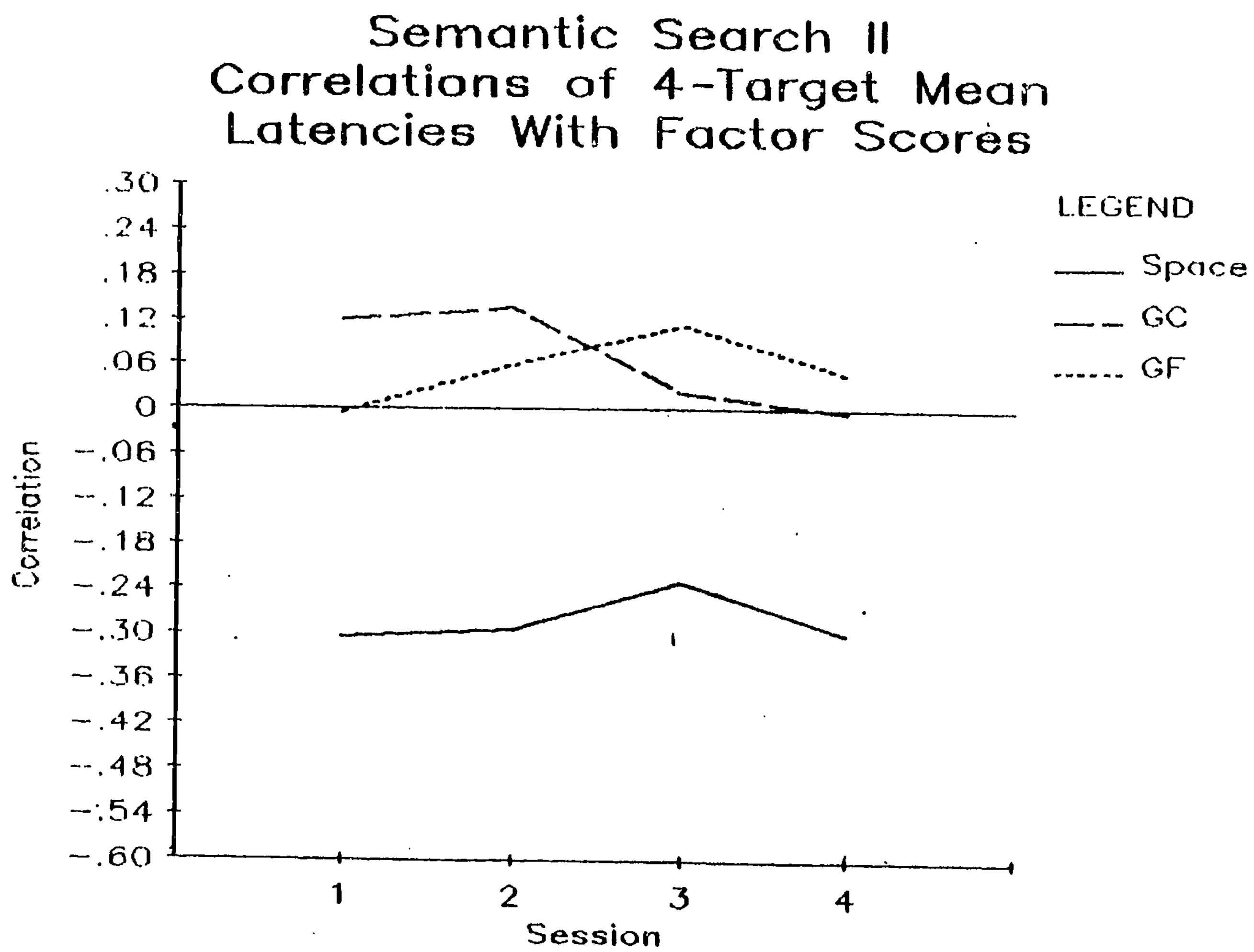

Figure 46 (Concluded)

consistent with Ackerman's theory. Second, there is a trend regarding the correlations for the two general ability factors. As task complexity increases by increasing the number of active targets, the correlations of task performance measures with general abilities change from negative, to zero, to positive. This is most apparent for the Crystallized ability factor but also occurs for the Fluid ability factor. Ackerman's theory would predict the opposite pattern. We are uncertain whether this is a genuine trend or simply some unimportant fluctuation in non-significant correlations of low magnitude.

