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INTRODUCTION

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Participants in the 1985 SFRP competed for funding under the 1985 RIP. Participants submitted cost and technical proposals to the contractor by 1 November 1985, following their participation in the 1985 SFRP.

Evaluation of these proposals was made by the contractor. Evaluation criteria consisted of:

1. Technical Excellence of the proposal
2. Continuation of the SFRP effort
3. Cost sharing by the University

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Copies of the Final Reports are presented in Volumes I through III of the 1985 Research Initiation Program Report. There were a total of 82 RIP awards made under the 1985 program.

1

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FINAL REPORT

INDIVIDUAL DIFFERENCES IN ABILITIES,

LEARNING, AND COGNITIVE PROCESSES

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INDIVIDUAL DIFFERENCES IN ABILITIES,

LEARNING, AND COGNITIVE PROCESSES

Phillip L. Ackerman

University of Minnesota

ABSTRACT

This paper represents the final report of my participation in the 1986 Air Force Office of Scientific Research -- Research Initiation Program, which followed the 1985 Summer Faculty Research Program in the Test and Training Branch of the Air Force Human Resources Laboratory (AFHRL) located at Brooks AFB. This research program has a combined focus of a) the determination of the basic causes and manifestations of individual differences in learning during skill acquisition and knowledge acquisition task practice; and b) refinement of a theoretical/empirical approach to interrelating cognitive abilities with individual differences in learning -- that provides a foundation for improved predictors of present and future performance in learning and training environments. The approach to these issues involves an integration of information processing theories of learning, practice, and skill acquisition with intellectual/cognitive ability constructs.

During the 1985 summer research period several experiments were completed that converge on the derivation of information about individual differences in learning and the relations between cognitive/intellectual abilities and learning. During the efforts continuing over the 1985-1986 research initiation period, data reduction, analyses, and theory modifications were performed, as specified in the research proposal. What follows is a description of the results of these labors.

Specifically, a theory is presented that links normative models of skill acquisition with ability determinants of individual differences in performance. Three major patterns of individual differences during skill acquisition are considered: the simplex pattern of intertrial intercorrelations, changing ability/performance correlations with practice, and changes in between-subject variability. In addition to a review of previous data, six experimental manipulations are used to evaluate the cognitive ability demands associated with different levels of information processing complexity, novelty/transfer of training, and consistency. Examinations of practice-related between-subject variance changes and ability/performance correlations are used to demonstrate that an equivalence exists between the three phases of normative skill acquisition and three cognitive/intellectual determinants of individual differences in performance.

INTRODUCTION

It is perhaps traditional for theories of individual differences to lag behind experimental (normative) psychology in understanding the underlying bases for behavior (Underwood, 1975). Evaluation of the domain of individual differences in skill acquisition, in particular, yields further supporting evidence for this tradition.

During the last decade or so there has been a great deal of movement in the differential psychology domain towards incorporating ability theory with normative, information processing theory (e.g., Carroll, 1980; Hunt, Frost, & Lunneborg, 1973; Hunt, Lunneborg, & Lewis, 1975; Sternberg, 1977). Although much evidence has been collected that links specific information processing task requirements with relatively static human cognitive abilities, the majority of these investigations have given little attention to the dynamic domain of skill acquisition, in spite of (or perhaps because of) the fact that this area has proved to be one of the most intractable sources of data in ability theory (e.g., see Fleishman, 1960, 1972; Cronbach & Snow, 1977; Corballis, 1965; Humphreys, 1960; Woodrow, 1946). In fact, for many differential psychologists, practice is still essentially a nuisance variable (for example, see Jensen & Munro, 1979; Jensen, 1982).

On the other hand, substantial advances have been made in the prediction and understanding of information processing aspects of normative skill acquisition, most specifically during the period from the 1960's to date (e.g., Fitts, 1964; Fitts & Posner, 1967; Neisser, 1974; Neisser, Novick, & Lazar, 1963; Posner & Snyder, 1975; Schneider & Shiffrin; 1977; Shiffrin & Schneider, 1977; Anderson, 1982, 1983). Among other findings, normative investigations have forcefully documented that the *type* of information processing that during early skill acquisition trials differs qualitatively and quantitatively from the type of information processing that takes place after task practice (Anderson, 1982, 1983; Fitts, 1964; Newell & Rosenbloom, 1981; Schneider & Shiffrin, 1977).

Such findings appear to put some static information-processing based theories of cognitive/intellectual abilities directly at risk, as a result of these dynamic changes in information processing over practice. Further, a comprehensive understanding of ability/skill relations is crucial to breaking the limitations in applied psychology predictions of training success and job competence that have stood for many years (see Brown & Ghiselli, 1952; Schmidt, Hunter, & Pearlman, 1981). That is, in order to predict individual differences in skilled performance, it is necessary to be able to directly predict ability/performance relations across various levels of practice and training.

The purpose of this paper is to provide a theoretical and empirical framework that links the information processing bases for skill development with cognitive/intellectual ability determinants of performance. The theory describes the interplay of particular abilities and crucial information processing variables during skill acquisition. Further, the theory provides a basis for predicting performance individual differences at various levels of practice and training. Finally, this dynamic framework is used to re-examine several major issues pertaining to establishing ability theory in terms of information processing constructs.

STRUCTURE OF SKILL ACQUISITION

A review of the normative skill acquisition literature lies beyond the scope of this paper (though see Fitts & Posner, 1967; Adams, in press; Anderson, 1982, 1983; Schneider & Shiffrin, 1977). However, from the groundbreaking studies of Bryan & Harter (1899), and the theories of William James (1890) and others, commonality has been established for the fundamental characteristics of skill acquisition. Converging delineations have been offered from several perspectives over the last few decades. For example, Fitts (Fitts & Posner, 1967) suggested that, from a cognitive information processing perspective, normative skill acquisition can be segmented into three phases: "Cognitive" (Phase 1), followed by "Associative" (Phase 2), finally, "Autonomous" (Phase 3). These three phases have been alternatively represented by more recent production system models of learning, for example, by Anderson (1982, 1983) as (1) Declarative Stage, (2) Knowledge Compilation, and (3) Procedural Stage. Similarly, these skill acquisition phases have been also identified from a more empirical framework, for example, by Shiffrin & Schneider (1977; Schneider & Shiffrin, 1977; Schneider, 1985), as (1) Controlled Processing, (2) Mixed Controlled and Automatic Processing, and (3) Automatic Processing.

Across these three models the underlying processes at each skill acquisition Phase are qualitatively identical (and, by and large, quantitatively identical - for the Anderson and Schneider & Shiffrin approaches; see Anderson, 1982, 1983). Initial confrontation with a skill-acquisition task (assuming that the task and its information processing requirements are relatively novel) involves a strong demand on the cognitive/attentional system. During this phase, performance is slow and error-prone, while strategies (productions) are formulated and tested. Furthermore, subjects performing at this level of skill acquisition devote most (if not all) of their attention to understanding and performing the task in question. (That is, when confronted with additional information processing requirements, as with the inclusion of a secondary task, subjects are unable to adequately devote attention to the secondary task and to the learning of the criterion task simultaneously; e.g., see Nissen & Bullemer, in press.)

With consistent practice, though (as described by Schneider & Shiffrin, 1977), performance speed and accuracy increase markedly and attentional demands are reduced (Fisk & Schneider, 1983). At the level of production systems, the productions needed to accurately perform the task are fully formulated after consistent practice. During this second stage (Phase 2) of skill acquisition, the stimulus-response connections of the skill are refined and strengthened. Throughout this phase, demands on the cognitive/attentional apparatus are reduced. Under dual-task conditions, criterion performance may not improve to the same degree as under a single task condition, the criterion skill is less susceptible to interference from other (albeit different) attentional demands (Yeh & Schneider, 1985).

Ultimately, there is the final stage of performance, which is best characterized as "autonomous" or "automatic" (Phase 3). After a substantial amount of consistent practice, skilled performance becomes fast, accurate, and the task can often be performed with minimal cost while attention is also being devoted to other tasks (e.g., Schneider & Fisk, 1982a). Although improvements in performance during practice are still found at this final level of skill acquisition, practice functions at this stage are well described in terms of diminishing returns, in keeping with the Power Law of Practice (Newell & Rosenbloom, 1981).

MAJOR DETERMINANTS OF SKILL ACQUISITION

<u>Novelty/Transfer</u>

There appear to be three major classes of variables that moderate the general course of skill acquisition. The first variable is one of <u>transfer of training</u> (or task <u>novelty</u>). As Ferguson (1956) and others have pointed out, except for the limited case of the neonate, *all* tasks which a learner confronts have some element of transfer-of-training. Other than ability (cognitive and non-cognitive) and motivational differences between learners, the variance in initial task performance found in normative studies of skill acquisition can be thought of as attributable to differential levels of transfer-of-training. In some cases, such transfer is crucial to successful performance (such as having working knowledge of the language in which experimental instructions are given); in other cases transfer can impair initial performance (e.g., as is found studies which utilize reversal paradigms). Various theories of transfer abound (e.g., Cormier, 1984; Osgood, 1953; Woodworth, 1938), though none have found unqualified success. From the normative skill acquisition literature, though, two aspects of transfer are apparent. The first, <u>narrow</u> sense of transfer concerns task/knowledge experiences that are directly controlled within the overall experimental paradigm (such as transfer conditions using pre-training manipulations). From this perspective, transfer generally is present when any pre-treatment results in some task performance differences - as compared to an appropriate control group. Clearly, under transfer conditions, skill acquisition may be facilitated or inhibited, depending on the nature of the pre-training paradigm (e.g., Woodworth, 1938; Schneider & Shiffrin, 1977).

The <u>broad</u> sense of transfer, which includes the construct of novelty, is implicit when researchers utilize common semantic, syntactic, and physical feature categorizations which are well-learned in the subject population prior to the time the subjects enter the laboratory. Such situations as the use of high frequency category exemplars or categorizations of letters and numbers (Jonides & Gleitman) are prototypical examples. Generally, but not always (Fitts, 1964) broad transfer of knowledge and skills is used to *facilitate* the development of skilled performance, which entails more efficient initial task performance levels.

If a relatively novel (moderate broad transfer) task is considered as a standard, initial task performance with increased broad transfer (or narrow positive transfer) will move the task further along the course of skill development (e.g., from predominantly Phase 1 to Phase 2). In the limiting case, transfer from an identical pre-training task (to asymptote) will imply that initial criterion task performance will tap only Phase 3 information processing. Negative transfer, though, has the capability to decrement performance even beyond the standard, novel task levels, as well as slow the rate of skill acquisition (e.g., Schneider & Shiffrin, 1977). Under such a situation, the learner must ignore (or disassemble) previously learned production systems that directly interfere with successful criterion task performance. This phenomenon is generally believed to impose demands on cognitive/declarative/controlled information processing; that is, a shift to Phase 1.

<u>Complexity</u>

Representing the second class of variables, <u>complexity</u> is perhaps even more nebulously defined than transfer/novelty, although there is usually consensual

agreement as to operational implementation of complexity manipulations. Common complexity manipulations include altering memory load, display load (number of items), number of response choices, display duration, number of intermediate results necessary to solution, amount of S-R compatibility (outside of population stereotypes - which would be considered under the broad sense of transfer), amount of information provided to the learner, and many, many others. While each of these paradigms impose somewhat different requirements on the learner (for example, number of memory set items and number of display items appear to have differential effects on the course of skilled performance - Flach, 1986), there is more than minimal underlying commonality for these effects. Generally, changes in these variables impact the amount of attention demanded by the task, the accuracy with which the learner can perform the task, and/or the amount of time to complete a trial (Wood,1986). [For present purposes, manipulations which affect the asymptotic accuracy level of performance are not easily tractable (Wickelgren, 1977). For example, when some learners cannot perform the task at all (such as with extremely short display durations), given even very long reaction times, it is often necessary to explicitly examine out Speed-Accuracy Tradeoff functions. However, more will be said about this below.]

From the perspective of the three models of normative skill acquisition, increases in task complexity will result in longer RT's at initial performance levels. In most cases such as with S-R Compatibility (Brainard, Irby, Fitts, & Alluisi, 1962), increased complexity will also bring about a slower rate of skill acquisition. In a few other cases, for example when standard task version does not demand all of the attentional apparatus, increased complexity may actually enhance the speed of skill acquisition (as in the case of dual-task situations; see Gopher & North, 1977). Considered independent of other influences, increases in task complexity are believed to raise the demands on Phase 1 processes. Decreases in complexity, on the other hand, may lessen Phase 1 demands to a trivial level -- thus propelling the learner almost immediately into Phase 2 skill acquisition.

Consistency

Finally, as the cornerstone of the Controlled/Automatic Processing theory of skill acquisition, task consistency has been found to have a strong moderating influence on skill acquisition during practice (Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977; Fisk & Schneider, 1983). As such, this construct must be included in any integrated framework for individual differences in skill acquisition. Consistency, all other things being equal, does not have direct impact on the initial demands of the criterion task. That is, learners confronting both predominantly consistent and predominantly inconsistent tasks begin at Phase 1 (controlled processing). With practice, though, consistent tasks allow for skill acquisition, while inconsistent tasks generally do not. Rather, inconsistent tasks remain cognitively involving (Phase 1) over long periods of practice.

Task vs. Component Consistency. For present purposes, it is important to distinguish between the level of consistency for a total task (which is some ratio, based the relative frequency of consistent and inconsistent task components) and the consistency of a single task component (which can be represented as the ratio of consistent to inconsistent instances of particular stimulus-response patterns). For simplicity, these two types of consistency are termed 'between-component' and 'within-component.' Fisk and Schneider (1984; Schneider & Fisk 1982b) have noted that, for

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moderate degrees of inconsistent information processing requirements, the nature of skill acquisition is dependent on whether inconsistency occurs between-components or within-components.

When inconsistency occurs between-components (i.e., some components are consistent, others are inconsistent), and, presumably when these task components are separable (a la Garner, 1974; see Kramer, 1984), the consistent components can be performed automatically after practice, while the inconsistent components remain controlled-processing-intensive. (The Fisk & Schneider [1984] paradigm contrasted the consistency of attending [stimulus components] with the consistency of responding [response components].) Under such circumstances, skilled performance is limited by the controlled-processing intensive components.

On the other hand, when the degree of consistency is altered within a single component (as with the manipulations of the frequency that otherwise consistent target stimuli are inserted as distractor items -- see Schneider & Fisk, 1982b), the development of automaticity is affected, *for that component*. When compared against skill acquisition of a completely consistent component, each instance of target-distractor reversal pushes the skill-acquisition sequence further back (towards Phase 1). As the proportion of inconsistent trials increases, the component (as a whole) becomes more and more controlled-processing intensive, a quite different result from the situation regarding between-component consistency effects. However, more will be said about this below.

This description of major influences on skill acquisition is surely an oversimplification of the normative literature. However, the strong commonality that can be found among these influences in investigations of skill acquisition allows for generalization at a level conducive to a first step in integrating normative and individual differences perspectives of skill acquisition. The effort here is to identify the most important general effects, rather than a detailed evaluation of all potential moderators of skill development and maintenance.

INDIVIDUAL DIFFERENCES DURING SKILL ACQUISITION

Previous theory and data have indicated three basic phenomena of individual differences in task performance during practice: (1) the simplex structure, (2) changing ability/performance intercorrelations, and (3) changes in between-subjects variability. These phenomena will be discussed in turn below.

Simplex

First, a fundamental and ubiquitous finding in the study of inter-individual differences over task practice is the simplex (or superdiagonal) pattern of intertrial intercorrelations (Humphreys, 1960). The characteristic quasi-simplex pattern of correlations is for the largest values to occur in the diagonal entries (i.e., adjacent task trials), and declining correlations as the trials become more distant from one another (i.e., the lowest value will correspond to the correlation between the first and last trial). Generally, these correlations are found to decline in a smooth fashion. An example quasi-simplex intercorrelation matrix (over skill acquisition trials) is presented in **Table 1**.

Table 1. Example of Quasi-Simplex Within-Task Correlation Matrix*

					SESSION OF PRACTICE						
SESSION	1	2	3	4	5	6	7	8	9	10	11
2	.77										
3	.66	.82									
4	.52	.65	.74								
5	.44	.55	.68	.67							
6	.35	.41	.54	.57	.81						
7	.36	.43	.54	.67	.77	.77					
8	.25	.29	.38	.54	.64	.68	.79				
9	.28	.31	.38	.53	.61	.66	.78	.78			
10	.26	.32	.41	.51	.63	.70	.78	.71	.78		
11	.26	.35	.39	.41	.53	.57	.64	.56	.66	.77	
12	.22	.28	.38	.46	.50	.55	.53	.51	.59	.64	.72

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* Practice data for Category Search task (Consistent Mapping, Memory Set Size 2 items).   See
text for full description of task.

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            Insert Table 1 about here
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The clear inference from this pattern of intercorrelations is that individuals continuously change their rank order on performance over practice. These changes indicate that the underlying determinants of performance cannot be identical from one trial to the next. So far, hypotheses about the specific causes of these changes have not successfully identified the ability determinants of performance. Much theoretical discussion has been accorded to this topic (e.g., Corballis, 1965; Jones, 1962, 1970; Alvares & Hulin, 1972). Jones (1962) initially hypothesized that practice is a process of "simplification;" that is, the ability factors that determine individual differences during initial task performance reduce in influence (i.e., drop out) as skills are acquired. Later, Jones (1970) argued that a two-process model could also explain the basic simplex phenomenon. That is, "rate [of improvement]" and "terminal [final asymptotic performance]" factors may underlie the data.

Corballis (1965) has pointed out, though, that the simplex can be equally-well resolved mathematically by an infinite number of different models, including a factor accretion model (new factors being added over practice), and a random walk model (changes in individual performance occurring randomly with practice). Given this non-uniqueness problem, it is evident that analysis of only trial-by-trial intercorrelations does not yield a sufficient method for determining the causes of changes in individual differences during skill acquisition. Thus, external referents must be used in order to determine the causes of the simplex pattern of trial intercorrelations.

On the other hand, analysis of the patterns of trial-by-trial intercorrelations has been used (if not extensively) in identification of two particular skill acquisition characteristics. As has been discussed elsewhere (Ackerman, in press; Jones, 1970b; Reynolds, 1952a, 1952b), these two characteristics relate to the rate of correlation attenuation (that is, the rate of decline between initial [or early] task performance and each additional set of trials), and the rate of change in adjacent correlations with practice (i.e., changes in stability of individual differences in performance). Both of these characteristics provide crude measures of the amount of change in the underlying determinants of task performance. By manipulating the information processing requirements of tasks, comparisons might identify task characteristics that produce (a) greater or lesser changes in ability requirements from initial to final performance, or (b) increases or decreases in the stability of performance determinants over task practice.

A few extreme examples (where the use of false performance feedback was used) have indicated that such parameters of intertrial correlations can be altered (Jones, 1970). However, as a result of dynamic changes in the array of other determinants of task performance (such as fatigue and motivation), the present thesis is that such measures are otherwise less sensitive to changes in task information processing demands, as compared to ability/performance correlations.

Ability/Performance Correlations

Briefly, there are few studies that have examined the association between performance levels during task practice and reference cognitive abilities. The older

psychometric literature has been recently reviewed elsewhere (Ackerman, in press). The substantive findings from this literature have been that (a) ability/performance correlations change as skills are acquired, and (b) particular ability/skill relations change differently, depending on the task -- that is, some abilities increase in association with performance individual differences over task practice, some decrease, and some remain essentially constant (Fleishman, 1972). For a sample of simple, consistent tasks, two general findings by Fleishman, et al. have been substantiated. These are, that (1) intellectual abilities appear to correlate substantially with initial task performance, but attenuate as skills are acquired; (2) some perceptual/motor abilities show small correlations with performance at early trials, but increase in association during practice.

A more recent investigation (Ackerman, 1984; 1986) has demonstrated that information processing consistency moderates the relations between particular abilities and performance during skill acquisition. That is, when tasks differ in consistency, General ability/performance correlations are higher for the tasks with fewer consistent elements. While Ackerman's (1984) framework of ability/skill relations does predict these differences (for the General ability, and for broad content abilities), as noted elsewhere, that model does not yield veridical predictions for Perceptual Speed associations. Some of the specific results and data will be discussed below, in the context of the new theory.