Figure 47 shows the results for the Semantic Search IV task. Again, there is a trend across search conditions such that the correlations shift from negative, to zero, to positive as task complexity increases. This trend again occurs for the Fluid ability factor but also is present for the Perceptual-Spatial ability factor. There is also a trend for all correlations across all search conditions to move towards zero with increased practice which, is generally consistent with predictions made by Ackerman (1986). Finally, during the early sessions of task practice, for all search conditions, there are correlations between task performance and the Crystallized ability factor, with these diminishing to zero after 3 to 6 sessions of practice. These results are partially consistent with Ackerman's (1986) predictions. The session correlations are also generally consistent with the earlier presented correlations between reference ability factor scores and process and practice parameters.

These analyses of the relationships between measures of task performance at different stages of practice and reference ability factors have produced results partially consistent with predictions from Ackerman's theory regarding varied and consistent mapped tasks. There are also certain inconsistencies in the results both relative to Ackerman's theory and across subject samples. Particularly troubling is the lack of consistency in specific correlation patterns obtained for the two separate subject groups tested with the same semantic search task. In one sample, relationships with Perceptual-Spatial ability were observed and in the other sample, relationships with Crystallized ability were obtained. The clearest results were obtained for the Visual Search II task but we remain uncertain about the validity of these results in the absence of a replication study. Thus, we can only conclude that there are potentially interesting relationships between task complexity, task content, task consistency and reference abilities at different stages of task practice. However, larger samples of subjects may be needed to verify subtle differences in correlational patterns.

VII. SUMMARY AND GENERAL DISCUSSION

In the preceding sections we reviewed several facets of this program of research. As a basis for summary and discussion of the results, it is useful to restate our goals and then consider the extent to which they have been met. A primary goal was to determine if computer-based assessment procedures could be developed to reliably assess an individual's current levels of information processing efficiency. A second goal was to determine if these procedures (tasks) could also provide information about changes in information processing efficiency, or what we have termed "movement towards automaticity." A third goal was to determine if these measures of information processing efficiency