Between-Subject Variability

In addition to the changes in average RT (from normative studies), trial intercorrelations (simplex), and ability/performance correlational changes, between-subject variability measures also show change during skill acquisition. Two prominent effects from the individual differences/skill acquisition data have been described. First, declines in performance variability with practice occur, and second, moderation of variability (and changes in variability) as a function of consistency of information processing are found as well. Under standard conditions (i.e., generally consistent information-processing requirements), substantial reductions in between-subject variability measures are nearly universally found. In a review of 24 short skill acquisition experiments (practice ranging from 9-200 minutes total time-on-task), Ackerman (in press) found that between-subjects final *sd*'s were reduced an average of 34% from initial levels. That is, subjects become more alike in performance as skills are developed. In contrast, when tasks contain predominantly inconsistent information processing requirements (i.e., controlled processing intensive), the lack of skill acquisition (normatively determined by mean performance levels and attention demands) is also associated with *stable* between-subject *sd*'s throughout task practice. That is, when learners cannot make the transition to skill acquisition Phase 2, the magnitude of individual differences in performance does not decline, even though performance (RT) does improve with practice.

NORMATIVE AND DIFFERENTIAL APPROACHES: MAPPINGS

Explicit mappings between normative and individual differences phenomena may be drawn. Specifically:

1.   The normative description of skill acquisition is that it is generally a continuous process during task practice, without breaks as processing transitions from Phase

1 through Phase 3. (Marked individual differences exist at all levels of skill acquisition.) The individual differences description of skill acquisition (from trial intercorrelations) indicates that rank orderings of subjects change, also in a continuous process, without breaks during task practice.

2. During skill acquisition, load on cognitive processes declines from novice attention-demanding processing, to skilled attention-insensitive processing. Initial ability/performance associations are higher for heavily cognitive abilities. After consistent practice, these abilities show attenuated correlations.

3. The presence of inconsistent information processing task demands slows, or precludes, the development of Phase 2 and Phase 3 skill levels, that is, the task remains attention-dependent. Similarly, the presence of inconsistent information processing demands appears to maintain the cognitive ability/performance association over task practice.

4. Other variables, namely novelty and complexity manipulations also appear to moderate intellectual ability/performance relations in the same direction as found in normative task analysis (Ackerman, 1986). That is, increases in novelty and complexity (as measured by attention demands and speed of responding) are associated with increases in association between performance and cognitive abilities.

From an evaluation of the range and types of processes underlying the three normative Phases of skill acquisition, and the individual differences data described above, a mapping of ability factors to skill acquisition Phases is possible. Three major ability factors may be parsimoniously mapped to the three Phases of skill acquisition. Respectively, these factors are General Intelligence (or General Ability), Perceptual Speed, and Psychomotor Ability. Descriptions and definitions of these abilities are provided below.

ABILITIES UNDERLYING SKILL ACQUISITION.

Defining cognitive/intellectual abilities is a task no less difficult than defining such normative concepts as short-term memory or attention. Theoretical (stipulative) and operational definitions of abilities abound (cf. Robinson, 1940; Miles, 1957). However, there is enough commonality among most definitions to allow for a reasonable working description of the constructs.

General Intelligence (General Ability)

A general cognitive/intellectual ability is commonly defined in two different ways. The first method is an indirect one; in this framework, this ability is implied by the variance common to the universe of all psychological ability tests (Humphreys, 1979; Burt, 1949; Vernon, 1961; etc.) Such an ability is often found to account for about 50% of the individual differences variance on large batteries of ability tests (Vernon, 1961). The inference is that the general ability represents a broad construct that underlies non-specific information processing efficacy (i.e., it excludes specific types of processing individual differences - that are mostly associated with separable abilities, such as dealing with verbal, figural, or numerical item content). For example, the reasoning processes that account for individual differences across the different content

domains would represent one component of a general intellectual ability. The fact that all such mental tests revealed positive intercorrelations provides the major justification for the construct of general intelligence (Humphreys, 1979).

The direct method of defining a general ability is to identify particular processes as central to the expression of intelligence, such as the "eduction of relations" (Spearman, 1904). Many different processes have been posited, such as "the ability to learn" (Buckingham, 1921). Other candidate definitions include "the power to think abstractly" (Terman, 1921), and "...the ability to undertake activities that are characterized by (1) difficulty, (2) complexity, (3) abstractness, (4) economy, (5) adaptiveness to a goal, (6) social value, and (7) the emergence of originals, and to maintain such activities under conditions that demand a concentration of energy and resistance to emotional forces." (Stoddard, 1943).

Finally, Humphreys (1979) has given a broad definition of intelligence that adequately summarizes the character of the construct for present purposes. He states that *"[General] intelligence is the resultant of the processes of acquiring, storing in memory, retrieving, combining, comparing, and using in new contexts information and conceptual skills...."* In this view general intelligence <u>must</u> be a determinant of individual differences in the processes that are described by Fitts, Anderson, and Schneider & Shiffrin as underlying Phase 1 of skill acquisition.

Markers for General Intelligence (that is, tests which are found to have high loadings on this factor) include such tests as Raven's Progressive Matrices, WAIS total scores, Analogies (e.g., the MAT), as well as some complex content-domain tests (Vocabulary, Arithmetic Reasoning, Spatial Relations, etc.).

Perceptual Speed Ability

Less research, discussion, and controversy have been accorded to the construct of Perceptual Speed ability than to the General ability. Two contrasting views represent the general orientation of the field. One view (Marshalek, Lohman, & Snow, 1983) identifies a single major dimension of abilities, denoted level/speed. At one end of the continuum are abilities that are associated with an individual's facility in solving items of increasing complexity (which is a move towards broad content abilities and the General ability). At the other end of the continuum are abilities that are associated with the *speed* of processing. Perceptual Speed would be found at this end of the continuum. That is, Perceptual Speed represents individual differences in the speed with which cognitive test items can be completed, when the domain only includes simple items (i.e., that can be easily answered by most or all members of the subject population).

The other view takes a more pragmatic, operational perspective. In this view, a general Perceptual Speed ability is defined by a subjective judgement based on review of tests which cluster together along some general lines. The first distinction from this perspective is that Perceptual Speed is, indeed an ability class that can be separated from the domain of Spatial Abilities (e.g., see Thurstone, 1944; Ekstrom, French, Harman, & Dermen, 1973; Lohman, 1979). These are especially important demonstrations, since the many prototypical tests designed to measure Perceptual Speed contain spatial content.

A wide range of tests have been posited to load on the Perceptual Speed ability. Marker tests include Finding a's (or X's) (Thurstone, 1944; Ekstrom, et al., 1973) which entails searching through a list of words and marking any word containing the target letter. Another test is the digit-symbol test (Wechsler, 1955), which entails a paired-associates type of information processing -- that is, memorization (or rapid reference to a list) of a set of digit-symbol pairs and transcribing symbols on a list of digit probes. Other tests include comparisons of identical items (i.e., a proofreading task) of numbers, verbal, or figural content, with a requirement to indicate mis-matches. Many of these tests appear to involve the generation of very simple production systems that must used to effectively solve the test items. In the language of normative skill acquisition, individual differences found on such tests are directly attributable to the speed with which these productions can be implemented and proceduralized/compiled.

A definition that is perhaps most illustrative of this view (as well as provides independent justification for the current theoretical intentions) has been provided by Werdelin & Stjernberg (1969). They state that:

> "The perceptual speed factor is a measure of the capacity to automatize, by means of practice, the solution of perceptual problems, which have originally depended on the visual-perceptual factors (p.192)."

Psychomotor Ability

As with the preceding abilities, the Psychomotor domain represents an amalgamation of a family of related -- but independently identifiable sub-abilities. A general Psychomotor ability represents individual differences predominantly in the speed of responses to test items with little or no cognitive processing demands. That is, where the Perceptual Speed ability represents cognitive processing of generally simple (but still cognitively involving) items, Psychomotor ability represents processing speed (and accuracy to a certain degree), mostly independent of information processing, per se.

Prototypical measures of Psychomotor ability include Simple Reaction Time, Rotary Pursuit, Tapping Speed, Rate of Manipulation, Finger Dexterity, and so on (Fleishman, 1954). While some of these tests require minimal information processing (mostly in terms of sensory feedback), the underlying characteristic of these tests is that *the examinee knows exactly what responses need to be made, ahead of time.* Reasoning (as with the General ability), Memory, and the formation of new production systems (as with Perceptual Speed) are all minimized in these assessment techniques.

A stipulative, but nonetheless operational definition of Psychomotor ability from the current theoretical perspective is as follows: Psychomotor ability represents individual differences in the speed (and accuracy) of motor responding that are characteristic of psychophysical limitations of the human subject. That is, the underlying differentiating processes of psychomotor ability are those that reveal the efficacy of <u>asymptotically</u> compiled and tuned production systems.

REPRESENTATION OF ABILITIES

Up to this point, the theoretical discussion has considered each of the three

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abilities as independent factors. What this orientation gains in parsimony comes at a cost of integration. What follows is a more integrated approach to placing these abilities in the context of the general structure of cognitive abilities.

Many representations of cognitive/intellectual abilities which allow for linkage with types of information processing have been offered in the literature. Some are essentially piecemeal mappings of abilities with information processing paradigms (Carroll, 1980), while others are general, all encompassing theories of abilities and information processing (e.g., Sternberg, 1985). In order to allow for an empirically-based mapping of abilities to information processing skills, an intermediate approach is required.

Modern ability theories are often categorized as hierarchical in nature, with the General Ability defining the highest level node in the hierarchy. Major group factors (such as Verbal, Spatial, Number, etc.) are located at lower nodes in the hierarchy, and specific abilities at still lower nodes (Vernon, 1961). For present purposes, a functionally equivalent (and possibly more parsimonious) representation of the major components of intellectual abilities is the circumplex (Guttman, 1954; Marshalek, Lohman, & Snow, 1983; Snow, Kyllonen, & Marshalek, 1984).

A useful spatial representation of the structure of intelligence, from this framework is illustrated in **Figure 1** (from Marshalek, et al., 1983). Here, general intelligence is represented as the centroid, with different major content abilities as slices of the ability pie. That is, <u>complexity</u> of processing is reflected in the distance from the center of the circle, the most complex task/item requirements located close to "g." As one moves to the periphery, less complex task/items are located. In actuality, for most purposes, this two-dimensional representation is only a useful approximation to the relations between the major components of intelligence.

Insert Figure 1 about here

In the Marshalek et al. model of abilities, tests that tap speeded abilities appear in the periphery of the relevant content slices. In fact, in the model proposed by these authors, a broad Perceptual Speed ability is not represented as a single ability at all, but rather represents a family of abilities specific to particular content domains, such as a speed of lexical access, a speed of figural comparison, and so on (though, see Snow, Kyllonen, & Marshalek, 1983 for some alternative solutions). For this to be a valid representation, a random sample of tests assessing Perceptual Speed will demonstrate little common variance. However, a number of studies in this field indicate that greater common variance is found than would be expected from this perspective (see, for example, Thurstone, 1944; Roff, 1952; Fleishman, 1954; Ekstrom et al., 1973).

The problem of representation can be rectified by explicitly segregating the complexity/specificity dimension from one of level/speed. From this perspective, the three ability classes of interest can be incorporated into a single spatial model. Here, a third dimension is added to allow for representation of both Perceptual Speed and Psychomotor abilities. Using the basic two-dimensional surface at the extreme on the power (level)-speed dimension (i.e., a zero value for speededness of information

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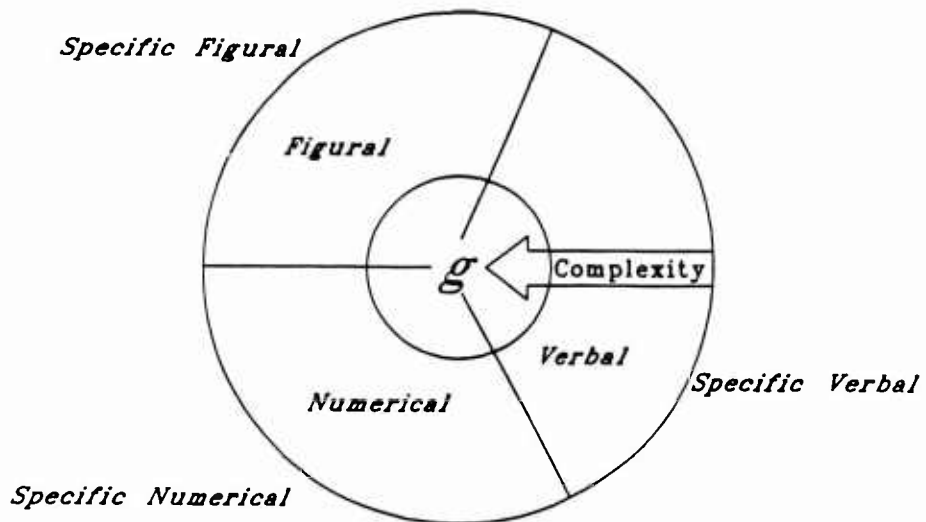
From Marshalek, Lohman, & Snow (1983)

Figure 1.   A radex-based model of cognitive/intellectual abilities (from Marshalek, Lohman, & Snow (1983). The construct of Complexity/Specificity is represented as the proximity to the center of the circle. Content abilities are represented as different slices of the circle. In the Marshalek, et al. model, Perceptual Speed is represented as content domain specific. See text for discussion.

processing demands), and an arbitrary positive value representing the extreme in speededness (with the absence of cognitive processing -- i.e., non-cognitive motor speed), the structure of human abilities can be represented as a cone, as idealized in **Figure 2**. Theoretically, as one moves down the cone, concentric sections represent the basic cognitive ability groups, with increasing demands on speededness.

Insert Figure 2 about here

THEORY PRINCIPLES

1. Skill Acquisition Phase 1 -- <u>Cognitive</u> corresponds to demands on General (and Content Abilities).

With a mapping of General ability with Phase 1, the theoretical representation of the associations of ability and performance is given in **Figure 3, Panel A**. The standard task for this representation is of moderate complexity and novelty, and is relatively high in consistency (a typical skill acquisition task). Initial performance individual differences will be moderately associated with the Gen al ability. With practice (as Phase 1 transitions into Phase 2), the ability/performance association will attenuate, reaching an asymptote late in practice (which will be dependent on the actual level of inconsistency of the task - see below).

Insert Figure 3A-C about here

For novel tasks, initial performance individual differences (i.e., in the absence of pre-treatment practice) will be determined to some degree by general cognitive abilities, as well as by task-appropriate broad content abilities (e.g., verbal abilities for tasks that demands processing of semantic material; spatial abilities for tasks that demand figural processing, etc.). The overall magnitude of association of these abilities with performance will primarily depend on task complexity and novelty (see below), but also on the adequacy of instructions, and, of course, on the subject population under study. With practice, once production systems are formulated to accomplish the <u>consistent</u> components of the task, the influence of general/content abilities will diminish.

2. Skill Acquisition Phase 2 -- <u>Associative</u> corresponds to demands on Perceptual Speed Abilities.

If Perceptual Speed is equated with compilation and tuning of production systems, there will be an **inverted U-shaped** function which describes ability/performance relations over practice (see **Figure 3, Panel B**). Early in practice, the productions are still being formulated and tested, thus compilation and tuning are only involved to the degree that previously learned productions can be readily adapted for successful performance of the current task. Therefore, there is an initially increasing association between Perceptual Speed ability and performance, once the productions are formulated. That is, in Phase 2, the facility and speed of compilation of production systems that determine performance efficiency are the essence of Perceptual Speed ability.

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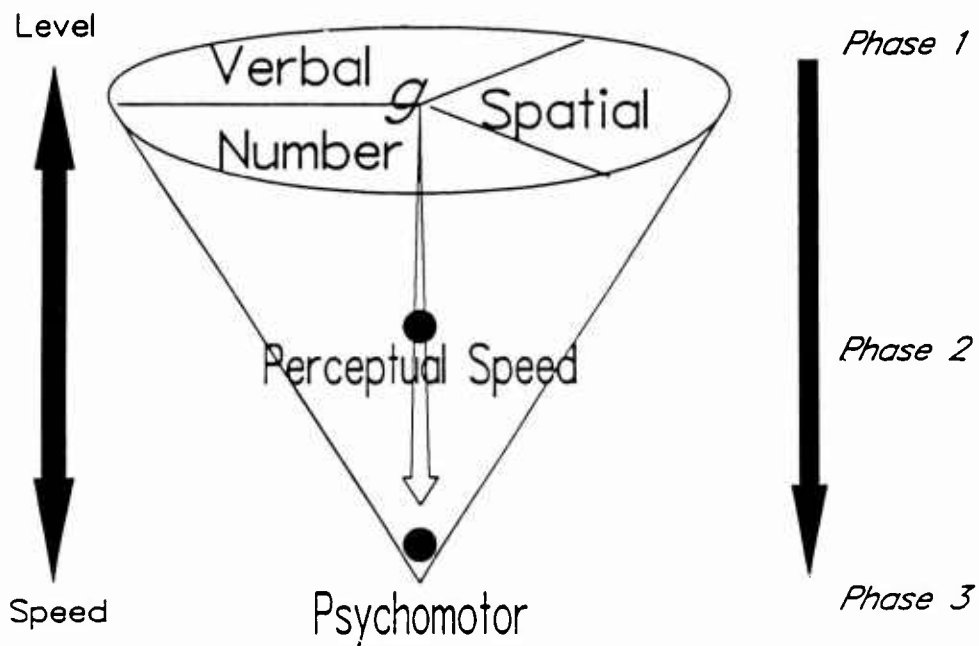
Figure 2.   A modified radex-based model of cognitive abilities. Complexity is
            represented as in the Marshalek, et al. model. However, the dimension of
            Level/Speed is added to account for Perceptual Speed and Psychomotor
            Abilities.

Figure
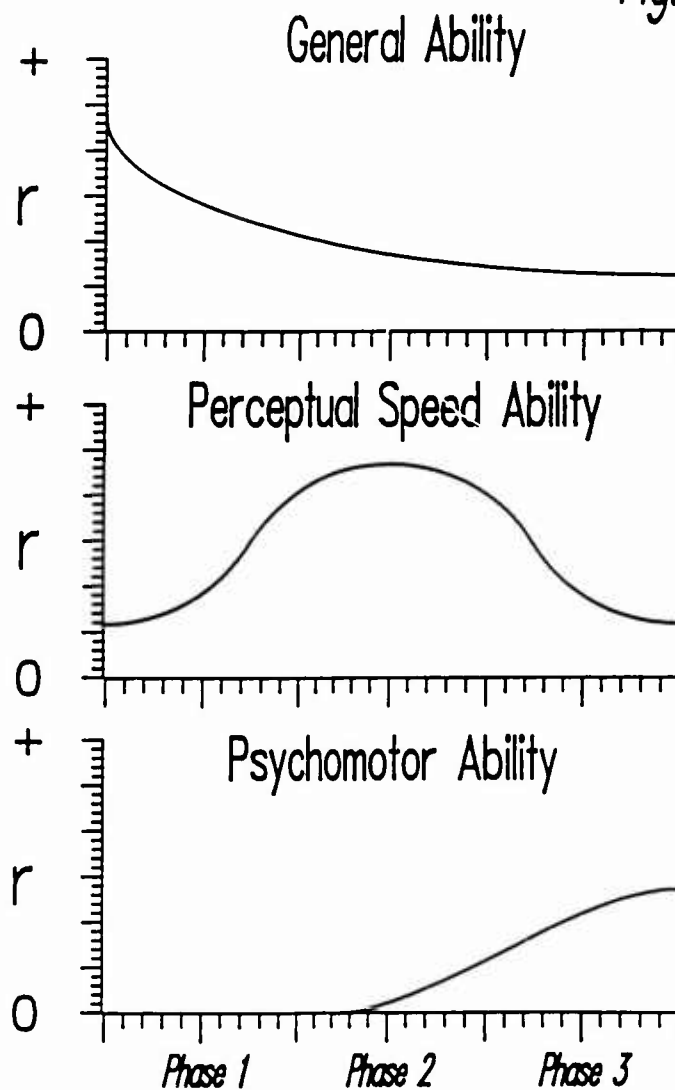
Figure 3. Hypothetical ability/skill relations derived from the theory. The hypothetical task is moderately complex, involves a moderate amount of broad transfer, and requires predominantly consistent information processing.