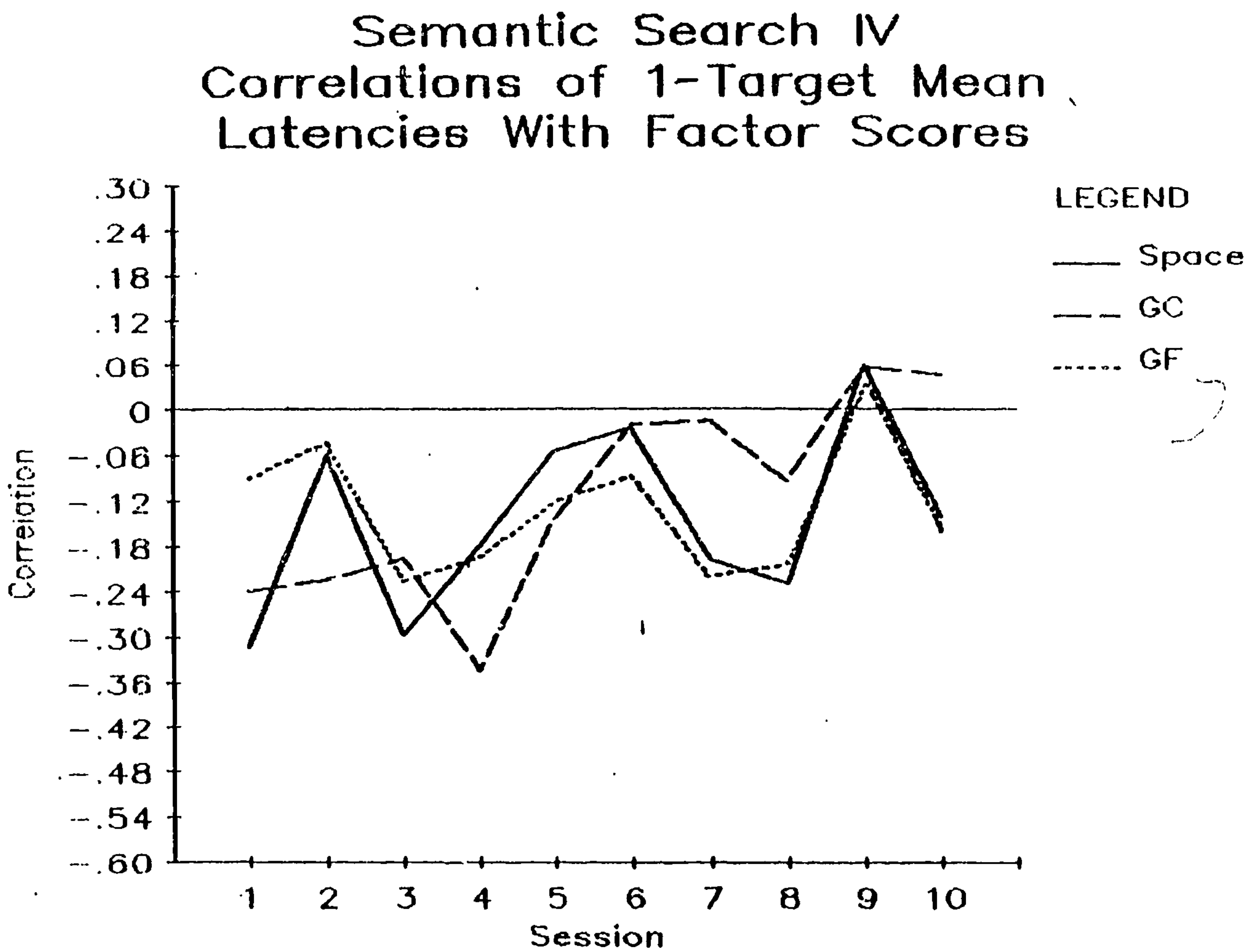

Figure 47. Correlations of Semantic Search IV Mean Session Latencies with Reference Ability Factors.