However, as learners reach their psychophysical limitations of skilled performance, the influence of this variable will attenuate (i.e., as Phase 2 transitions to Phase 3). Finally, as Phase 3 and asymptotic performance levels are reached, Perceptual Speed will further decline to some asymptotic level (as determined by the consistency parameters of the task -- see below).

3.   *Skill Acquisition Phase 3 -- Autonomous corresponds to predominantly non-cognitive Psychomotor Abilities.*

For tasks which allow successful performance across a wide range of ability, ultimate task performance individual differences will be more dependent on non-cognitive motor abilities than cognitive abilities. That is, as cognitive abilities no longer serve to limit performance, individuals converge on performance asymptotes that are finally determined by (non-cognitive) psychomotor speed differences (e.g., as in cigar-rolling, see Crossman, 1959; or choice RT tasks, Newell & Rosenbloom, 1981) Even so, the actual performance differences between the fastest and slowest learners at this level of skill development are vastly reduced. That is, *sd*'s of performance are reduced with consistent practice.

Therefore, as Phase 2 gives way to Phase 3, psychomotor speed variables will increase in association with performance, ultimately stabilizing to a moderate degree of correlation. It follows, then, that the theoretical predictions of Psychomotor Speed/Performance relations are as illustrated in **Figure 3, Panel C**. During Phase 1 and 2 of skill acquisition, Psychomotor Speed has an inconsequential influence on performance. However, as Phase 2 transitions to Phase 3, whatever information processing productions there are, have been formulated, compiled, and tuned at that point. Asymptotic performance, when little or no new information must be processed from trial-to-trial, will be associated with individual differences in Psychomotor Ability. Thus, as Phase 3 is reached, Psychomotor Speed/Performance associations will increase to some moderate level, and then asymptote.

A DYNAMIC REPRESENTATION OF ABILITIES AND SKILLS

From this viewpoint, this theory of ability/skill relations predicts that novel tasks are located towards the top of the cone (in Figure 2), performance on the task will have high correlations with Content and General abilities, relatively low correlations with perceptual abilities, and thus, negligible correlations with Psychomotor speed. As automaticity develops, the task moves downward through the ability structure. At intermediate levels of practice, association with Content and General abilities declines, association with Perceptual/Psychomotor Speed Abilities increases. When the appropriate production systems are compiled and tuned, the task moves further away from the cognitive ability domain. Ultimately, even associations with Perceptual Speed decline, as individual differences in asymptotic performance are determined by Psychomotor speed abilities. At this point, the task can be located towards the bottom of the cone.

Novelty/Transfer of Training

Decreasing novelty (or similarly increasing access to broad transfer-of-training) essentially allows learners to begin the initial task at a point further along the skill acquisition phase continuum. Under such circumstances, learners may have little in the

way of Phase 1 cognitive requirements, thus processing at Phase 2 performance levels (or even at Phase 3 if an identical task has been pre-trained). It follows from the ability/performance theory then, when transfer is high, there will be little or no early increase of association with Perceptual Speed Abilities. Rather, early performance individual differences on such tasks will be highly associated with Perceptual Speed (and thus, less associated with general ability, all other things being equal). However, the ramp-down in perceptual speed ability/performance association will still occur, as any necessary compilation/tuning aspects of skill acquisition are completed. Thus, increases in transfer-of-training can be depicted by a shift along the practice continuum (the abscissa in Figure 3). That is, starting position on the ability/performance curves will change, although asymptotic levels of association will not.

Increasing novelty (beyond the standard) will move the time line back in a complementary fashion. Extrapolating the ability/performance curves further back in time reveals that the general ability will have a stronger influence on performance individual differences. However, since Perceptual Speed and Psychomotor abilities are at asymptotically low levels at the beginning of practice (for the standard task), these levels will not change (only the actual ramp-up will be delayed in the total course of practice).

While the novelty and broad transfer result in changes of the skill acquisition time-course only, narrow, *negative* transfer-of-training will alter the form of ability/performance relations. Normative data (reversals - Schneider & Shiffrin; S-R incompatibility - Fitts, et al.) indicate that skill acquisition is much slower, and more attention-demanding under negative transfer conditions. As such, in keeping with the theory principles, negative transfer will be associated with much greater initial correlations between performance and the General ability. Further, the changes in correlations with practice will follow a much slower rate-of-attenuation than for the standard task.

Complexity

As with increasing novelty, increasing task complexity places a greater load on the cognitive/attentional apparatus. As such, an increase in task complexity (e.g., by raising the number of items that must be held in memory, the number of and types of processing, such as the differences between mental addition to mental multiplication - with three digit numbers) will increase the association between general ability and performance. From the production system perspective, more complex tasks will require a greater number of productions (or more complex productions) for successful skilled performance. As a result, initial, Phase 1 RT's will be increased over a standard task of moderate complexity. By definition, increased task complexity will be associated with an increase in the non-redundant productions necessary for task completion. If these productions can be performed in parallel with practice, asymptotic performance levels will be identical for tasks differing in complexity (such as for memory search, see Schneider & Shiffrin). Under these conditions, the ability/performance relations of two task versions of differing complexity levels are predicted to converge with practice, provided the tasks are consistent.

When the increased production system demands cannot be performed in parallel (as with multiple, serial response requirements), RT levels will not converge with practice.

That is, given that operation of productions is time intensive, adding productions in series will result in longer performance RT's. However, for each of the component productions, the ability/performance mappings will independently hold true. So, ability/performance associations will ultimately reach the same asymptotic levels with practice (although at a slower rate, contingent on the increased Phase 1 demands). The theory therefore predicts a decoupling between mean RT asymptotic levels of performance and ability/performance associations.

Summary

Given the inverse relations between General Ability/performance and Perceptual Speed/performance associations for Phase 1 and Phase 2, task component novelty and complexity (which affect the starting phase of skill acquisition) serve to effect a tradeoff between the dependence of performance on General cognitive abilities and Perceptual Speed abilities. For example, when S-R compatibility is high, there is less cognitive demand on the learner to determine and initiate the appropriate response. Thus, for the universe of cognitive tasks, there will be a negative association between initial ability/performance loadings on general/cognitive factors and perceptual speed factors.

Consistency

The contrast to the standard skill acquisition situation occurs when the task requires a moderate or substantial degree of inconsistent information processing. Performance individual differences on tasks with substantial inconsistency remain dominated by the Phase 1, cognitive/controlled type of information processing (i.e., General ability). In the limiting case, individual differences on a task with no consistent components, will show no reduction of association with General ability over practice, since a new set of productions Phase 1 must be formulated on every trial. Such effects are illustrated in **Figure 4, Panel A.**

Insert Figure 4A-C about here

Between-Component degree of consistency

Initial performance on tasks with intermediate levels of consistency will be determined by General abilities (i.e., equivalent to other levels of consistency). After practice (normally associated with a transition to Phase 2), performance will still be determined to some degree by the General ability, because of the cognitive load associated with the inconsistent task components. As the General ability/performance association attenuates, Perceptual Speed will increase in influence. The extent of such influence will be determined by the number of consistent components present in the task (see **Figure 4, Panel B**). Similarly, the influence of the Psychomotor ability will also be limited by the degree of controlled processing load caused by the inconsistent task components. As such, although the Psychomotor ability may be related to asymptotic performance individual differences (for the consistent components), the cognitive determinants of performance are predicted to overshadow other abilities (see **Figure 4, Panel C**). That is, while Psychomotor speed may increase in the raw amount of performance variance explained, the relative contribution will ultimately be small.

1-20

Figure 4. Idealized effects of between-component consistency manipulations. Changes in between-component degree of consistency set upper limits on the number of separable components that can be automatized.

Within-Component degree of consistency

If a mostly consistent task is taken as the standard, manipulation of the frequency of inconsistent (reversal) events can be used to demonstrate a somewhat different set of effects of consistency on skill acquisition (Schneider & Fisk, 1982). In this case, a single component of the task is sometimes consistent and other times inconsistent. The predictions of consistency vs. ability/performance relations change, given that the critical task component cannot be broken down into consistent and inconsistent information processing productions. The data indicate that each increment in the number of (unpredictable) inconsistent information requirements raises the level of (Phase 1) controlled processing demands. That is, if some minimal level of consistency is allowed, skill acquisition will procee a ng the normal route. However, each instance of inconsistency will a) require cor. rolled processing (Phase 1), and b) decrement the strength of the learned associations (Phase 2). These relations are illustrated in **Figure 5, Panels A-C**. While the predictions for the General ability are the same as for between-component consistency (Panel A), predictions for the other abilities are different. Changes in degree of within-component consistency will moderate the asymptotic levels of association between Perceptual Speed and performance (Panel B), as well as <u>when</u> the transition to Phase 3 will occur (Panel C). It should thus be possible to manipulate overall task consistency to a level that allows some development of Phase 2 skilled performance (during consistent trials), but maintain Phase 1 attentional demands (for inconsistent trials, and for monitoring for the occurrence of such trials). Data will be presented below that at least partially address this issue.

Insert Figure 5A-C about here

Other Influences

There are three basic sources of individual differences in skilled performance after substantial consistent task practice. One source, motivation, will not be considered here (see Humphreys & Revelle, 1984; Kanfer, in press for discussion of these issues). The second and third influences relate to the efficacy of the initial productions formulated in Phase 1 of the skill acquisition process (a function of g/c abilities), and to the learner's ability to develop efficient and accurate compilation/tuning of the productions (perceptual/motor speed abilities), respectively. The involvement of the latter two influences (and the first, to the degree that motivation and cognitive abilities are related) guarantees that some performance individual differences will maintain more than minimal association with cognitive abilities, even at extended levels of practice. The performance differences between learners who fail to develop automaticity will remain associated with these abilities. Furthermore, the asymptotic ability/performance correlations will be dependent on task complexity; specifically when increased levels of complexity effectively preclude development of adequate production systems crucial for successful task performance (see Ackerman, 1984).

EMPIRICAL VALIDATION OF THE THEORY

Although it was not feasible to test all of the major predictions of the theory,

General Ability

+

r

0

NEAR φ CONSISTENT
LOW
MODERATE
HIGH CONSISTENCY

Perceptual Speed Ability

+

r

0

HIGH
MODERATE
LOW
NEAR φ

Psychomotor Ability
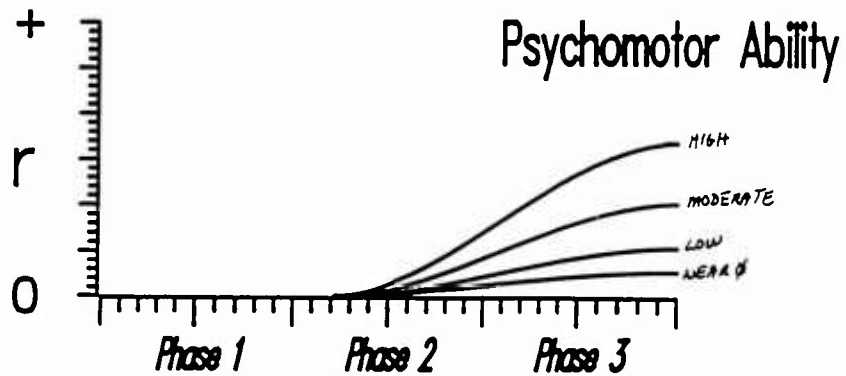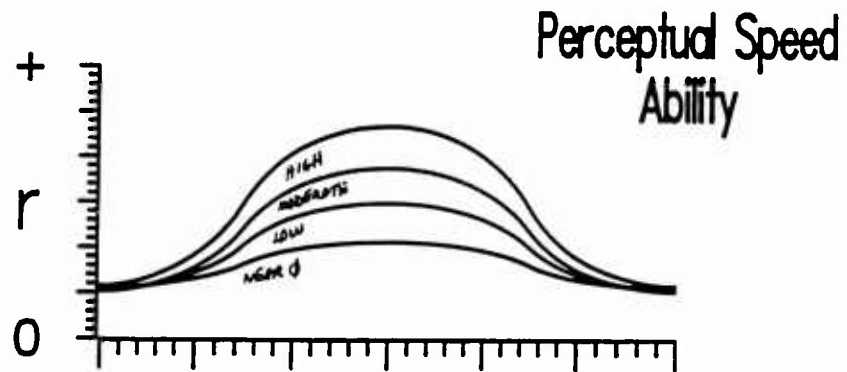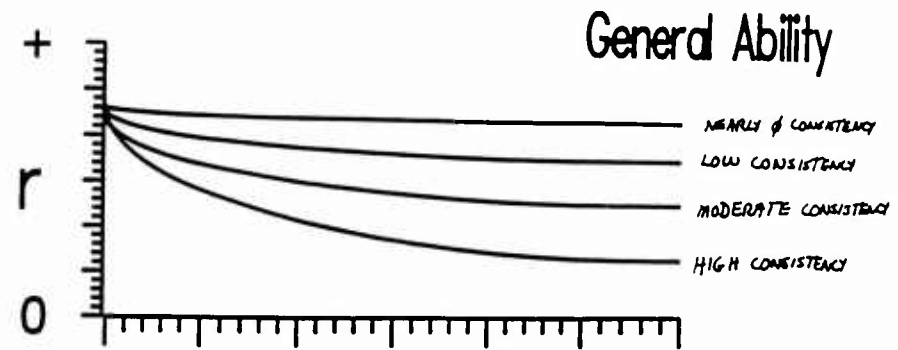
+

r

0

HIGH
MODERATE
LOW
NEAR φ

Phase 1   Phase 2   Phase 3
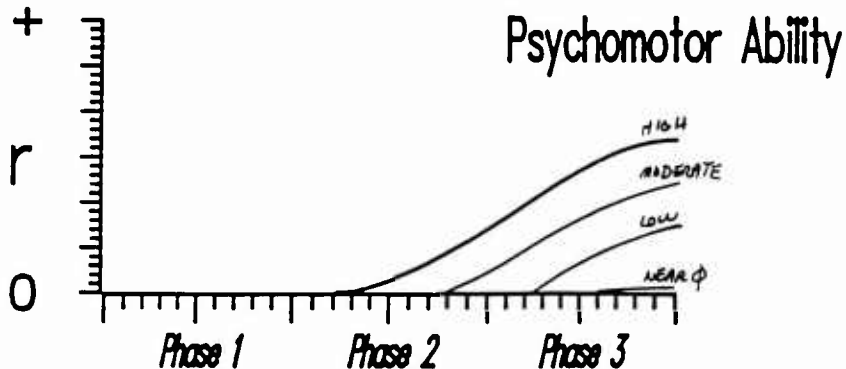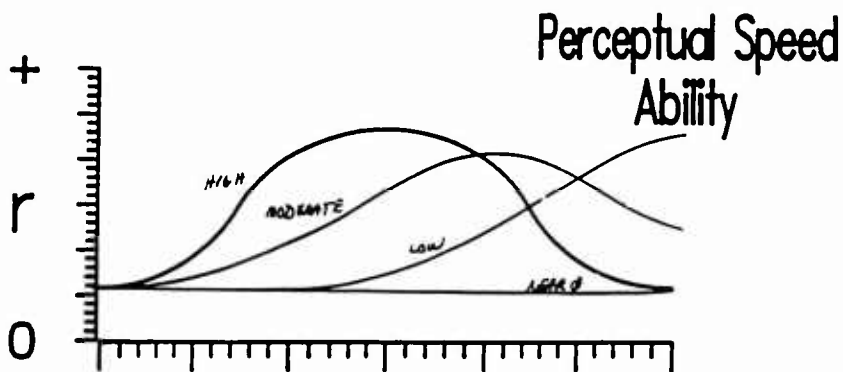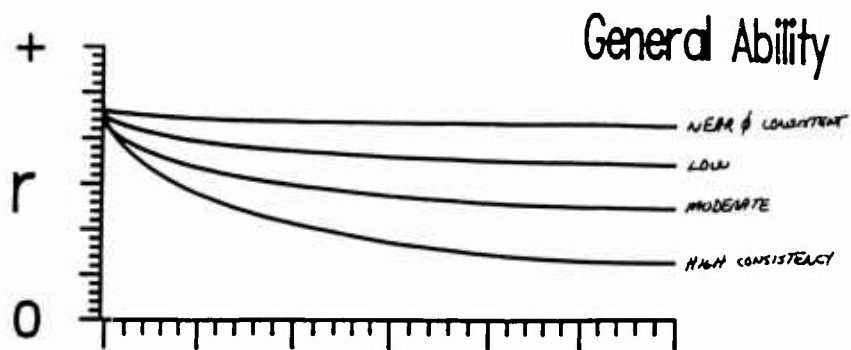
Figure 5.   Idealized effects of within-component consistency manipulations. Changes in within-component degree of consistency results in changes in level of asymptotic ability/skill associations.

data from several short skill acquisition experiments (and some data from the older literature) are presented to assess the adequacy of the theory. Given that there are common elements to most of these experiments, methods for the first five are all listed first. Next, a review of the common results is presented, followed by specific contrasts across experimental tasks.

Method: Experiments 1 through 5

Experiment #1

Subjects. A total of 338 subjects participated in this experiment. Subjects were U. S. Air Force recruits enrolled in basic training at Lackland Air Force Base. Record keeping difficulties precluded obtaining exact age and sex information for the subjects. However, most subjects were between 18 and 22 years old at the time of testing. For the subjects with complete testing records (297 of 338), 258 were males.

Apparatus. Instructions, stimulus preparation, presentation, and response collection were performed with Terak 8510A microcomputers, with standard keyboards (number keypad on the right side of the keyboard), and white on black (short persistence) cathode-ray tube (CRT) terminal. Displayed instructions were augmented with oral reading of the material (by the experimenter) over a public address system, which broadcast over individual headsets. Each subject sat at an individual microcomputer workstation, within a carrel. The carrels provided visual restriction to the subject's own display and general sound-deadening to maintain an undisturbed environment. Normal office lighting (florescent bulbs) was provided. Subjects were run in groups (ranging from 25 to 29 subjects at a time). At the conclusion of the experiment, subjects were debriefed and data were off-loaded from the Terak microcomputers to a mainframe computer for storage and reduction.

Stimuli. The taxonomic category classes and the exemplars of the categories were selected from locally developed norms on category search RT (Fisk, 1982). These norms were composed of a subset of categories and exemplars from Battig and Montague (1969). Twelve categories were selected and distributed across conditions to insure equivalence of initial RT (prior to implementation of task condition manipulations). The displays of category labels and exemplars were always in uppercase text using the standard terminal character set.

Procedure. The standard task represented a visual category search procedure (see Ackerman, 1986; Fisk & Schneider, 1983 for a detailed description of the task). To provide for the maximal amount of information processing consistency, a consistent mapping (CM) of "target" and "distractor" items was implemented (Shiffrin & Schneider, 1977; Fisk & Schneider, 1983). Two mutually exclusive sets of taxonomic categories were created for use in this experiment, a CM Target set and a CM Distractor set. Categories in the CM target set *only* appeared as memory set items; the categories in the CM distractor set never appeared as memory set items. Thus, whenever an exemplar from a CM target category appeared in a probe display, that was the "target" and was to be responded to. On the other hand, each of the exemplars of the CM distractor categories would only appear in the probe frames as "distractors," or items that were not to be responded to (i.e., ignored).

On each trial, two taxonomic category labels randomly selected from the CM

Target Set (such as "ANIMAL" and "CLOTHING") were first presented on the terminal screen for memorization. The memory set was displayed for 5 sec. Subsequently the terminal screen would clear, and three fixation dots (indicating the positions of the probe words) were displayed for 500 msec. Immediately afterward, three probe words were displayed (e.g., "HOUR," "PINE," and "LION"). The probe words remained on the screen until the subject responded, or for 5 sec if no response was entered.