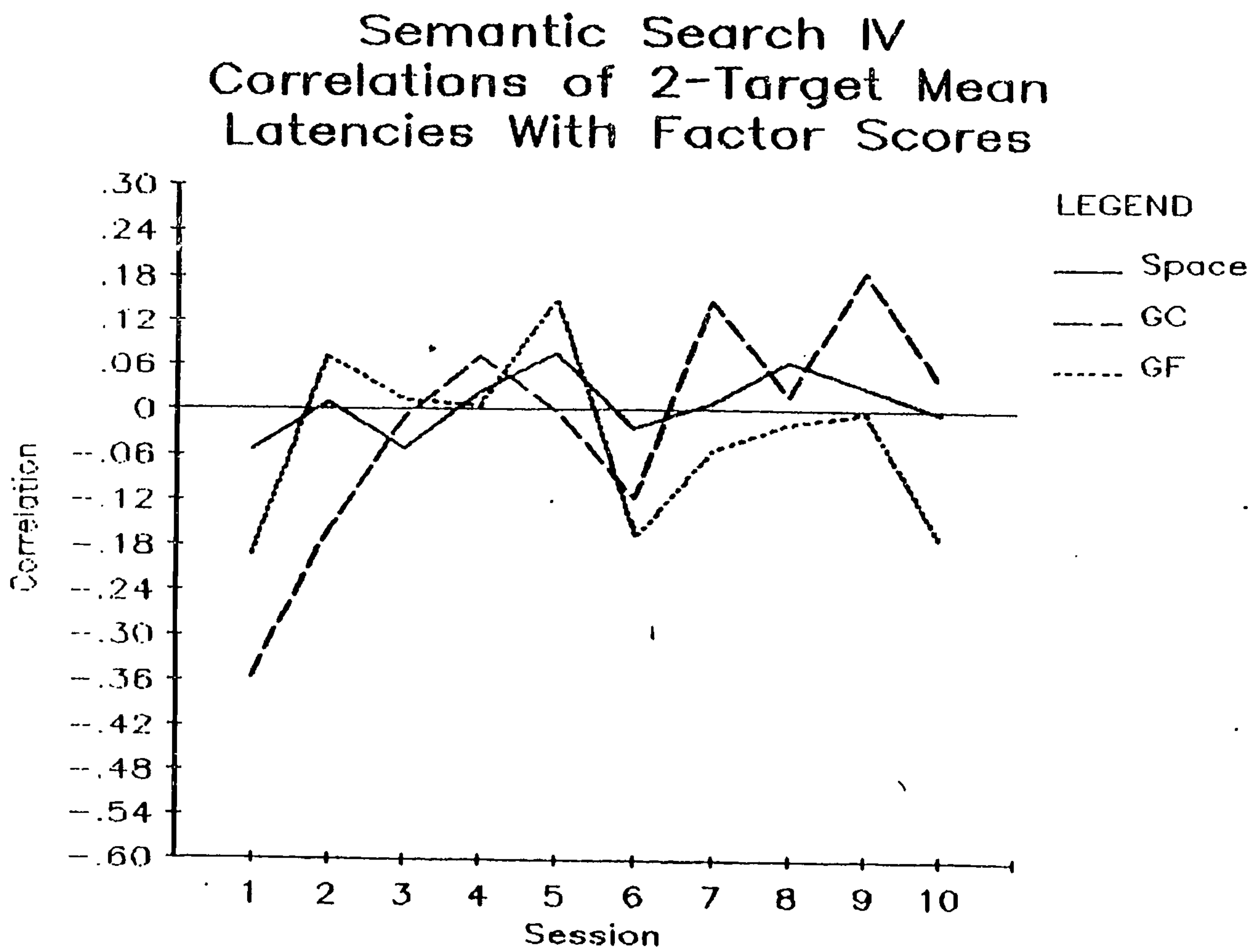

Figure 47. (Continued)

2̈03 2̈04

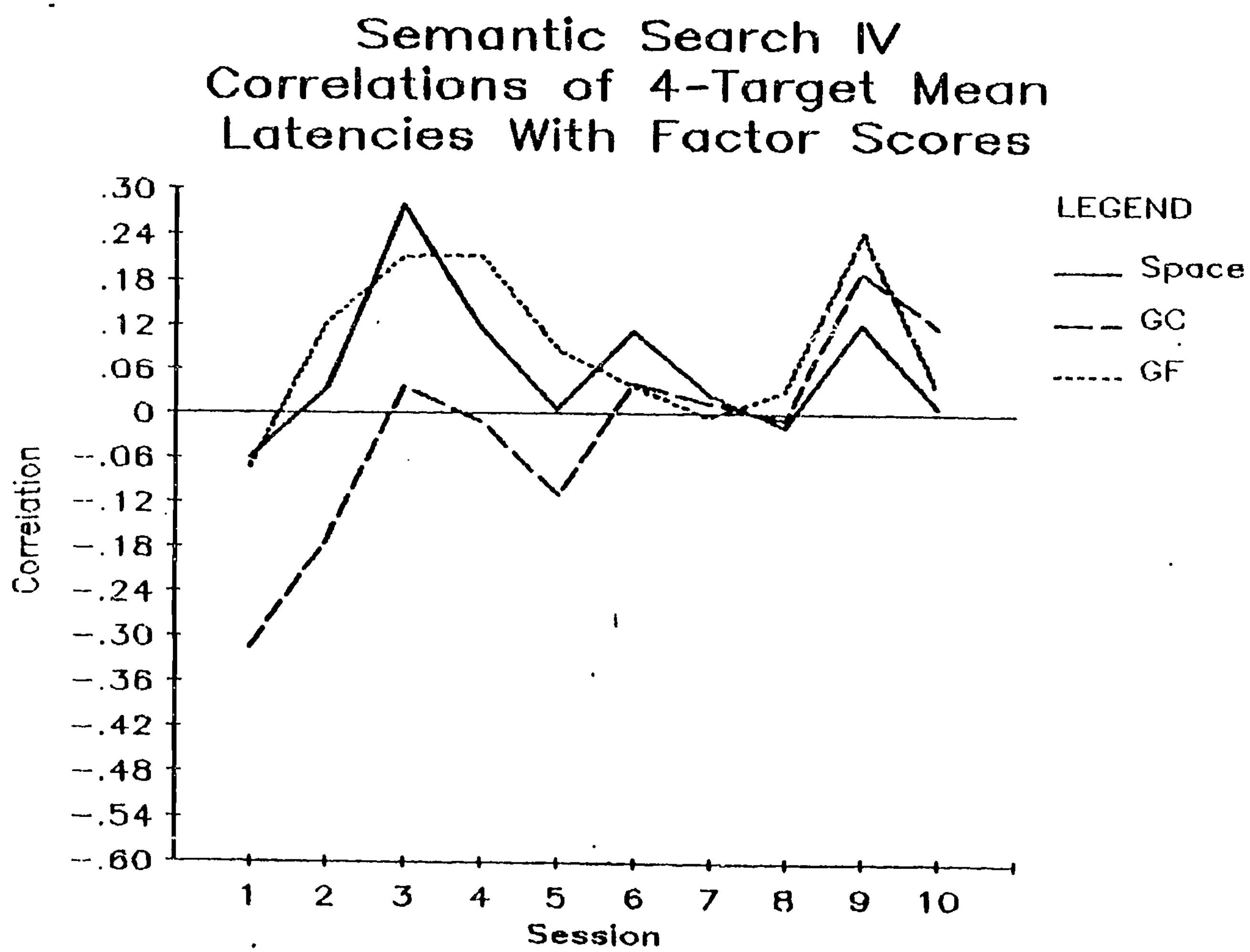

Figure 47 (Concluded)

were related to extant ability measures. A fourth goal was to determine if it is possible to assess movement towards automaticity within a reasonable time period. A fifth goal was the analysis of general versus specific aspects of skill acquisition in information processing tasks.

To accomplish these goals, we conducted 13 studies using information processing tasks varying in complexity and domain of information processing. These studies were divided into five task batteries and each task battery was administered to 24-60 individuals who varied in cognitive abilities as assessed by a reference ability battery. With respect to our first goal, we have demonstrated in Sections IV and V that it is feasible to assess an individual's current level of efficiency in executing various cognitive processes. All of our microcomputer-based tasks demonstrated a high level of internal validity. Models of task performance provided excellent accounts of the group mean data within each task. In addition, when these models were fit to individual subject data, they produced estimates of process execution speed that were highly reliable. Eight of the 13 studies used tasks that had a total testing time of less than 2 hours. Thus, it is possible to reliably assess components of information processing efficiency within a reasonable time period.

With respect to our second goal, all the information processing tasks demonstrated overall practice effects over the time course of testing. The practice effects were consistent with general power functions. One important general result was that practice effects varied in magnitude as a function of task complexity and stimulus familiarity. Such differences among tasks in practice effects were demonstrated for mean response latency as well as for more refined analyses in terms of information processing components of task performance. Practice effects were relatively small for highly speeded simple decision tasks with familiar content. In such tasks, improvements in performance were primarily attributable to motor response processes. Certain basic processes such as category retrieval and visual comparison showed relatively high levels of efficiency at early stages of task performance with little change over practice.

More substantial practice effects occurred in two types of situations. One situation involved same-different identity judgments for (a) unfamiliar stimuli of varying complexity and (b) rotated stimuli. In both of the preceding cases, subjects "learned" the stimuli and learned how to mentally manipulate the stimuli leading to substantial practice effects in both overall mean response latency and component process execution. Both of these cases also seem to represent constant mapping situations, which is an apparent precondition for demonstrating substantial practice effects with substantial progress toward highly efficient and automated responding. We demonstrated in two studies that stimulus familiarity effects are important and one study also showed that the general task context in which judgments are elicited affects the nature of performance, determining how subjects respond to stimulus differences and what they learn about specific stimuli that can facilitate or hinder subsequent performance when the global task context changes.