Subjects were instructed to rest their right hand index, middle, and ring fingers on three horizontally aligned adjacent keys on the numeric keypad (numbers "1," "2," and "3," respectively). The subjects were told that, during the probe display, they were to press button #1 if the "target" (i.e., an exemplar from one of the memory set categories) was located in the top position of the probe display; button #2, if the target was in the middle position; or button #3 if the target appeared in the bottom position of the probe display. All trials were positive trials (i.e., a target always appeared in the probe display, and no probe displays contained more than one target word). Subjects were instructed that their goal was to maintain accuracy at the 90-95% correct range and to respond as fast as they could, holding that accuracy level. (This accuracy level was selected so as to minimize differential effects of speed-accuracy tradeoff on performance measures -- see Wickelgren, 1977 for a discussion of this issue.)

After a subject's probe response was made (or the 5 sec wait time limit was reached), the trial was scored, and the subject was provided with two forms of knowledge of results. For the first form of knowledge of results on correct responses, an asterisk appeared to spin to one side of the terminal screen, originating at the position of the target word. On an incorrect response, or if no response was made in 5 sec, the target word was displayed on the screen for 800 msec. The second form of knowledge of results contained feedback from a block-of-trials perspective as well as current trial RT performance. This display included the cumulative RT for the present trial block in msec units, cumulative accuracy level, and present trial RT in msec (for correct trials). When the trial was scored incorrect, present trial RT was replaced with an error message. This information was presented for 1 sec. (At the end of a block of trials, average RT and accuracy levels were reset to 0.) Multi-block cumulative feedback was provided after each block of trials, with a bar graph arrangement of previous RT levels and an evaluation-recommendation about slowing-down or speeding-up, based on current trial block accuracy level.)

Prior to the initial presentation of the actual critical learning trial sequence, subjects were given displayed and oral task instructions, and a set of three, narrated, practice trials. During the practice trials, which were p esented about three times slower than the regular trial pace, the experimenter ca ed attention to the requirements of the task (e.g., which memory elements were to be memorized, when the fixation dots would appear, what the target item was and what category it corresponded to). Given the mostly passive nature of these task trials, the practice performance data were not incorporated into the other task practice data.

Twenty trials were presented in each trial block. The entire learning sequence consisted of 36 trial blocks (720 trials), with 9 min. breaks given after Trial Block #9, #18, and Trial Block #24. The entire sequence, including instructions, learning trials, breaks, and debriefing, were completed within a period of three hours.

Ability Testing. Armed Services Vocational Aptitude Battery (ASVAB). Subjects were administered the ASVAB prior to induction into the Air Force under standardized testing conditions. The ASVAB contains ten ability/information tests as follows: General Science (GS), Arithmetic Reasoning (AR), Word Knowledge (WK), Paragraph Comprehension (PC), Numerical Operations (NO), Coding Speed (CS), Auto and Shop Information (AS), Mathematics Knowledge (MK), Mechanical Comprehension (MC), and Electronics Information (EI).

Experiment #2

Subjects. A total of 272 subjects participated in this experiment. For the subjects with complete testing records (231 of 272), 230 were males.

Procedure. As a contrast to the maximal consistency underlying the procedure used in Experiment 1, this experiment minimized the *within-component* information processing consistency (at the stimulus level, while allowing consistency of stimulus-response mappings). This type of procedure has been denoted Varied Mapping (VM) by Shiffrin and Schneider (1977). In this VM condition, target categories and their respective exemplars were not constrained to be targets consistently. That is, one large super-set of categories and exemplars was created for selection of target and distractor items. (The total set was equivalent in size to that of the combined target and distractor sets used in the CM condition - Experiment 1.) On each trial, a subset of the categories was randomly selected to be the memory (target) set; another subset (mutually exclusive to the memory set) was drawn to provide exemplars for probe frame distractors. At the end of each trial, all categories in the VM condition were available for sampling on subsequent trials. Thus, a given exemplar might be a target on one VM trial and appear as a distractor on the next trial (see Shiffrin & Schneider, 1977 for a more extended discussion of the CM and VM manipulations).

In all other details, Experiment #2 followed the method of Experiment #1.

Experiment #3

Subjects. A total of 242 subjects participated in this experiment. For the subjects with complete testing records (220 of 242), all were males.

Procedure. In order to provide an intermediate level of stimulus consistency, a mixed mode (CM/VM) condition was created. The difference between this condition and the baseline CM condition was that on 30% of the trials (randomly selected), the CM Target and CM Distractor sets were *reversed*. On these "reversal" trials, the subject would be presented with memory set items from the original CM Distractor set. On the probe display, the "distractor" items would be selected from the original CM Target set. The other 70% of the trials were given using the standard CM procedure.

In all other details, Experiment #3 followed the method of Experiment #1.

Experiment #4

Subjects. A total of 216 subjects participated in this experiment. For the subjects with complete testing records (191 of 216), 171 were males.

Procedure. An increase in memory load (i.e., task complexity) over the standard CM baseline task was provided by increasing the memory-set-size from *two* items (as in Experiment #1) to *three* items. It is important to note that this procedure was otherwise identical to that used in Experiment #1. That is, the total number of target categories was fixed across both tasks. Subjects in this condition were required to keep a larger portion of the same CM Target set categories in memory during each trial.

In all other details, Experiment #2 followed the method of Experiment #1.

Experiment #5

Subjects. A total of 283 subjects participated in this experiment. For the subjects with complete testing records (245 of 283), 203 were males.

Procedure. This task had many elements common to the baseline (CM M=2 word category) task. The major difference between the tasks relates to the type of stimuli under consideration. Rather than being presented with a categorical memory set, subjects were presented two dot figure "prototypes" as the items to be remembered. On the probe frame, three figures were displayed. One of these figures represented a "configuration" of one of the initial "prototypes." An appropriate target configuration was defined as a figure which could be rotated (in 90 degree steps) or reflected about an axis (horizontal, vertical, or either diagonal) to obtain the prototype figure. This classification has been denoted as "rotation and reflection" equivalent figures by Garner and Clement (1963). Subjects were instructed about the patterns by the experimenter describing and illustrating the possible configurations resulting from rotation and reflection operations on prototypes. Consistent Mappings (CM) of targets and distractors were used, as in Experiment 1.

Stimuli. The prototype stimuli and their respective rotation and reflection configurations were selected from the 17 rotation and reflection equivalence sets developed by Garner and Clement. Each figure was constrained to have five dots in an imaginary 3x3 cell square grid. These figures are constrained to have at least one dot in every row and column of the imaginary grid. The particular stimuli selected represent an intermediate range of judged figural "goodness" (which closely corresponds to the degree of symmetry -- Ackerman & Hake, 1982). Assignment of figures to task conditions was structured so that equivalent mean figural "goodness" prevailed across the consistent target and consistent distractor sets. Dots were simulated by use of the period "." character. Given that the spatial stimuli consisted of "." characters, fixation characters for the spatial task were small "x"'s rather than the "." used in the verbal task, in order to prevent confusion.

In all other details, Experiment #5 followed the method of Experiment #1.

Results -- Experiments 1 through 5

Scoring Methods

Performance data included two dependent variables, RT latency and Accuracy. By constraining accuracy to a level well below the asymptotic perfect performance, small differences between sub-group accuracy levels can be tolerated, when examining

latencies. As stated in the method section above, subjects were instructed to try to maintain accuracy in the 90-95% correct range during task practice. The overall results indicate that subjects followed the instructions quite well. The average accuracy rates for experiments 1 - 5 were 89.27%, 87.86%, 87.80%, 89.32%, and 88.10%, respectively. With the large sample sizes and standard errors in the range of .25%, it would be no surprise to find that these constituted "significantly" different means, but the range of 1.5% from the highest to lowest mean accuracy levels is well within the tolerance for asserting a lack of *meaningful* differences between sub-group accuracy levels. Furthermore, the ordering of accuracy levels mirrored that of mean RT levels, (i.e., the higher acc. levels were associated with the better [faster] mean RT values), thus assuring the notion that speed-accuracy tradeoff differences between conditions could not account for any findings of latency-based effects. Therefore, the main thrust of the data analyses below are concerned solely with RT measures.

Session Data

Ideally, analysis of ability/performance relations would include comparisons at the individual trial or block level. However, since correlations are the measures of interest (as opposed to mean performance levels -- which are more stable) it was necessary to average over multiple trial sequences in order to obtain adequate stability. In the present situation, performance data were aggregated over 12 sessions of sixty trials (i.e., each "session" included three trial blocks of 20 trials each). Because of the complex relations between RT, task requirements and incorrect responses, and, further as a result of the fact that only executions of the correct response were of interest, data from trials marked incorrect were excluded (either the result of a inappropriate response, or no response before the expiration of the 5 sec. wait period). Performance measures for individual subjects represented the arithmetic mean RT over these trials. Given the overall accuracy rates, this scoring scheme resulted in exclusion of an average of 12% of the responses made.

Means

A brief comparison of mean performance levels is necessary to document the fundamental information processing/skill acquisition differences between the various task conditions. The first comparison (**Figure 6**) shows the mean RT levels for the three tasks differing solely in the degree of information processing consistency. The least complex, least novel consistent task version (CM M=2), that is, the baseline task shows the common finding of rapidly decreasing RT levels initially, with a diminishing returns from further practice, as asymptotic, automatic processing of the task is developed (e.g., see Shiffrin & Schneider, 1977; Fisk & Schneider, 1983; Ackerman, 1984). In contrast, the least consistent task (VM M=2) shows a much shallower mean learning curve with practice. The level of performance reached during the three hour practice period would not be expected to change, even after much greater practice time (see Schneider & Shiffrin, 1977). The intermediate consistency condition (CM/VM M=2), as expected (Fisk & Schneider, 1982b), shows a skill acquisition rate and final level intermediate to the other two conditions.

Insert Figure 6 about here

1-28
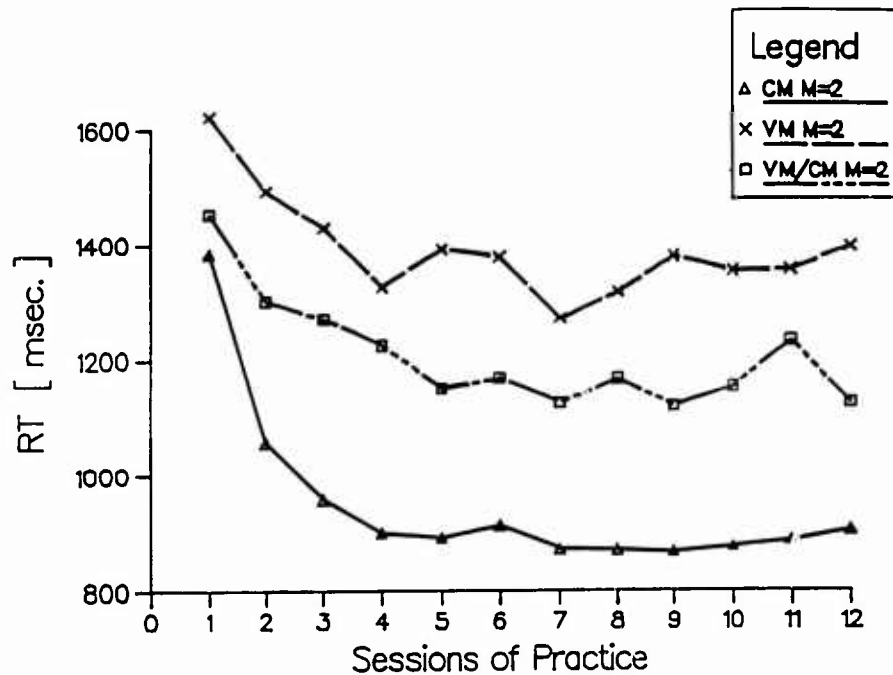
Figure 6. Mean RT levels (across subjects and trials) as a function of practice for conditions of differing levels of within-component consistency. CM = completely consistent, CM/VM = 75% consistent, VM = not consistent. Each session of practice contained 60 trials.

The comparison of mean RT levels for the consistent tasks over practice (**Figure 7 & 8**) illustrates that, while complexity (or novelty) levels differ for the three CM conditions, two major similarities are found. First, each of the tasks follows roughly the same pattern of improvement with practice (that is, considering the different starting points). Also, the three tasks asymptote at roughly the same RT levels after 7 sessions (420 trials - or about 1.5 hours of practice), though the CM Spatial task is closer to the CM M=2 baseline (**Figure 8**). Apparent in **Figure 7** is a substantial interaction between CM M=2 and M=3 conditions, such that mean RT levels actually crossover after 4 sessions, the M=3 condition having lower RT values. A two-way (condition x practice session) repeated measures ANOVA was performed (using only subjects with complete data) to evaluate the statistical veracity of this visual result. As expected, no omnibus condition effect was present ($F[11,523]=.57, p > 0.45$), the obvious effect of practice session was significant ($F[11,5753] = 717.59, p < .00001$), and a significant interaction of condition by practice was found ($F[11,5753] = 15.69, p < .00001$). That is, by increasing the *front-end* or initial complexity in creating the M=3 task (which occurs because memory load is increased, but the underlying total sets of categories and exemplars are identical for the two tasks), initial performance is slower, but with practice, efficient productions are developed and compiled more quickly than in the task with less memory load (M=2). These results, as discussed below, have major ramifications for the comparative ability/performance relations.

Insert Figure 7 and 8 about here

Standard Deviations

Changes in between-subject *sd* measures are similarly reflective of the task demands and expected changes with practice (also see Ackerman, in press). Initial and final (Session 12) *sd*'s are presented in **Table 2**. All of the consistent tasks show significant declines in *sd* levels with practice, while the inconsistent and mixed consistency tasks do not decline. In fact, as with other studies (Ackerman, in press), the two tasks with moderate or higher amounts of inconsistency show small increases in variability with practice (even as the mean level of performance is declining -- see **Figure 7** above). The consistent tasks with increased complexity (CM M=3) and novelty (CM Spatial) show initially elevated *sd*'s, though, as with the convergence of mean performance levels, these tasks show final *sd*'s roughly equivalent to the CM M=2 baseline task.

Insert Table 2 about here

Within-Task Intercorrelations

The ubiquitous quasi-simplex results found in learning and other longitudinal data were also found in the experiments reported above. (The example quasi-simplex matrix in Table 1 derived from Experiment 1 is prototypical of these patterns of correlations.) Although this general pattern is common to all of the task conditions, the Session-to-Session stability data and the rate of attenuation in correlations with Session 1 performance can be examined for differences.
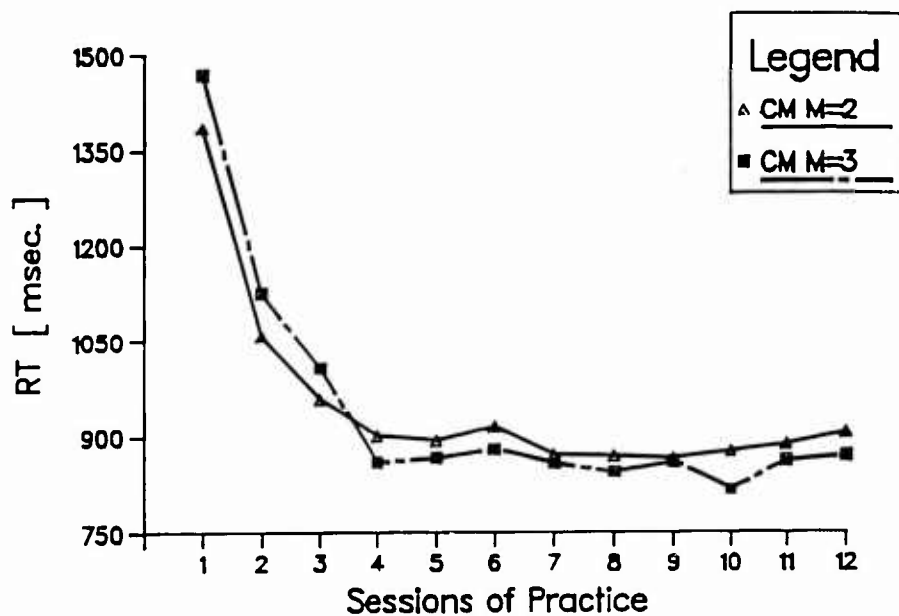
Figure 7. Mean RT levels (across subjects and trials) as a function of practice for two consistent conditions differing in level of front-end complexity. CM M=2 -- memory set size of 2 items. CM M=3 -- memory set size of 3 items. Each session of practice contained 60 trials.
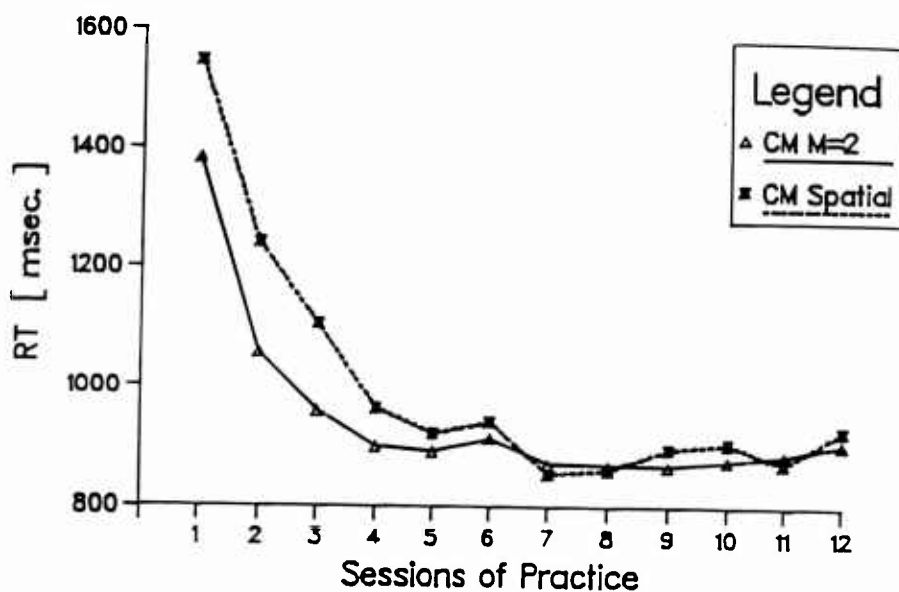
Figure 8. Mean RT levels (across subjects and trials) as a function of practice for two consistent conditions differing in level of novelty (but also of content). CM M=2 -- memory set size of 2 items (verbal). CM Spatial -- memory set size of 2 items (5-dot figures). Each session of practice contained 60 trials.

Table 2. **Practice and Variability -- Consistent vs. Inconsistent Information Processing Task Requirements.**

Task Condition	N	RT $\hat{\mu}$ in msec				RT $\hat{\sigma}$ in msec			
		$\hat{\mu}_i$	$\hat{\mu}_f$	$\hat{\mu}_i - \hat{\mu}_f$	%Change	$\hat{\sigma}_i$	$\hat{\sigma}_f$	$\hat{\sigma}_i - \hat{\sigma}_f$	%Change
CM M-2	338	1,384	906	478	-34.%	271	209	62	-33.%*
VM M-2	272	1,622	1,396	226	-14.%	281	316	- 35	+13.%
CM/VM Mixed M-2	242	1,453	1,125	328	-22.%	258	290	- 32	+12.%
CM M-3	216	1,468	870	598	-41.%	404	196	208	-52.%*
CM M-2 (Spatial)	283	1,548	929	619	-40.%	316	236	80	-25.%*
DRT (Training)	334	878	666	212	-24.%	153	122	31	-20.%*
DRT (Transfer)	334	1,230	990	240	-20.%	261	232	29	-11.%*

Varied-Mapping task versions (VM and CM/VM Mixed) require controlled processing (attention-demanding). Consistent-Mapping task versions (CM and Discrimination Reaction Time [DRT]) allow for the development of automatic processing (attention-attenuating). M - Memory Set Size (number of categories or prototypes in the memory set). i - initial. f - final.

* $p \leq .05$ (one-tailed test for the difference between two standard deviation measures).

The stability data suggested a differential trend, but on the whole were inconclusive. The adjacent session correlations were uniformly high across all tasks (range *r* = .67-.90, mean= .81). A regression of the changes in adjacent session intercorrelations found no slope measure significantly different from zero, that is, no increase or decrease in the stability of individual differences in performance over sessions. However, the trend was for the tasks with consistent components (CM M=2, CM M=3, CM Spatial, and CM/VM) to show slightly decreasing stability with practice, while the predominantly inconsistent task (VM M=2) showed a slight increase in stability. Post-hoc contrasts of the various task conditions showed only the difference between the VM and CM M=3 conditions (*r* = .304 and -.374, respectively) even approached significance (*t test of difference between regression slopes* [df=18] = 1.54 [critical $t_{.05}$ = 1.73]). Considering the size of the respective subject samples, it can reasonably be concluded that these measures of stability are insensitive to marked skill acquisition changes resulting from manipulation of task information processing requirements (as measured by mean and *sd* values, see above).