The second situation producing substantial practice effects involved increases in task complexity through requiring multiple-target searches. However, even in these situations, there were variations in the magnitude and locus of the practice effects in the multiple-target search conditions. In the complex visual search tasks, practice effects were not as substantial as in the complex semantic search tasks. Furthermore, changes in the slopes of the multiple-target search conditions occurred only in the semantic search tasks. One important difference between the visual and semantic search tasks was the varied stimulus-response mapping in the former and the constant stimulus-response mapping in the latter. Thus, constant mapping seems to be a precondition for demonstrating substantial changes in task performance, with evidence of movement towards a parallel, automated response mode. However, the amount of practice necessary for demonstrating such changes in performance is substantially more than 2 hours of testing.

Analyses of practice effects for individual subjects were consistent with the general group trends just mentioned. Two components of a general power function could be estimated for each subject in each task, although there are questions about the reliability and utility of one of these measures; namely, the rate-of-change parameter. We consider this issue in more detail subsequently.

One of the most important issues was whether our measures of information processing efficiency were related to standard reference ability measures. The data reported in Section V indicate that many of the process measures are related to Perceptual-Spatial ability scores. There are also some relationships with more general cognitive abilities such as Fluid and Crystallized ability. The simple correlations of process measures with reference ability scores diminished in size and frequency across task batteries. We think there is a plausible explanation for these results. As we move from Task Battery I to Task Battery II and then to Task Batteries III-V, the tasks become more complex; i.e., there are more stimuli to be processed and more decisions to be made before executing a final response. In addition, the visual-perceptual stimuli become more novel and complex. In Task Battery I, all three tasks present highly familiar stimuli--alphanumeric characters for visual comparison, simple word pairs and simple numeric equations. All three tasks also require a simple positive or negative verification response. Thus, it is not surprising that measures derived from these tasks correlate with extant measures of Perceptual-Spatial ability. As the tasks become more complex and as the stimuli become less familiar, the correlations with Perceptual-Spatial ability diminish. However, the multiple regression analyses suggested that performance in the more complex tasks involved processing components related to general cognitive abilities, Fluid ability in the case of complex visual search and both Fluid and Crystallized ability in the case of complex semantic search. We hypothesize that such relationships emerged because of (a) the requirement of making multiple decisions regarding any single stimulus, (b) the memory load imposed by multiple target criteria, and/or (c) the trial-by-trial shifting in task demands.

There are several ways to view our results with respect to information processing-reference ability relationships. One is from the perspective of explaining existing aptitude measures in terms of cognitive processing measures. This has been done before in the literature and generally it has been shown that measures of processing speed in simple cognitive tasks correlate between .3 and .5 with aptitude measures. Our results are consistent with such prior findings. Measures of processing speed do not yet provide a thorough account of aptitude measures, although our data suggest that such an account may be possible with respect to Perceptual-Spatial ability.

A second perspective on our results arises from consideration of the conditions leading to the derivation of the individual subject process parameters for each task. To estimate process parameters through model fitting, mean or median latencies were derived for the individual problem types in each task. Thus, the number of data points contributing to each mean or median was usually substantial since these data were collapsed across all sessions of practice. The result was that individual subject process parameters were highly reliable as illustrated earlier in Section V. These parameters thus reflect an individual's average level of efficiency in process execution over all trials of task performance. Given the changes that occur with practice, particularly in the more complex tasks, it is entirely possible that aptitude-process relationships change over practice and thus, the estimation procedure may lead to severely attenuated correlations of process parameters and reference ability scores. Unfortunately, it is not a simple matter to correct for this by deriving process estimates for each subject at each session of practice since the reduced data set typically leads to the opposite problem of unreliable process estimates. Thus, there is a need for caution in assuming that measures of information processing efficiency are largely unrelated to measures of general cognitive abilities.

A third way to look at these results is to say that aptitude measures provide some indication of a person's current level of information processing efficiency. In our studies this is most apparent with respect to basic encoding, comparison and motor response processes for highly overlearned stimuli. Aptitude measures also provide an indication of an individual's likely initial level of overall performance in many information processing tasks. As demonstrated in Section VI, measures of Perceptual-Spatial ability predict starting values (Beta parameters) of practice functions in several different cognitive tasks. The level of prediction depends on the simplicity of the task, the extent to which it assesses perceptual comparison processes, and the familiarity of the content. In more complex tasks, measures of general ability appear to predict initial levels of task performance as well as subsequent performance differences among subjects. This issue needs to be investigated more thoroughly.