The rate-of-attenuation data offer little more information than the stability data. In general, each of the conditions shows a rapid attenuation in correlations as the Sessions become more temporally displaced (i.e., from Sessions 1,2 to Session 1,12), see **Figure 9**. Analysis of the slope measures reveals that two of the consistent tasks (CM M=2 and CM M=3) show significantly greater attenuation than either the novel, consistent task (CM Spatial), or the two tasks with inconsistent information processing requirements (CM/VM and VM M=2). Other contrasts, such as the difference between the CM M=2 and CM M=3 all failed to reach significance. Again, even though the trends are consistent with theoretical expectations (i.e., greater changes in the consistent tasks and lesser changes in the inconsistent, or partially consistent tasks), these measures similarly fail to fully discriminate among the different information processing requirements of the tasks.

Insert Figure 9 about here

Test data (ASVAB)

Given the need for comparisons of ability/performance relations across each of the experimental tasks, it was necessary to put each of the ASVAB test results into a single common framework. This was accomplished by a set of multivariate procedures designed to provide exactly this result, as described below.

The first step in deriving reference abilities (common to each of the experiments) involves testing whether the ability test interrelations for all of the subject samples are equivalent. A sensitive evaluation of multivariate equivalence is provided by the Box test for the equality of several covariance matrices (see Morrison, 1967). To carry out the test, covariance matrices (based on the 10 ASVAB tests) for each of the sub-samples of subjects and a pooled covariance matrix were derived. The Box test provides a criterion statistic that is approximately distributed as chi-squared. For these data, with derived df = 275, the resulting test statistic was 210.59, a non-significant result (Chi-squared criterion at *p* = .05, was 313.5). An exact power analysis can not be derived, given the inability to specify a fixed magnitude of effect. However the test has proved sufficiently sensitive to violations of the null hypothesis,

Within–Task Correlations with Session 1
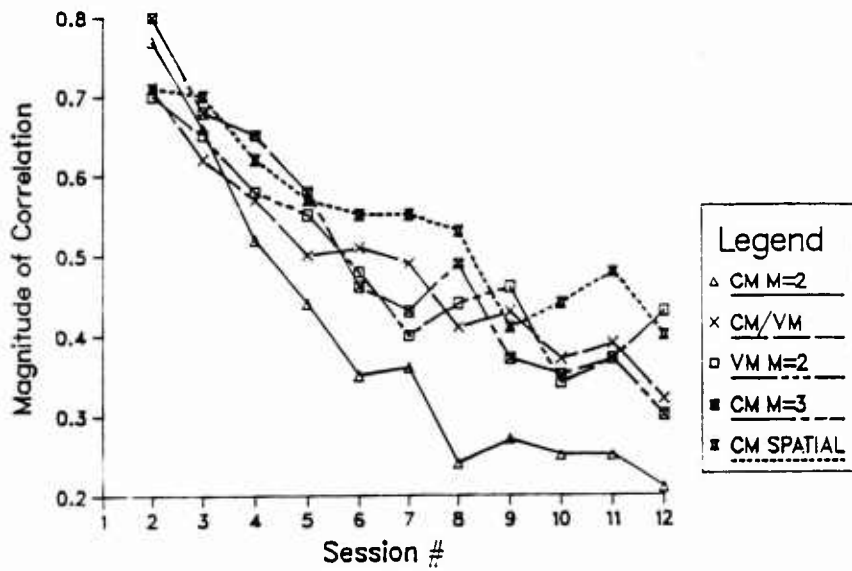
Figure 9. Within-task correlations with Session 1. Points represent the correlations between task performance at Session 1 and performance at each subsequent practice Sessions.

and the present sample is substantial enough (total sample = 1,486 subjects) to merit a retention of the null hypothesis, that is, that the individual sub-sample data are all derived from the same, common population.

This hurdle passed, it was necessary to derive a single, factor-analytic solution that would represent the common abilities underlying the ASVAB test data. For this purpose, the Air Force normed reference group was chosen to provide this basic model of abilities (Ree, Mullins, Mathews, & Massey, 1982). The initial norm data were collected on a sample of 2,620 applicants to the U. S. Armed Forces. Initial factoring was accomplished with squared multiple correlations in the diagonal, with four factors resulting from the analysis (see Ree, et al. for details). In order to derive a representation of the ability data which includes an statistically independent "general" intellectual factor, the reference factor matrix (from Ree et al.) was rotated using an orthogonal hierarchical rotation procedure (Schmid & Leiman; 1957). This method allows for the derivation of higher order factors (in this case, a single general ability factor), and representation in a single orthogonal factor solution. That is, the final factor solution contains the first order factors (in this case, Verbal, Vocational-Technical Information, Math, and Perceptual Speed factors), along with, *and independent of,* a General Ability factor. The resulting normed solution is presented in **Table 3**.

Insert Table 3 about here

With this normed factor solution as the target solution, each of the sub-sample ASVAB intercorrelation matrices were independently factored, and then rotated (by a Procrustes procedure -- see Sh nemann, 1966) to the normed target solution. With the exception of the communality estimates, all of the sub-sample matrices well-fitted the target solution after transformation. The reason for the differences in communality estimates between the current data and the normed data, is simply attributable to the restriction-of-range-of-abilities found in the current samples -- these subjects were all of high enough ability to pass the initial selection hurdles based on the ASVAB test scores. Also, the fact that the Procrustes procedure succeeded so well is not remarkable, given that such results are found even when the underlying factor solutions are based on random data (Horn & Knapp, 1973). However, given the initial Box test results, and the present purposes, the use of these transformations does not encounter any of the common objections to the use of the Procrustes procedure in other situations.

The next, and final step in determining ability/performance correlations was via the Dwyer Extension procedure (Dwyer, 1937) for determining the factor loadings (i.e., correlations with the abilities - in this orthogonal factor space) of the individual task performance variables. This is simply a general linear model procedure for providing factor loadings of variables not originally in the factor solution. Its use is necessitated by the presence of statistical artifacts when test and task practice data are factor analyzed in a single solution (for a detailed discussion of this issue, see Humphreys, 1960; also, see Ackerman, 1986, in press)

The results from this rather lengthy (but straightforward, least-squares estimators), series of calculations are correlations between the five ASVAB abilities (g,

Table 3. Normative ASVAB Target Hierarchical Solution

FACTOR

TEST		g	Verbal	Vo-Tech Info.	Math	Perceptual Speed
GS	1	.77962	.35088	.19228	.16866	-.02277
AR	2	.77790	.13645	.10682	.38273	.07970
WK	3	.77990	.45484	.11394	.08433	.04555
PC	4	.74734	.40286	.08546	.09730	.09678
NO	5	.55995	.08447	.05697	.12325	.32451
CS	6	.52553	.04548	.14243	.06487	.31882
AS	7	.68722	.14945	.48426	.02595	.00569
MK	8	.70976	.06498	.08546	.40219	.09678
MC	9	.72670	.08447	.41305	.18812	.00000
EI	10	.75966	.21442	.39880	.09082	.01139

FACTOR 1 -- "g" (all tests)
FACTOR 2 -- "VERBAL" (GS, WK, PC)
FACTOR 3 -- "VO-TECH INFORMATION" (AS, MC, EI)
FACTOR 4 -- "MATH" (AR, MK)
FACTOR 5 -- "PERCEPTUAL SPEED" (NO, CS) [also denoted as "Clerical Speed"]

V, VT Info, Math, and Perceptual Speed) and task performance at each practice session, for each experiment.

Ability-Performance Correlations

The ASVAB, while available for these experiments, does not represent an optimal selection of test measures that identify all of the major factors of interest. Specifically, relevant content abilities and Psychomotor Speed abilities were not sufficiently measured to be used in the following comparisons. In fact, no psychomotor speed tests are included in the battery, and the verbal part of the battery is apparently very highly associated with general ability - to the exclusion of well-defined, independent verbal ability. (A discussion of Content ability/performance relations can be found in Ackerman, 1986; and a discussion of Psychomotor Speed abilities will be presented with other data further below.) However, the General ability and Perceptual Speed factors were adequately measured, and will be presented below. Ability/performance correlations based on these factors serve as the basic data for evaluating the adequacy of the theoretical ability/performance predictions during skill acquisition.

Results: (Experiments 1, 2, 3)

Within-component degree of consistency

Predictions: The memory requirements of each these three tasks were equivalent at the individual trial level, that is, two categories in the memory sets. However, in the CM/VM and VM task versions, over the cumulative course of the trials, the subjects were required to learn six different category labels (while in the CM case, only three category labels were given as memory set items, the others only as distractor items.) Thus, while initially equivalent in complexity (i.e., on the first trial), skill acquisition rates, and thus changes in ability/performance levels are predicted to differ between the task versions.

1) The CM, CM/VM and VM tasks share the same, moderate (M=2) memory load and the same initial information processing requirements. Thus, these three tasks are predicted to have equivalent General ability/performance correlations on initial performance. With practice, CM task performance is predicted to show a steep decline in correlations with general ability, as productions are formulated (Phase 1), and compiled/tuned (Phase 2). In contrast, given that fewer consistent components exist for the VM task (i.e., including the consistent response components), the declining correlations with general ability are predicted to be much more shallow than those of the CM task. Finally, the CM/VM task is predicted to correlations intermediate to the other two tasks.

2) Again, given the only moderate level of task complexity and the high level of S-R compatibility, CM task performance is predicted to begin with initially moderate correlations with Perceptual Speed (i.e., the transition from Phase 1 to 2 is expected to begin even within the first block of trials). With practice, the association with Perceptual Speed, will decline (as the performance transitions into Phase 3). In contrast, the CM/VM and VM conditions (as a result of the more enduring General Ability requirements) are expected to have later development of Perceptual Speed/Performance correlations (*much* later in the case

of the VM task). Thus, the CM/VM curve is predicted to show initially rising correlations with PS, that even off and then decline with practice (at a slower rate than the CM baseline task). In contrast the VM condition will show even later development of PS correlations, thus revealing more of the ascending part of the Phase 2 curve (as indicated in **Figure 5, Panel B**) and a later asymptote.

<u>Results</u>. Ability/performance correlations for the three degree of consistency conditions are presented in **Figure 10 (General ability) and Figure 11 (Perceptual Speed)**. First of all, it is clear that the ability/performance relations show much less session-to-session stability than would be optimally desired. However, this variability is characteristic of information processing tasks as simple as those studied here. More complex tasks (which would involve RT changes over practice in the neighborhood of many seconds rather than msec) do not usually involve such variability, but also would not have allowed for Phase 2 of skill acquisition in the three-hour time frame allowed with this population. Nonetheless, general patterns of ability/performance changes are adequately represented by way of the plotting of regression lines, along with the actual data points. For General ability/performance results, the regression lines plotted were linear (given the near-linear predictions, at least after the first several trials). That is, although at Trial 1, all of these tasks are identical, given the rapidity which skill acquisition occurs for the CM task (Ackerman, 1986), by the end of the first block of trials, the ability/performance relations will have already sufficiently diverged so as to yield more linear, than the theoretical cubic functions. For the Perceptual Speed/performance results, decidedly non-linear predictions were made over the entire course of practice. Thus, the Perceptual Speed data were fitted by third-order polynomials (cubic curves). While the higher order curves allow for the predicted curvilinear functions, such curves do capitalize to a greater degree on small deviations in the data, and therefore should be interpreted with some caution.[1]

Insert Figure 10 and 11 about here

For the General ability/performance comparisons, there is a clear distinction between the CM and VM tasks. As predicted, CM performance rapidly becomes predominantly "insensitive" to individual differences in the General ability. VM performance, in contrast, shows shallower attenuation during task practice (attributable to the few consistent components of the task). While the CM/VM condition did not

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[1]The actual magnitudes of the ability/skill correlations throughout practice are below those that would be expected in the population. This condition is a result of the fact that the subject sample is somewhat truncated in range-of-talent (both at the top and bottom ranges), because some military service applicants are rejected on the basis of low aptitude scores, and some high-ability members of the population are excluded because of self-selection. Samples of subjects from the current population generally show about <u>half</u> of the variability (sd) found in norms collected on unselected high school students [Tirre, **personal communication 8/4/86**]. While corrections for restriction-of-range would raise the magnitude of these correlations, the patterns (which are of direct concern) would remain essentially unchanged.

Figure 10. Ability/Performance relations for tasks of differing levels of within-component consistency. Correlations between derived General ability and task performance. Lines indicate linear regression of *g* loading over practice.
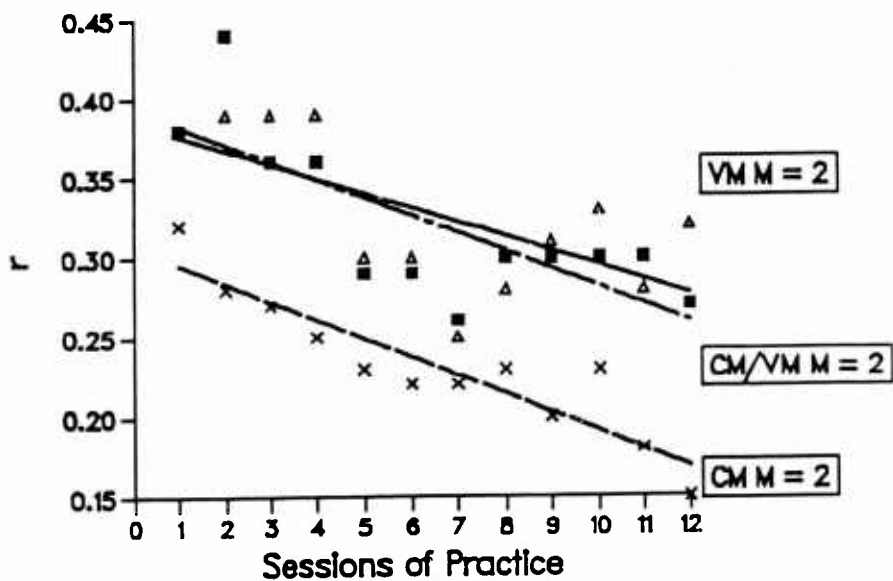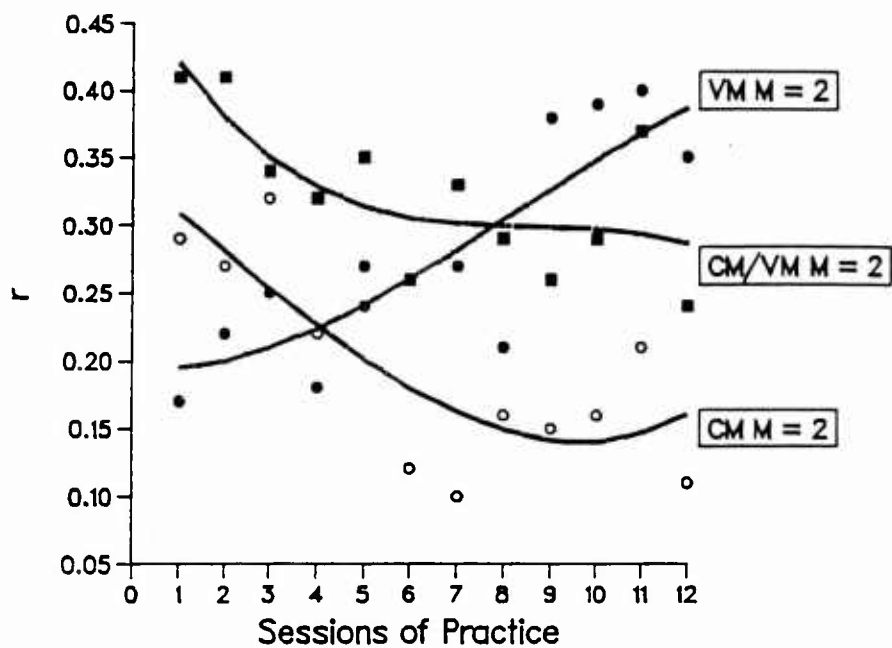
Figure 11.   Ability/Performance relations for tasks of differing levels of within-component consistency. Correlations between derived Perceptual Speed ability and task performance. Lines indicate polynomial (cubic) regression of ability loading over practice.

show the expected ascending correlations, and more rapid attenuation than the VM task, the pattern of correlations is congruent with the prediction that decreasing the within-component consistency brings about greater, enduring load on Phase 1 cognitive processing.

Further, as predicted (**Figure 11**) the rapid development of Phase 2 processing which occurs in the CM condition allows for an early peak in Perceptual Speed/performance associations, and rapid attenuation with additional practice. In contrast, the VM condition (which has much greater and longer associations with the General ability) results in initially lower Perceptual Speed/performance correlations. However, as the few consistent components of the VM task begin to be proceduralized (with the ensuing drop in General ability/performance correlations), increasing correlations with Perceptual speed are found. Given that total practice time was short, it was impossible to test whether asymptotic correlations between performance and Perceptual speed had been reached.

The CM/VM condition proved to be less well-fitted by the theoretical predictions. The theory indicated that the mixed mode should show relatively smaller correlations with the General ability than for the VM tasks (although these correlations are equivalent in these data). On the other hand, the Perceptual Speed data are consistent with the fact that the CM/VM task reaches Phase 2 later than the CM baseline task, and earlier than the consistent components of the VM task. A post-hoc inference for this pattern of results is that the mixed mode task requires greater amounts of Phase 1 processing than previously believed. That is, from an information processing perspective, the mixed consistency (70% consistent) paradigm involves a) the ability to develop and tune adequate productions as in the CM version; b) the ability to ignore previous targets (during the 30% reversal trials) as in the VM version, and finally, c) the attentional vigilance to monitor the change in conditions. As a result, the CM/VM version might be expected to be as dependent on the General ability as the VM task. Of course, this post hoc reasoning must be checked by further experimentation.

Results -- Experiments 1 and 4

The increase in memory load, from a two-item to a three-item memory set, does not result in an enduring increase in task complexity, given that both versions sampled from the same three-item set of categories. That is, as with the traditional consistent mapping (CM) design, although subjects in the M=2 condition were required to only memorize two items on every trial, once the entire set of categories and exemplars are learned, memory load no longer has an effect on mean performance levels (that is category search after practice proceeds nearly fully in parallel -- see Fisk & Schneider, 1983). With initial performance, though (when memory search is predominantly serial), memory load does indeed have an effect on task performance. That is, the increase in memory load is essentially a "front-end" increase in task complexity. In addition, this increased experience with the full set of target categories will also speed-up the development of automaticity. As such, the CM M=3 task provides an ideal contrast for the M=2 baseline condition for exploring the theory predictions.

Predictions

1)   In comparison to the baseline M=2 condition, the increase in front-end task

complexity of the CM M=3 condition is predicted to yield initially higher correlations with the General Ability factor. However, there is a predicted interaction that should occur given the faster transition from Phase 1 to Phase 2 (this was also reflected in the mean and sd data). That is, with practice, correlations with general ability will attenuate *faster* in the M=3 condition. Finally, asymptotic correlations should be equivalent for the two tasks.

2) In contrast, the theory predicts that the higher CM M=3 General Ability loadings (Phase 1) will come at a cost of reducing the association of performance with Perceptual Speed. With practice, though, as the General Ability correlations decline, the Perceptual Speed correlations will increase, that is, a later development of Phase 2 skill levels. Thus, as the CM M=2 correlations with Perceptual Speed ability are declining (as Phase 2 moves on to Phase 3), CM M=3 will increase, level off, and then decrease during the three Phase process of skill development. The expectation, then is for an interaction of correlations to also be found in the CM M=2/M=3 contrasts for Perceptual Speed.

Specific Results

Although the CM M=3 mean performance level at Session 1 is 84 msec. slower than the CM M=2 mean, these tasks show the convergence of mean RT (actually a full crossover) interaction at Session 4 (see above). The standard deviations (Session 1: 404 msec. for the M=3 condition, 271 msec for the M=3 condition) show convergence at Session 5, and stabilize at equivalent levels in later sessions.

The interactions of the ability/performance correlations over practice are also found, as predicted. **Figure 12** shows the comparison for the General Ability correlations. For this ability, M=3 starts off with a higher correlation with General Ability, but by Session 7, the M=3 faster attenuation causes the expected cross-over, with CM M=2 having moderately higher correlations. A test for the difference between regression slopes (McNemar, 1962) was performed towards confirming this result. With $df = 20$, the test statistic ($t = 5.45$) was found to be significant ($p < .001$). The data are less regular for the Perceptual Speed correlations (depicted in **Figure 13**), but the interaction is apparent ($t[df=20] = -3.82, p < .01$), even if the exact crossover point is unclear. (The linear interpolation reveals a crossover at Session 4, the actual reversal of correlations occurs at Session 5.) Nonetheless, the general pattern of results are quite consistent with the theoretical predictions.

Insert Figure 12 and 13 about here

Results -- Experiments 1 and 5

The spatial task, while different in content from the other tasks, required many of the same underlying information processes for successful performance (i.e., two-item memory set, determination of categorical relations, and the same S-R mapping scheme). As opposed to the word-based tasks, the spatial task requires novel categorizations.

Figure 12. Ability/Performance relations for tasks of differing levels of front-end complexity. Correlations between derived General ability and task performance. Lines indicate linear regression of g loading over practice.

Figure 13. Ability/Performance relations for tasks of differing levels of front-end complexity. Correlations between derived Perceptual Speed ability and task performance. Lines indicate polynomial (cubic) regression of ability loading over practice.

<u>Predictions</u>

1. The increased novelty of the task was inferred to require additional front-end information processing during skill acquisition. That is, production systems were required that allowed for generation of the relevant configurations from the prototype/memory items. As a result, an increase (over the Experiment 1 CM M=2 task) in performance correlations with general ability was predicted at the initial sessions of practice.

2. The response components of the spatial task were identical to the other tasks, thus implicating a moderate correlation with Perceptual Speed early in practice. However, following from (1) above, the Perceptual Speed factor was predicted to have a later peak in performance correlations as compared to the baseline task. Finally, the presence of these additional requirements of the task imply that the decay rate for Perceptual Speed influence should be somewhat attenuated over the three hour practice period.

<u>Specific Results</u>

The ability/performance correlations for the Spatial task (along with the CM M=2 baseline task) are presented in **Figure 14** (for the general ability) and **Figure 15** (the Perceptual Speed ability). As predicted, the performance correlations for the General ability are higher overall for the Spatial task, but show a similar decline with practice. Further, the predicted pattern is revealed for the correlations with Perceptual Speed. That is, as a result of the greater initial influence of General ability, the peak Perceptual Speed correlations come later in practice (Session 1 for the baseline task, Session 7 for the CM Spatial task), and remain above the levels for the baseline task at the end of the practice period.

Insert Figure 14 and 15 about here

It is interesting to note that, in the case of the Spatial task, although mean performance levels are nearly equivalent to the baseline task after (7 Sessions of practice), the increased influence of the ability factors is also reflected in the higher *sd* levels of the Spatial task (see **Table 2** above).

Experiment 6

In order to directly manipulate the ability/performance relations in a single within-subject paradigm, Experiment 6 utilized two variants of a nine-choice discrimination reaction time task. An initial simple, consistent, S-R compatible task was used in the Training segment. In this condition, subjects were presented a single digit between 1 and 9, and responded with a corresponding key-press (on the separate numeric keypad).

A Transfer segment was created for evaluating the theoretically predicted changes in General and Perceptual Speed ability/performance relations when a novel, but consistent task component is added to a well-practiced task (i.e., as information processing is moved from Phase 2 back to Phase 1). In this Transfer segment, the
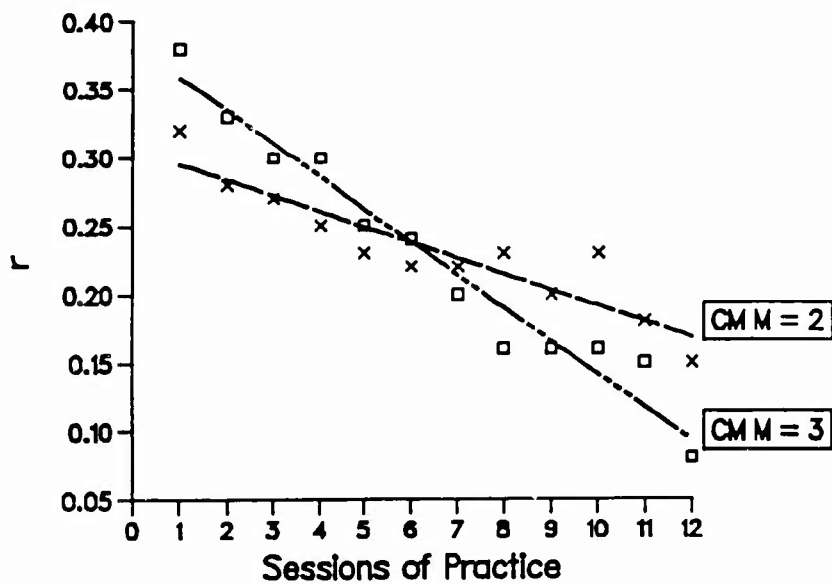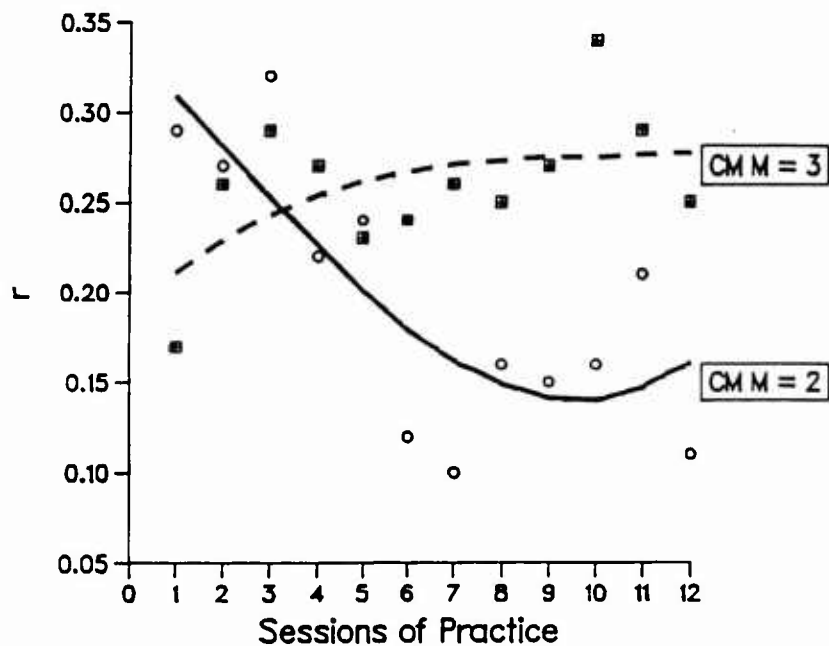
Figure 14.   Ability/Performance relations for tasks of differing levels of novelty (and content).   Correlations between derived General ability and task performance.   Lines indicate linear regression of *g* loading over practice.
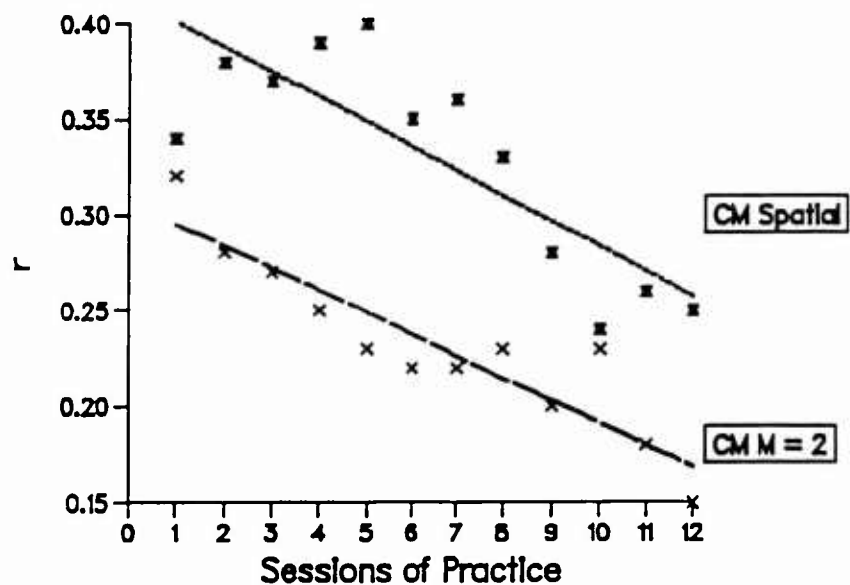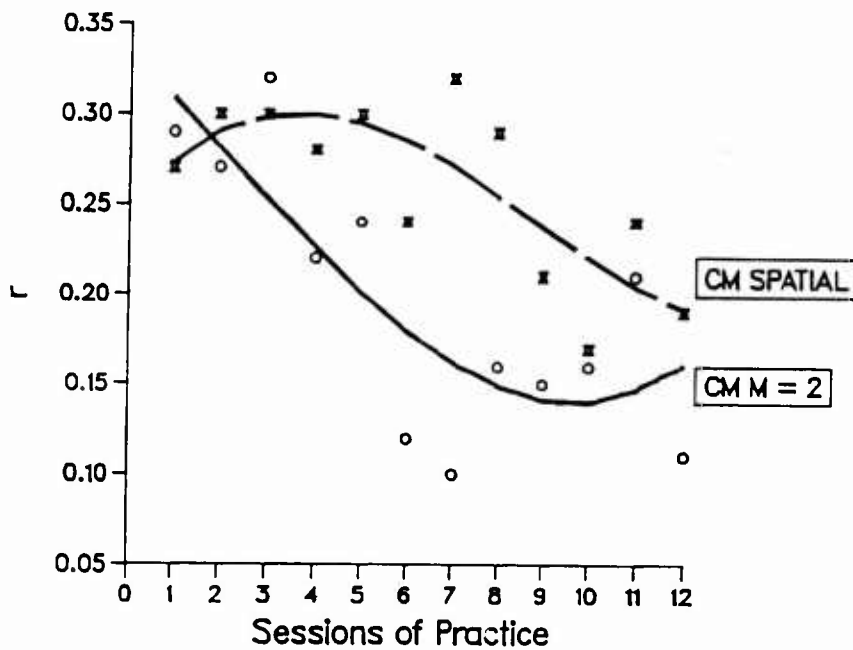
Figure 15. Ability/Performance relations for tasks of differing levels of novelty (and content). Correlations between derived Perceptual Speed ability and task performance. Lines indicate polynomial (cubic) regression of ability loading over practice.

additional task component required subjects to first encode and translate a two-letter abbreviation for the number stimulus (rather than the number itself, as in the Training segment). With the exception of this additional requirement, the Training and Transfer tasks (i.e., the response components) were identical.

Method

Subjects. A total of 334 subjects participated in this experiment. For the subjects with complete testing records (302 of 334), 231 were males.

Stimuli. In the Training phase of this experiment, stimuli were digits "1" through "9", displayed on the CRT as in the preceding experiments. In the transfer phase, the digits were replaced with two-letter abbreviations for the location of the number key on the keyboard. The following mapping was used: "1" - "LL", "2" - "LM", "3" - "LR", "4" - "ML", "5" - "MM", "6" - "MR", "7" - "UL", "8" - "UM", "9" - "UR". That is, the first letter in the abbreviation represented "Lower Row," "Middle Row," or "Upper Row" -- i.e., the vertical position of the key, the second letter in the abbreviation represented "Left," "Middle", or "Right" -- i.e., the horizontal position of the key.

Procedure. For each task trial, an "X" was initially presented in the center of the CRT for .50 sec (as a focusing reference). Immediately thereafter, (in the Training segment) a number between 1 and 9 was presented. In the Transfer segment, rather than a single digit, the two-letter key position abbreviation was presented. Subjects were instructed to press the number-pad key that corresponded to the number on the screen (or the position of the number of the screen - in the Transfer Phase) as fast as possible, with the provision that Accuracy remain in the 90-95% correct range. Subjects were instructed to rest their right hand index, middle and ring fingers on buttons "4", "5", and "6" respectively.

Again, 20 trials/block were presented to the subjects. After Trial Blocks #9 and #18, subjects were given 10 min. breaks. Subsequent to the second break, instructions for the Transfer Phase were presented, including an explanation of the new stimulus-response mapping requirements. No additional task practice was given prior to Transfer. During the transfer phase, subjects were also given breaks after every 9 Trial Blocks (i.e., after Blocks #27 and #36).

In all other details, Experiment #6 followed the method of Experiment #1.

Specific Results

The within-subject design of Experiment 6 provides a more decisive source of evaluation for the theory. The Training portion of the experiment was designed with to demonstrate that for simple, consistent, and highly S-R compatible tasks, skill acquisition Phase 1 is quite brief (for most intents and purposes, bypassed). The Transfer portion of the task was designed to demonstrate how, when a novel, but consistent component is added to the task, cognitive/declarative/controlled (Phase 1) information processing requirements are introduced (i.e., demands for the formulation of new productions). With practice, though, the Transfer paradigm allows for transition to the later Phases of skill acquisition.

Means/Standard Deviations. As with the more complex tasks in Experiments 1 -

5, accuracy data in Experiment 6 were quite close to the instructed values. For the simple Training task, average accuracy was 93.2%. In the more complex Transfer condition, mean accuracy was 88.1%. Similarly, as with the other consistent tasks (Experiments 1, 4, and 5), mean RT performance declines substantially with practice in both tasks (see **Figure 16**). The comparative complexity of the Transfer task is best illustrated by the initial 564 msec. average increase over the Training task final performance level. (This performance decrement is found in spite of the expected positive transfer from one task to the other). In line with the increased task complexity indicated by the slower mean RT levels, between-subject performance *sd*'s doubled from the end of the Training segment to the beginning of the Transfer segment (from 122 msec to 261 msec -- see Table 2 above). Thus, the mean and *sd* initial levels and changes with practice are consistent with the theoretical expectations regarding, a) a simple, consistent Training task and b) a more complex, but also consistent Transfer task.

Insert Figure 16 about here

Ability Measures. Estimates of ability factors and ability/performance correlations followed the procedures outlined for the previous experiments.

Predictions

1)   Initial loadings of general ability are predicted to be small, given the inherent simplicity/consistency of the Training task (i.e., given a very brief Phase 1 of skill acquisition). Conversely, given that early performance is dominated by Phase 2 skill levels, Perceptual Speed is predicted to have high correlations with performance, which decline as Phase 3 skill levels are reached.

2)   When the Transfer condition is imposed, novel productions must be formulated to successfully perform the task (i.e., Phase 1). Thus, General ability is predicted to increase in correlation with performance, and by implication, Perceptual Speed ability influence attenuates. With practice, as Phase 1 productions are built and the subjects move into Phase 2, General ability is predicted to attenuate in influence, and Perceptual Speed is predicted to increase in influence.

Specific Results

The correlations between both factors (General and Perceptual Speed) and performance are given in **Figure 17**. As predicted, during the Training portion, the Perceptual Speed factor is highly correlated with performance, but shows a decline with practice. The General ability factor shows stable, attenuated correlations with performance. With addition of the translation component, the relative influences of the two factors is reversed, as Phase 1 information processing is required. Finally, with practice, General ability declines in influence (once the new productions are developed) and Perceptual Speed regains influence, as the new productions are compiled/tuned. While total practice time was short (i.e., about three hours), the pattern of changes are consistent with the expectation that General ability will ultimately asymptote at a lower level and perceptual speed will ultimately level off and then decline as Phase 3 is reached. (However, while consistent with the theory, the
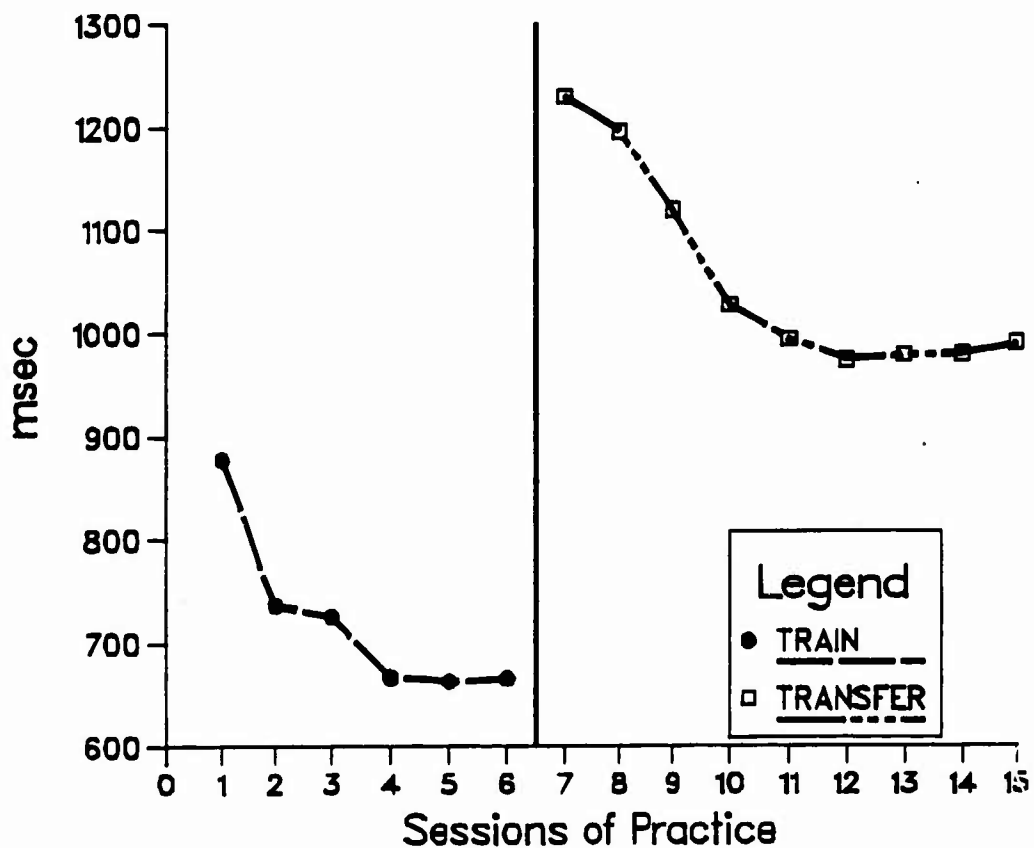
Figure 16. Mean RT levels (across subjects and trials) as a function of practice for Experiment 6, Training and Transfer phases. Each session of practice contained 60 trials.

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data do not decisively indicate what later ability/performance correlations would be.)

Insert Figure 17 about here

OTHER SOURCES OF DATA

An examination of the role of Psychomotor ability (and further comparisons with Perceptual Speed) is provided by review of the few studies in the literature which contain data adequate to address the issues. In particular, three studies by Fleishman et al. (Fleishman, 1960, Fleishman & Hempel, 1954, 1955) are sufficient for providing a contrast between Perceptual Speed abilities and one major Psychomotor ability factor (Rate of Arm Movement) for three tasks over practice. The tasks, Complex Coordination, Rotary Pursuit, and Discrimination Reaction Time and procedures are described in detail elsewhere (see original references and reanalysis by Ackerman, in press). It is important to emphasize that all three of these tasks are highly consistent, and essentially simple, from an information processing perspective.

Predictions

A general consideration of some ability/performance relations have been reported by Ackerman (in press), but the specific comparisons are provided here as an illustration of (a) the predicted decreasing correlations between Perceptual Speed and performance with practice, and (b) the predicted increasing correlations with Psychomotor speed (Rate of Arm Movement) with practice.