In contrast, aptitude measures provide no indication of an individual's rate of change in performance in any of our information processing tasks. The lack of prediction of rates of change in performance in information processing tasks is potentially an important result. It is consistent with the view that aptitude scores may not be the best indices of an individual's trainability or capacity to become more efficient in performing certain tasks and in executing certain processes in a highly efficient and automated mode. We must be cautious, however, in drawing premature conclusions. First, the practice effects and rates of change for the simple tasks in Battery I were not substantial. In many cases individuals appeared to begin the tasks at near-optimal levels of performance and their rate of change was minimal and unrelated to changes in performance in other tasks where they were less efficient at the start of practice. This was also true for tasks in Battery II. Our analyses of the data for tasks in Batteries III-V show that practice effects are more substantial. Of particular interest are the search tasks in Batteries III-V where we had conditions with varying levels of stimulus familiarity and where we could compare single- versus multiple-target processing. The data from these tasks suggested that the study of practice effects and movement towards automaticity is best pursued in the context of more complex processing situations. Nevertheless, the data on correlations of rate-of-change parameters with reference abilities were much the same as for the simpler tasks in Batteries I and II. It would appear that rate-of-change parameters are problematic with respect to their utility and meaningfulness. (cf., Ackerman, in press).

Given our results to date, we feel that substantial progress was made in attaining our goals. Two considerations need to guide future studies in the area of skill acquisition. First, tasks must be developed that have greater degrees of processing complexity. Second, it is apparent that as tasks increase in complexity, longer testing periods will be needed to examine movement towards automaticity. In search tasks with multiple targets, our data show that there is evidence of convergence but terminal levels of performance are still far removed from a stage of parallel processing. Thus, considerably more trials and sessions will need to be administered. Longer testing periods are also needed to obtain more extensive, reliable and refined practice parameters. We have used a simple two-parameter power function to fit individual subject data. A goal of research in this area should be to examine more sophisticated practice models with three or four parameters. The latter include estimates of asymptotic levels of performance and prior experience. Longer testing periods would also provide sufficient amounts of data for examining acquisition effects for specific components of processing in addition to overall measures such as mean latency and accuracy. By increasing task and processing complexity and by varying stimulus familiarity, it would be possible to obtain a more substantial data base within which to examine the issue of general versus specific skill acquisition effects and their relationship to existing aptitude measures.

It would also be useful if more extensive validation studies could be conducted for some of the information processing tasks and measures. At present, external validation is based on reference ability scores and we see a need for validation against other forms of performance. Examples include learning measures and course performance such as those proposed under Project LAMP (Learning Abilities Measurement Project). Measures of information processing efficiency may not "predict" existing aptitude scores but they may augment such measures in predicting performance in learning and training situations where there are significant real-time processing demands. These issues remain to be explored.

REFERENCES

Ackerman, P. L. (1986). Individual differences in information processing: An investigation of intellectual abilities and task performance during practice. Intelligence.

Ackerman, P. L. (in press). Individual differences in skill learning: An integration of psychometric and information processing perspectives. Psychological Bulletin.

Anderson, J. R. (1982). Acquisition of cognitive skill. Psychological Review, 89, 369-406.

Ashcraft, M. H. (1982). The development of mental arithmetic: A chronometric approach. Developmental Review, 2, 213-236.

Bennett, G. K., Seashore, H. G., & Wesman, A. G. (1974). Manual for the Differential Aptitude Test (5th ed.). New York: The Psychological Corporation.

Cattell, R. B. (1971). Abilities: Their structures, growth and actions. Boston: Houghton Mifflin.

Cooper, L. A. (1975). Mental transformation of random two-dimensional shapes. Cognitive Psychology, 7, 20-43.

Cooper, L. A. (1980). Spatial information processing: Strategies for research. In R. E. Snow, P-A. Federico, & W. Montague (Eds.), Aptitude, learning and instruction (Vol. 1). Hillsdale, NJ: LEA.