Results

Figure 18 depicts the association between Perceptual Speed and performance for the three tasks. While the tasks are differentially dependent on Perceptual Speed at early levels of practice, all three follow the same predicted declining pattern of correlations expected when tasks are simple (and the initial association with content/general abilities is low). **Figure 19** shows the analogous correlations between Rate of Arm Movement and performance over practice. As predicted, each of the three tasks shows an increasing association with this Psychomotor Speed ability as practice proceeds. Furthermore, the initial and post-practice orderings of performance correlations on both abilities are in agreement with the theoretical predictions regarding the transitions from Phase 2 to Phase 3. That is, the substantially greater association of the Discrimination Reaction Time task with Perceptual Speed early in practice is associated with a later development of association between Rate of Arm Movement and performance. As predicted, when tasks can be solved by simple productions (or already formed ones), as in the Complex Coordination and Rotary Pursuit tasks -- as signaled by the lower correlations with Perceptual Speed, Psychomotor abilities become more important determinants of performance earlier during practice. While these data do not allow for a comparison of general/content abilities with performance, the overall results are quite consistent with the theoretical predictions and the data reported in the previous sections.

Insert Figure 18 and 19 about here
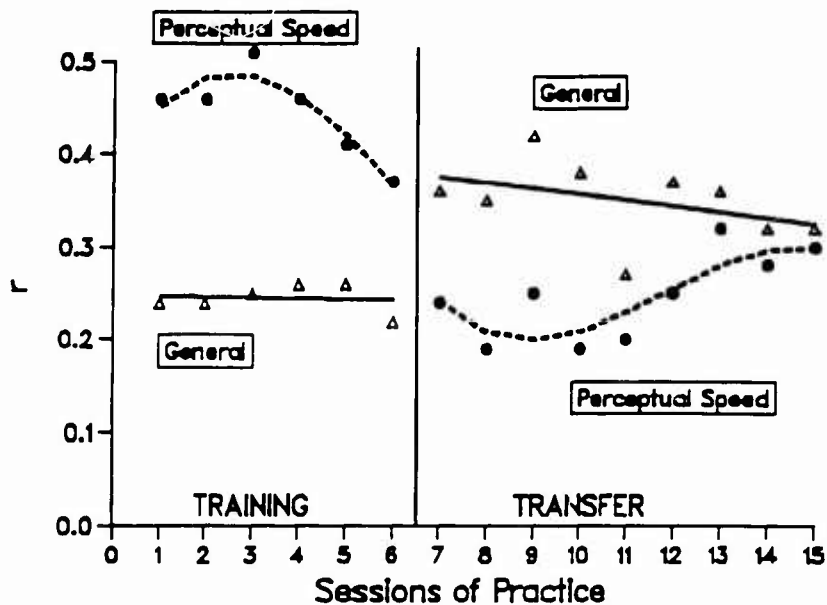
Figure 17. Ability/Performance relations for Experiment 6, Training and Transfer phases. Correlations between task performance and derived General and Perceptual Speed abilities. Lines indicate linear regression of general ability loadings, and polynomial (cubic) regression of perceptual speed loadings over practice.

Perceptual Speed & Performance
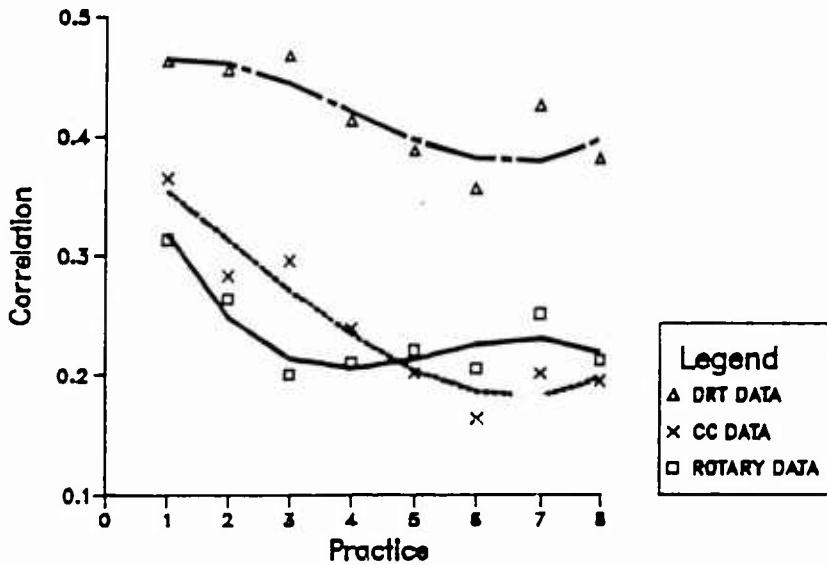
Figure 18. Ability/Performance correlations for data compiled from Fleishman, et al. (Ackerman, in press). Correlations between derived Perceptual Speed ability and task performance. Lines indicate polynomial (cubic) regression of ability loadings over practice.

Rate of Arm Movement & Performance
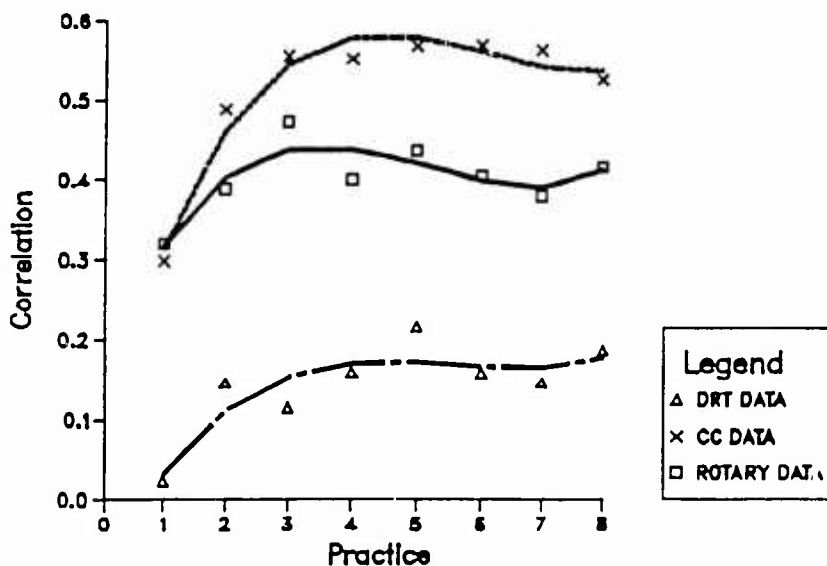
Figure 19.   Ability/Performance correlations for data compiled from Fleishman, et al. (Ackerman, in press). Correlations between derived Psychomotor ability [Rate of Arm Movement] and task performance. Lines indicate polynomial (cubic) regression of ability loadings over practice.

DISCUSSION

Adequacy of the theory

Many *specific* determinants of skill acquisition and individual differences in performance were not considered here (such as massed vs. distributed practice, dual-task processing, motivation, specific content abilities, and so on). The theory, and the underlying normative determinants of skill acquisition have been considered from a very broad perspective. In spite of these limitations, the data were generally congruent with the theoretical predictions. Manipulation of the degree of task consistency, complexity, and novelty have each illustrated the predicted dynamic ability/performance changes during skill acquisition Phases 1, 2 (and partly for Phase 3). The Fleishman et al. data offered further illustrations of the Perceptual Speed and Psychomotor Ability/performance changes for the late Phases (2 and 3) of skill acquisition.

By this point, it should be clear that Fleishman's notion (1972; Fleishman & Quaintance, 1984) that post-practice individual differences are *specific only to the criterion task* are contradicted by the current data (and, indeed, by the reanalysis of the original Fleishman data -- see Ackerman, in press). The major determinants of skilled performance individual differences are in fact tractable. In fact, when the task remains inconsistent (the VM condition), the ASVAB ability factors accounted for 25% of the performance variance at the end of Session 12, as opposed to only 18% at Session 1.

Simplex revisited

In many respects the quasi-simplex pattern of intertrial correlations during skill acquisition is a "red herring." The first problem in using the simplex pattern as a springboard towards theory of individual differences was the factorial indeterminacy outlined by Corballis (1965). If an infinite number of models are equally sufficient for fitting the data, the fact that a given theory (such as the one outlined in this paper) can predict a quasi-simplex structure, only results in very weak confirmatory support of the theory (Popper, 1963). The evidence most damning to dependence on these patterns, though, is not psychological at all. As Humphreys has noted (1985), the simplex pattern of correlations can be found in *any* individual differences data collected over several occasions. That is, the pattern is characteristic of repeated measures of intelligence or performance over time, just as it is characteristic of physiological measures of height and weight over occasions. Thus, there is nothing particularly special about the simplex patterns found in practice data, the patterns merely represent a general law of flux over time. Finally, use of two measures taken from within-task intercorrelations (i.e., rate of attenuation and stability) failed to directly reflect the task-dependent changes indicated in the ability/performance data. Part of the problem lies with the fact that individual differences variables other than those examined here (such as fatigue and motivation) affect session-to-session performance. Measures derived from within-task intercorrelations are simply too global to provide more than a rough index of the magnitude of change in <u>all</u> performance determinants over task practice.

CONCLUSIONS/FURTHER DIRECTIONS

Intelligence and Skill Acquisition

Does this theory answer the perennial question about whether intelligence represents the ability to learn? If the essence of learning is characterized as representing those processes underlying Phase 1, that is, formulation of production systems that allow a task to be performed, the answer is yes. However, if learning is defined by some achievement index (i.e., some final, asymptotic performance level attained), a more qualified answer is necessary. To the degree that the skill acquisition tasks discussed here are those within the ability repertoire of nearly all members of the subject population (albeit with different levels of initial performance), general intelligence does not limit final level of skilled performance. Instead, other, less general abilities determine individual differences at skill Phase 3. Thus, for the simple, consistent tasks that are often found in military and industrial settings, it should come as no surprise that job performance individual differences are only moderately correlated with General intelligence (Brown & Ghiselli, 1952; Ghiselli, 1966).

The abilities that predict performance in consistent tasks decisively change during skill acquisition. However, when tasks are not consistent, or are so complex to preclude initial successful performance, less attenuation of General Ability/performance correlations are predicted.

The theory and data presented here also point to potential solutions to the problems of predicting performance at various stages of task proficiency. An analysis of the major moderating influences of skill acquisition (namely consistency, complexity, and novelty/transfer) provides for predictions of what abilities limit performance during training. Coupled with evaluation of between-subject variability levels during training, this information can be further used to provide diagnostic information about (a) why subjects wash-out of training, and (b) what aspects of the training program are preventing (or facilitating) the normal phase transitions of skill acquisition.

Transfer and Abilities

A further question of interest regards the interplay between the acquisition of skills and changes in ability levels (Corballis, 1965; Ferguson, 1956; Alvares & Hulin, 1972). Previous discussions have been oriented to whether the underlying nature of the task changes or abilities of learners change with task practice. From the normative skill acquisition perspective, it is clear that as the learner transitions from Phase 1 to Phase 3, the character of information processing undergoes rather profound changes. How these changes feed back to ability changes is less clear.

The current theory indicates that different abilities are involved at each of the three stages of skill acquisition. Thus, one inference is that, for example, during Phase 3, any potential impact on the General ability will be minimal. Otherwise, ability transfer (i.e., increment in the ability in question) is expected to occur in parallel to the current Phase of skill acquisition. During Phase 1, successful formulations of efficient production systems will result in an increment in General ability. Phase 2 processing will result in increments to Perceptual Speed, and so on. When task training is given across all levels of skill acquisition, each of these ability classes are expected to show increments. However, given the broad nature of the

General ability, such increments may be relatively small. Although decisive experiments that address this issue are not available, cognitive training data (such as those of Pellegrino, 1983) are consistent with this inference.

Further linkages: Neurons and Intelligence

It is said that only rarely does the differential psychology approach lead back to insights into normative processes (Cronbach, 1957; Underwood, 1975). However, as quasi-neurological models of skill acquisition are developed and tested (e.g., James Anderson, 1982, Anderson, Silverstein, Ritz, & Jones, 1983; Schneider, 1985, Grossberg & Stone, 1986), the linkages established between abilities and information processing determinants of performance offer several sources of data for testing of normative models. In particular, sex differences in Perceptual Speed and Psychomotor Abilities found in the differential literature (e.g., Anastasi, 1982; Maccoby & Jacklin, 1974) provide one source of data that could be used to validate claims of the neurological bases for skill acquisition. Other differences, such as race and ethnic contrasts provide even more important sources of data for those researchers interested in remedial skill training (e.g., Frederiksen, Warren, & Rosebery, 1985). Finally, the vast literature pertaining to age-related changes in General, Perceptual Speed, and Psychomotor abilities point to functional distinctions that will allow for other tests of plausible neurological bases of information processing and learning (Horn, 1965, 1967, 1968). Such linkages appear capable of making good on the promise of progress from the unification of the "two disciplines of scientific psychology" (Cronbach, 1957).

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ABSTRACT

The hand grips of 18 male and 16 female subjects were studied to
determine the maximum, clockwise static torque that could be applied to
circular electrical connectors under six defined levels of interference
and four conditions of interference (types of obstruction) with and without
work gloves. The diameters of connectors tested were 0.9, 1.5 and 2.0
in., respectively. Torque strength and required separation were found
to be a function of level of interference, condition of interference,
connector size, and glove usage. Interference from an adjacent surface
to the right or below the grasped connector was less severe than inter-
ference from adjacent connectors to the left and right. The greatest
interference occurred when adjacent connectors were located to the right,
left, above and below the grasped connector. Large connectors permitted
greater torque and required less surface-to-surface clearance than small
connectors. The use of work gloves increased torque strength slightly
but required much larger clearances. Limitations in hand torque strength
and required clearances for exertion should be taken into account as ergono-
mic guidelines for maintainability.

1. INTRODUCTION

The maintenance of aircraft has become a major problem for the U.S.Air Force. It has been estimated that 35% of the life-cycle cost of military systems is spent for maintenance [1]. Physical and diagnostic demands of maintenance tasks have escalated rapidly with the growth in complexity of modern military aircraft. While computer-aided design presents the possibility of providing more maintainable aircraft, a lack of sufficient human factors data has prevented this approach until the present. Lacking human factors criteria, computer-aided design can magnify or proliferate rather than diminish maintenance problems by permitting hardware choices and configurations to be made rapidly with little regard for maintainability problems that may be encountered during the service life of aircraft. As a result of reduced time needed for aircraft design, ergonomic problems have increased in maintenance stemming from inadequate work space, restricted vision, and strength or body position requirements exceeding the capabilities of many maintenance personnel.

Therefore, representing the maintenance technician as a three-dimensional computerized model, showing anthropometric and strength limitation, is seen to be the most effective way to foresee maintainability problems in the design stage. Such a model would represent characteristies of male and female population data with respect to anthropometry, strength, material handling capability, and visual limitations. The development of this model, called CREW CHIEF, and the necessary supporting ergonomic data base for it is an ongoing project being carried out by the Armstrong Aerospace Medical Research Laboratory at Wright Patterson Air Force Base.

The CREW CHIEF model is complex in that many types of tasks and body configurations must be taken into account. Experience gained from the development of COMBIMAN [2,1], a biomechanical representation of a pilot used to evaluate cockpit design, and the outstanding success of this model were instructive and encouraging in planning CREW CHIEF. When fully developed, CREW CHIEF will represent the maintenance technician performing many basic tasks that constitute real maintenance tasks. Computer-aided design of aircraft will include these human limitations in maintenance work along with other physical and geometric constraints.

Overall requirements for CREW CHIEF were derived form a survey of ergonomic problems encountered by maintenance personnel. These problems included overstress injuries, inability to see, restricted mobility for lifting or gaining access to a component, inability to use tools effectively, and other related difficulties in working in cramped spaces. These problems were recorded and organized into defined categories suitable for a planned research program. The University of Dayton Research Institute (UDRI) was selected to coordinate and manage the overall development of CREW CHIEF. Other individuals and institutions have contributed research efforts in selected areas. It was apparent from the earliest phases that much supporting ergonomic data were unknown and would have to be obtained experimentally. Information was also needed on the effects of chemical defense clothing and gloves in maintenance work. The research effort to obtain basic ergonomic data to support CREW CHIEF was divided into a number of subtasks. The study of electrical connectors represents one of these selected areas.

The research described in this report is an extension, provided under a minigrant from the U.S. Air Force Office of Scientific Research, of work performed at Wright Patterson Air Force Base under the 1985 Summer Faculty Research Program in which the principal author participated as a research fellow. The 1985 study was intended to determine the maximum hand-grip torque for circular electrical connectors with no space restrictions in positioning the hand on the connector [3]. Independent variables included: connector size, grip type, connector orientation, use of gloves, connector height and direction of torque. One of the major unanswered questions at the conclusion of the study was the effect of additional surrounding connectors or other obstructions in forcing altered grip styles with resulting compromise in torque strength. The present study was designed to investigate this question for defined levels of interference and defined types of obstruction for a representative population of males and females who would qualify physically as Air Force maintenance technicians.

2. OBJECTIVES

The objectives of this study were as follows:

1. To define and quantify the relationship between hand-grip torque and the level of interference for six levels of interference.

2. To define and quantify the effects of interference by adjacent connectors to the right and left of the grasped connector, interference above and below as well as to the right and left of the grasped connector, and interference by a flat surface located to the right of or below the grasped connector.

3. To investigate the effects of wearing work gloves under the interference conditions indicated under objectives 1 and 2.

4. To develop a means of identifying behaviorally and specifying six levels of interference for the type of grip employed in exerting hand torque in confined spaces.

3. ELECTRICAL CONNECTORS AND MAINTENANCE

This study focused entirely on simulating the tightening of circular
electrical connectors. These devices are used to connect and disconnect
multi-wired electrical cables linking one electrical device to another
by means of a threaded, female connector ring that rotates onto a threaded,
male shaft, thereby forcing connector pins into their respective sockets.
The knurled ring is designed to reduce hand slippage. In addition to
the ring and cylindrical socket mounting assembly, the connector includes
a backshell that fits over the assembly behind the rotating connector
ring. This houses the cable connections entering the connector. It is
also knurled to permit holding while the ring is rotated. A cable clamp
with tightening bolts is used behind the backshell to provide rigid support
for the entering cable and its sheathing. The physical simulation of real
with simulated electrical connectors is presented in Fig. 1. Simulated
connectors made for use in the experiments consisted of knurled connector
rings and smooth backshells.

Figure 1 and its accompanying key describe the assembly of simulated
electrical connectors and a comparison between real and simulated connectors.
The subject applied clockwise static torque with the right hand to the
connector ring (part 5 in Figure 1A) which was coupled by slotted collars
(6 and 7) to the load cell (8). The collar (6) is an extension of the
connector ring itself. The lower collar (7) was connected to the torque
measuring shaft of the load cell. The shaft of the simulated backshell
(2) extended through the hollow threaded plug (4) used to hold the connector
ring on the torque measuring shaft and through the load cell. The shaft
was held in place by setscrew (9). Thus, no torque transmitted to the

backshell is transmitted to the load cell. The load cell was mounted

on an aluminum plate which could be raised or lowered to fit individual

subject heights (See Figures A8 and A9 in the Appendix).

Figure 1B shows the assembled simulated electrical connector. Figure

1C illustrates a real electrical connector shown as it is assembled by

rotating the female threaded connector ring (12) onto the male portion

(13) thereby forcing pins into their receptacles. Static torque measured

in the experiment was applied to connector ring (5) on the simulated connectors

to simulate static torque applied to the locking ring (12) on the real

connector.

In the 1985 study [3], simulation of cabling was omitted. Since

cabling can contribute to space constriction and possibly affect hand

torque, flexible plastic tubing was used to simulate cable entering the

backshell in the present study. This was provided on all connectors including

noninstrumented "dummy" connectors used to produce effects of crowding,

as well as on those connectors used to measure hand torque by means of

an attached load cell. The overall configuration is shown in Figures

A8 and A9.

.4. LITERATURE REVIEW

Only a few studies have been conducted on the measurement of hand-

grip torque strength. No published studies other than the authors' 1985

research (3) were found that involved the use of electrical connectors.

Results of other studies were found useful in suggesting a theoretical

basis for interpreting some of the findings and in suggesting future extensions

of the present investigation.

A. Simulated Connector
1. Polyvinyl tubing to simulate electrical cable.
2. Aluminum simulated backshell (3 sizes).
3. Special driver used to attach connector ring by means of plug (2).
4. Threaded hollow plug for attaching simulated connector ring.
5. Simulated connector ring (3 sizes).
6. Slotted roller on simulated connector ring.
7. Notched collar on load cell (receives torque from connector ring).
8. Torque measuring load cell (not to scale).
9. Screw to hold backshell shaft.

B. Simulated connector shown assembled and attached to load cell.

C. Real Connector
10. Electrical cable (covered conductors inside sheath).
11. Backshell.
12. Connector locking ring (with female threads).
13. Receptacle or make half of connector with insert sockets for pins.

A   B   C
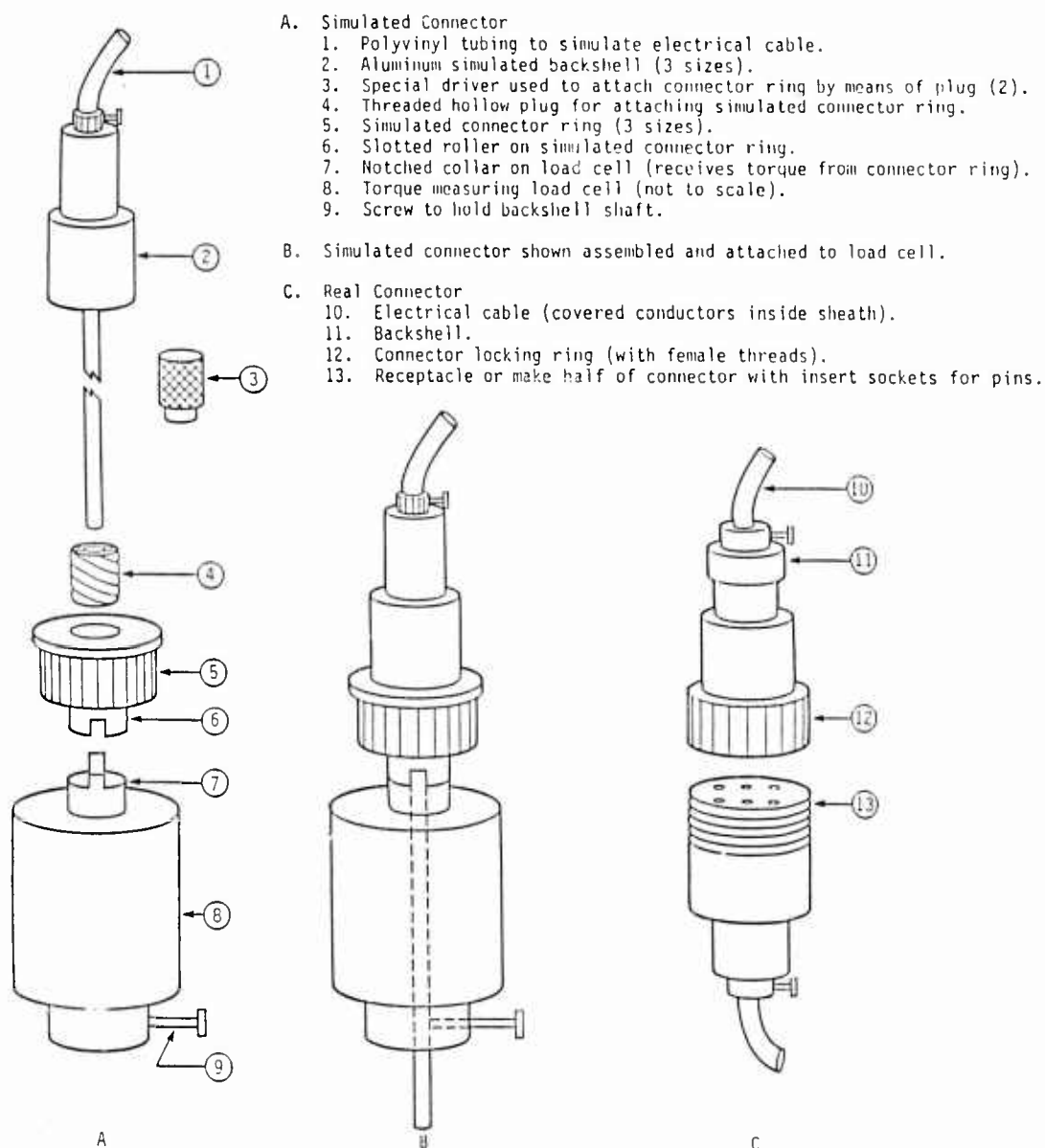
Fig. 1. Simulated connector assembly (A), assembled (B), and real
electrical connector (C).

2-7

The need for computer-aided design models to support ergonomics in equipment design has been expressed in a number of publications [1,2,4]. The development of the CREW CHIEF computer-aided design model of an aircraft maintenance technician is of particular interest for maintainability [1]. When completed, this model will provide an aircraft or missile system designer with the ability to simulate maintenance operations and to predetermine limitations imposed by technician anthropometry, mobility, strength, and visibility under defined field conditions. The present study is one of many that will provide the ergonomic data needed as a basis for development of the CREW CHIEF model.

A recent study of hand torque strength using smooth, phenolic cylindrical handles with diameters from 0.95 cm to 8.89 cm was reported by Replogle [5]. A theoretical model for predicting torque as a function of handle diameter, gripped area, and relative grip force (proportional to gripped circumferential angle) was proposed. Torque strength was found to increase with the square of the handle diameter up to about 2.5 cm (grip span diameter), then increased at a decreasing rate beyond that diameter up to a maximum at about 5 cm. Maximum torque was found to be approximately 1.5 times the torque exerted on the 2.5-cm diameter handle. Female torque strength was found to be approximately 40% of male strength. Grip span and maximum torque diameters did not vary greatly between males and females. Replogle's study proposes functional relationships among variables that affect grip strength all of which should be investigated further. Pheasant and O'Neill [6] conducted a study of screwdriver handles and the effect of size (diameter), shape, and quality of interface upon grip torque strength. They also made torque strength comparisons between the various screwdriver handles and

smooth and rough steel cylinders. Handle shape was found to be unimportant. Handle diameter and the quality of interface (affected by friction and contact area) were important. Maximum torque occurred at a diameter of 4 cm. Recommendations included the maximizing the hand and handle contact area and using of a 5-cm-diameter, knurled cylindrical handle as a basic simple design.

Swain, Shelton, and Rigby conducted an experiment to determine the maximum torque generated by men who were standing while operating small, diamond-shaped, knurled knobs [7]. The knobs were 3/8 in., 1/2 in., and 3/4 in. in diameter. Subjects represented civilian and military nuclear maintenance personnel. Work height was a tabletop level, approximately 29 to 30 in. above the floor. Tests were performed barehanded and with work gloves (wool inserts and an outer leather shell), from the front and from the right side (the edge of the panel holding the knob toward the subject). Torque was found to increase with knob size, to be consistently lower when gloves were worn, and to be greater for side grasping than front grasping. Overall mean torque was approximately 10 in.-lbs for the 3/4-in. knob, 5.6 in.-lbs for the 1/2-in. knob, and 4.3 in.-lbs for the 3/8-in. knob. Standard deviations for the three knob sizes were approximately 2.3, 1.2, and 1.1 in.-lbs, respectively. Fifth percentile maximum torque limits recommended for the three knob sizes were 5.6 in.-lbs for the 3/4-in. knob, 3.5 in.-lbs for the 1/2-in. knob, and 2.8 in.-lbs for the 3/8-in. knob. These limits include allowances for the use of gloves. Of the published studies surveyed, Swain's was the closest to the present study in its objectives, procedures, and experimental conditions.

Rohles, Moldrup, and Laviana investigated the jar opening capability of elderly men and women [8]. Eight common sizes of jar lids were tested, ranging in diameter from 27 mm to 123 mm (1 in. to 4.8 in.). Torque values for men ranged from (0.5-1) to (3-11) N-M or (4.4-8.8) to (26-97) in.-lbs for the smallest and largest diameters, respectively. Torque achieved for the largest diameters in this study exceeds any observed in the present study. This is very likely to be the result of the fact that the 123-mm lid (4.8 in.) was considerably larger than the largest simulated connector used (2.0 in.). Orientation of the hand and arm (palm downward) may also have provided an advantage to subjects in the Rohles study.

The effect of hand-grip span upon isometric strength and strength endurance was investigated by Petrofsky et al. [9]. An optimum hand-grip length was found to exist for each subject. On the average, this was approximately 5 to 6 cm (2 to 2.4 in.) for males and females. Endurance in exerting a given percentage of maximum grip was the same: between 80% and 90% of maximum grip for the optimal grip span, a 4.4 cm span and a 6.6 cm span. At 30% of r   grip, the 6.6 cm and optimum grip span resulted in a higher endur   than the 4.4 cm span. Endurances ranged from 40 seconds at 70% to 360 seconds at 30% of maximum grip. Maximum grip was defined as the stronger of two 3-sec exertions separated by a 3-min rest interval. This interval was also used between exertions throughout the experiment. Results of this study tend to support those of the present research in areas concerning the relationship between grip strength (which directly affects contact force needed to exert hand torque) and grip length (corresponding to the size of the connector ring).

The procedures used for measuring maximum, voluntary hand-grip torque in the present investigation were based on those recommended by Caldwell and others [10] with slight modifications. This method produced results that were consistent throughout the data and could be compared with the results of the other studies cited.

A recent study by Mital and Sanghavi [11] compared maximum voluntary torque using five different types of hand tools. Males and females performed torque exertions in seated and standing positions. Females were approximately 66% as strong as males. Height of application for a given posture, as well as the angle of the forearm, had little or no effect on torque strength.

Leveraging effects produced by the five different tools (short and long screwdriver, socket wrench, spanner (crescent) wrench, and adjustable vise-grip) resulted in significantly different torque capabilities. The mean torques for socket wrench, spanner wrench, and vise-grip were 284 kg cm, 241 kg cm and 213 kg cm respectively, while those for the long and short screwdrivers were only 28 kg cm and 32 kg cm. For screwdrivers, torque was found to be a function of grip size, while for wrenches, torque was a function of the resulting lever arm. Torque capability also varied with wrench type for a given leverage. Higher torques were produced in a sitting posture for screwdrivers and in a standing posture for wrenches. Isometric shoulder strength was found to limit hand torque strength.

The effects of knife handle design upon four directions of hand force and two directions of hand torque were investigated by Cochran and Riley [12]. Nine handle shapes were employed. Handle shape produced significantly different torque strengths in all cases. Except for a square cross-sectioned handle, torque was a function of the maximum moment arm created by the

distance from the outermost point on the handle cross section to the center

of the handle cross section.

5. INSTRUMENTATION

5.1. Measuring and Recording System

Instrumentation for the main experiment included the following items:

> load cell (torque measuring)
> bridge amplifier
> analog to digital converter
> digital computer
> printer signal tone generator
> test signal generator.

The system diagram for the instrumentation used in the experiment is given
in Fig. 2. Details pertaining to specific items used are as follows:

> Load cell--Lebow Model 2102, 200 in.-lb capacity, small flanged reac-
> tion torque sensor with single bridge manufactured by Eaton Corp.,
> Physical Measurement Products, 1728 Mapletown Road, P.O. Box 1089,
> Troy, Mich. 48099.

> Bridge amplifier--Accudata 218 bridge amplifier with signal conditioning
> and gauge control features manufactured by Honeywell Test Instruments
> Division, P.O. Box 5227, Denver, Colo. 80217.

> Analog to digital converter--Tecmar PC-Mate Lab Master manufactured
> by TECMAR, INC., Products Division, 6225 Cochran Road, Solon (Cleveland),
> Ohio 44139-3377.

> Digital computer--Compaq portable computer manufactured by Compaq
> Corp., P.O. Box 30, 19515 FM149, Houston, Texas 77070.

> Printer--Microline model 193 manufactured by OKIDATA, Inc., Japan.
> Signal generator--standard 9V tone generator. Test signal generator
> (for load cell)--this consisted of two 40 K-ohm resistors in series
> (80 K-ohm) mounted in parallel with the single bridge load cell.

5.2. Simulated Electrical Connectors

A set of three simulated connectors was designed to provide an effec-

tive method of accurately measuring hand torque strength using a muscular

effort closely matching that required to tighten similarly sized electrical

connectors. Each simulated connector consisted of a knurled aluminum
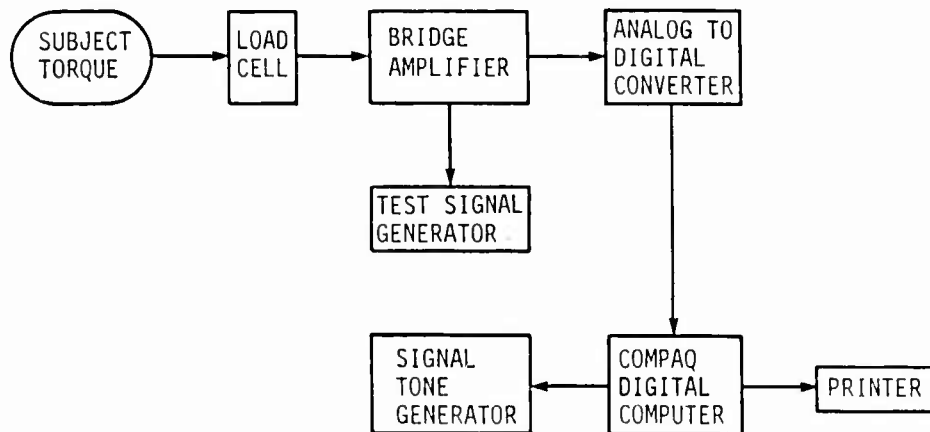
Fig. 2.   Instrumentation system.

ring and backshell. The three sizes chosen were typical of many actual connectors. They also provided for a representative set of hand grip styles by the subjects as well as an opportunity to investigate the effect of connector size upon hand torque strength. A solid aluminum backshell with a steel shaft was designed for each connector ring to simulate the backshell and attached cable on actual connectors. This facilitated full and fingertip grasping by fulfilling the requirement that the hand be positioned over or to the side of the simulated connector, since a cable prevents the hand from covering the backshell on an actual connector. The three simulated torque rings and backshells are shown in Figs. 1b and 1c. Detailed design features of the simulated connectors are given in Figs. A-1 through A-6 in Appendix A.

The torque rings were designed with a common inner diameter and a female-keyed slot that fit a male-keyed shaft where the load cell was mounted. The torque rings were attached using a common, threaded plug that was inserted into the ring and rotated to engage the thread on the shaft, where the load cell was mounted. This was slotted at the end so that it could be tightened and loosened quickly using a specially designed cylindrical driver with a key to fit the slot. The backshell shaft extended through the hollow shaft, where the load cell was mounted and through the load cell to the back of its mounting where it was held in place by means of a threaded screw key. This arrangement prevented any torque, which was applied to the backshell, from being transmitted to the load cell, so that all torque was measured with reference to the knurled connector ring (See Fig. 1).

In the present study, the effect of cabling was included by means of mounting 10-in. lengths of flexible plastic tubing on the backshells of simulated connectors grasped by the subjects and also "dummy" connectors (noninstrumented) used to simulate interference from adjacent connectors of the same size.

5.3. Simulated Maintenance Task Difficulty

Many factors contribute to anthropometric and biomechanical problems in aircraft maintenance. These relate to the interface among the technician, task, tools, and work space. One factor that significantly increases the difficulty of attaching or detaching electrical connectors is the space restriction around connectors caused by close grouping or by having connectors located close to a surface. The primary objective of this research was to investigate the effect of crowding from connectors or from adjacent surfaces upon maximum hand torque strength. This was done by defining six levels of grasp interference in terms of observable, behavioral criteria that could also be verified by reported subject perceptions. These were described to subjects as they were instructed in the experimental task and were verified by observations, as well as by reported experience of every subject during the experiment. Specific intervals of clearance between levels of interference varied from subject to subject because of varying hand anthropometry among subjects. This was done in order to standardize the level of difficulty for each subject and to determine average intervals at which subjects experience similar difficulties. The use of fixed intervals of clearance would have made the effect of a given clearance on torque strength more difficult to determine since

subjects with small hands would experience no interference while subjects

with large hands would experience severe interference for the same clearance.

In the analysis, levels of interference were defined in terms of clearance

and torque strength. The levels are defined as follows:

LEVEL OF INTERFERENCE	CRITERION AND DEFINITION
1-Unobstructed	Criterion: No noticeable interference with full grip (full wraparound grasp). Definition: No perceptible contact with surrounding obstacles by any part of the hand while exerting static torque using a full wraparound grasp.
2-First noticeable	Criterion: First detectable interference with full grip-first contact with obstruction. Definition: First noticeable contact between the hand and surrounding obstacles while exerting static torque using a full grip. This usually occurs on the dorsal side of a metacarpal-phalangeal joint.
3-Moderate obstruction for full grip	Criterion: Very noticeable interference with full grip--some compromising necessary on full wraparound grasp. Definition: Very noticeable contact interference when using a full grip. Reconfiguration of the hand is necessary because of contact inter-ference on the dorsal side of one or more metacarpal-phalangeal joints.
4-Loss of full grip	Criterion: Grip forced to change to fingertip grasp Definition: Full grip replaced by fingertip grasp. Only a grip between the fingertips (usually the first and second digits, sometimes assisted by the third) is possible. No contact or slight contact between the proximal inter-phalangeal joints and surrounding obstacles occurs when using a fingertip grasp.
5-Moderate obstruction for fingertip grip	Criterion: Very noticeable interference with fingertip grasp Definition: Very noticeable contact interference between the digits and surrounding obstacles while exerting static torque. Interference typically occurs at the proximal interphalangeal joints, limiting their flexion.

6-Limit of fingertip
 grip

Criterion: Minimum clearance for which a finger-
tip grasp is possible.
Definition: Minimum clearance for which grasping
between the distal phalanges of the first and
second digits can be maintained during static
torque. There is practically no flexing of
the proximal interphalangeal joint on the first
and second digits.

These clearances assume only slight incremental rotation of the hand or
fingers necessary in applying static torque. They do not assume large
loosening or tightening movements. Clearances were defined as the perpendicular
or normal separation between the adjacent surface at the farthest obstruction
(connector or flat surface) causing interference and the surface of the
grasped connector ring. They were provided by adjusting the position
of obstructing connectors or flat surfaced plate.

Four conditions or types of interference were used. These included:

1. Interference from adjacent connectors located to the right and
   left of the grasped connector (0 and 180 degree positions)

2. Interference from adjacent connectors located to the right and
   left and also at the top and bottom of the grasped connector
   (0, 90, 180, 270 degree positions) (Fig. A.8, Appendix A)

3. Interference from a flat surface located to the right of the
   grasped connector (Fig. A.10, Appendix A)

4. Interference from a flat surface located below the grasped con-
   nector (Fig. A.11, Appendix A).

In this study, a full grip refers to a wraparound grasp using the
thumb and forefinger. (A few subjects with small hands were able to partially
employ the middle finger.) A fingertip grip refers to grasping between
the surfaces of the distal phalanges of the thumb and forefinger. (A few
subjects with small hands were able to partially employ the middle finger.)
An illustration of a subject in the grasping position is given in Figure
A-9, Appendix A.

2-17

6. METHOD

6.1. Experimental Design

The basic objective of this study was to determine the effect of obstructions in the form of adjacent electrical connectors upon grip torque strength in tightening a circular electrical connector. The dependent variable is hand-grip torque strength measured as static torque in inch pounds. Independent variables are as follows

1. Level of Interference

   Six defined levels of interference were measured in terms of minimum normal distance between the grasped connector and the farthest surface causing interference.

2. Condition or Type of Interference
   Four obstruction configurations (referred to as conditions) include:

   - Interference by a connector on the right and left of the grasped connector

   - Interference by a connector on the right and left, above and below (Fig. A.8, Appendix A)

   - Interference from a flat surface obstruction to the right of the grasped connector (Fig. A.10, Appendix A)

   - Interference from a flat surface obstruction below the grasped connector. (Fig. A.11, Appendix A)

3. Gloved Effects

   Two conditions (no gloves and work gloves)

4. Connector Size

   Three sizes (0.9, 1.5, and 2.0 in. diameter)--connector height was kept constant at 60% of maximum reach height. Connector orientation was in front of the subject for all tests. Torque direction was clockwise throughout the experiment.

6.2. Subject Selection and Orientation

Subjects were volunteer graduate and undergraduate students attending Iowa State University during a summer session. The experiment was planned

2-18