Cooper, L. A. (1982). Strategies for visual comparison and representation: Individual differences. In R. J. Sternberg (Ed.), Advances in the psychology of human intelligence (Vol. 1). Hillsdale, NJ: LEA.

Egan, D. E. (1979). Testing based on understanding: Implications from studies of spatial ability. Intelligence, 3, 1-15.

Ekstrom, R. B., French, J. W., & Harman, H. H. (1976). Kit of factor-referenced cognitive tests. Princeton, NJ: Educational Testing Service.

Fisk, A. D., & Schneider, W. A. (1982). Task versus component consistency in the development of automatic processes: Consistent attending versus consistent responding (Technical Report No. 8106). University of Illinois.

Gitomer, D., Pellegrino, J. W., & Bisanz, J. H. (1983). Developmental change and invariance in semantic processing. Journal of Experimental Child Psychology, 35, 56-80.

Goldman, S. R., & Pellegrino, J. W. (1984). Deductions about induction: Analyses of developmental and individual differences. In R. J. Sternberg (Ed.), Advanced in the psychology of human intelligence (Vol. 2). Hillsdale, NJ: LEA.

Groen, G. J., & Parkman, J. M. (1972). A chronometric analysis of simple addition. Psychological Review, 79, 329-343.

Hakstian, A. R., & Cattell, R. B. (1972). Comprehensive Ability Battery. Champaign, IL: Institute for Personality and Ability Testing, Inc.

Hunt, E., & Lansman, M. (1982). Individual differences in attention. In R. J. Sternberg (Ed.), Advances in the psychology of human intelligence (Vol. 1). Hillsdale, NJ: LEA.

Lesgold, A. M., & Perfetti, C. A. (1981). Interactive processes in reading. Hillsdale, NJ: LEA.

Lohman, D. F. (1979). Spatial ability: A review and reanalysis of the correlational literature (Technical Report No. 8). Aptitude Research Project, School of Education, Stanford University.

Neisser, U. (1963). Decision time without reaction time: Experiments in visual scanning. American Journal of Psychology, 76, 376-385.

Newell, A., & Rosenbloom, P. S. (1981). Mechanisms of skill acquisition and the law of practice. In J. R. Anderson (Ed.), Cognitive skills and their acquisition. Hillsdale, NJ: LEA.

Norman, D. A., & Bobrow, D. B. (1975). On data-limited and resource-limited processes. Cognitive Psychology, 7, 44-64.

Pellegrino, J. W., & Kail, R. V. (1982). Process analysis of spatial aptitude. In R. J. Sternberg (Ed.), Advances in the psychology of human intelligence (Vol. 1). Hillsdale, NJ: LEA.

Posner, M., Boies, S., Eichelman, W., & Taylor, R. (1969). Retention of visual and name codes of single letters. Journal of Experimental Psychology, 79(1, Pt. 2), 1-16.

Rips, L. J. (1984). Reasoning as a central intellective ability. In R. J. Sternberg (Ed.), Advances in the psychology of human intelligence (Vol. 2). Hillsdale, NJ: LEA.

Schneider, W. A., & Shiffrin, R. M. (1977). Controlled and automatic human information processing: I. Detection, search and attention. Psychological Review, 84, 1-16.

Sternberg, R. J. (1977). Intelligence, information processing and analogical reasoning. Hillsdale, NJ: LEA.

Thorndike, R. L., & Hagen, E. (1971). The cognitive abilities test. Boston, MA: Houghton-Mifflin Co.

Thurstone, L. L. (1938). Primary mental abilities. Psychometric Monographs, No. 1.

Thurstone, T. G. (1962). Primary mental abilities. Chicago: Science Research Associates.

Van Parreren, C. (1978). A building block model of cognitive learning. In A. M. Lesgold, J. W. Pellegrino, S. Fokkema, & R. Glaser (Eds.), Cognitive psychology and instruction. New York: Plenum.

Vernon, P. E. (1961). The structure of human abilities. London: Methuen.

Wickens, C. D. (1980). The structure of attentional resources. In R. S. Nickerson (Ed.), Attention and performance VIII. Hillsdale, NJ: LEA.

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