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ABSTRACT

Prepared as part of a larger work on human intelligence, this report examines basic attentional and perceptual contributions to intelligence. The report is organized into two sections: the first summarizes and evaluates research that has tried to uncover basic information processing skills that account for individual differences in intelligence; the second considers the possibility that more flexible aspects of cognitive functioning might make more substantial contributions to individual differences in intelligence than do basic information processing skills. The report concludes with a general evaluation of the research reviewed and an outline of promising directions for future research in the area. (FL)

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ATTENTION, PERCEPTION, AND INTELLIGENCE

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Attention, Perception, and Intelligence

Lynn A. Cooper and Dennis T. Regan

Our goal in preparing this chapter has been to isolate basic attentional and perceptual contributions to intelligence. Relating the concepts of "attention," "perception," and "intelligence" at either empirical or theoretical levels has not been an easy task. The notion that attentional and perceptual capabilities might determine in significant ways overall intellectual ability has been alive since the early days of systematic intelligence testing (see, for example, Spearman, 1927; Thurstone, 1938). And, this same view has been one of the essential premises underlying the recent and much heralded unification of cognitive and differential approaches to the study of human intelligence (Carroll, 1976).

Nonetheless, providing a synthesis of these three psychological concepts has been difficult, at best. One problem that we have encountered is the lack of consensus in either the cognitive or the differential literature concerning the meaning of the concepts of "attention," "perception," and "intelligence." A discussion of alternative conceptualizations of the nature of attention, perception, and intelligence within cognitive psychology is beyond the scope of this paper. Suffice it to say that some theorists have regarded attention as a filtering mechanism (e.g., Broadbent, 1958) while others make reference to a limited-capacity pool of information-processing resources (e.g., Norman & Bobrow, 1975). Still others view attention as skill, modifiable through practice (e.g., Neisser, 1976). The nature of perception is also a matter of some debate, with one approach emphasizing the direct pick-up of environmental information (e.g., Gibson, 1966), and other approaches regarding perception as the outcome of a sequence of internal information-processing stages (e.g., Rumelhart, 1977). The nature of intelligence is probably the most controversial of the three concepts, and Sternberg (this volume) summarizes alternative attempts at a definition.

The view of the human organism that we adopt (and one that is currently popular within cognitive psychology) is of a system for processing and transforming environmental information, with component subprocesses being highly interactive and interdependent, rather than strictly sequential and independent. This interactive view of the information-processing system poses another problem for any analysis of attentional and perceptual contributions to intelligence. Under this account, it is difficult to isolate just where in the information-processing sequence attentional and perceptual factors most significantly influence intelligent behavior and where "higher-level" cognitive and memorial factors begin to provide more powerful contributions to intelligence.

We have not attempted to solve these problems in this paper. Rather, our strategy has consisted of carefully delimiting the areas of research and theory that we consider. For purposes of the present discussion, we have regarded as essentially synonymous "intelligence" and measures of ability on which individuals differ. We have defined "attentional" and "perceptual" operations as those lowest-level processes that might contribute to such ability differences. Our discussion necessarily includes reference to certain cognitive operations that might not traditionally be regarded as attentional or perceptual in nature. However, we have tried to avoid consideration of issues that clearly involve higher-level operations such as learning and problem-solving.

The overall structure of the chapter contains two major sections. In the first, we summarize and evaluate research that has tried to uncover basic information-processing skills that account for individual differences in psychometric measures of ability. This work is the product of the recent effort to link cognitive and differential approaches to the study of individual differences in intelligence. We conclude that this attempt to isolate information-processing correlates of ability differences has met with mixed success. In particular, information-processing measures that do distinguish more from less able people often account for only a small portion of the variance in the ability differences. In the second major section of the chapter, we consider the possibility that more flexible aspects of cognitive functioning may make more substantial contributions to individual differences in intelligence than do basic information-processing skills. The additional sources of individual differences that we consider in this second section include strategies--or procedures for organizing cognitive processes--and attentional factors.

We conclude with a general evaluation of the work that we review, and we outline what we see as promising and productive directions for future research.

Basic Information-Processing Skills Underlying Psychometric Measures of Ability

It is a generally accepted view in cognitive psychology that ability or intelligence reflects both a person's knowledge of the world and some more basic, general set of skills for processing information that does not depend on the content of the information being processed. Much of the thrust of cognitive psychology's recent interest in intelligence has been directed toward isolating these basic processing skills and determining the extent of their relationship to traditional psychometric measures of ability. The nature of the question that the cognitive psychologist wishes to ask is put nicely in the title of a pioneering paper by Hunt, Lunneborg, and Lewis (1975)--"What does it mean to be high verbal?" That is, "what does it mean" in the sense of what might be the nature of the basic information-processing skills that distinguish lower scorers from higher scorers on tests of verbal ability?

In this section, we review and evaluate a selected set of recent experiments designed to uncover correlations between information-processing skills, seemingly related to attentional and perceptual mechanisms, and measures of ability. The plan of the section is as follows: First, we discuss several studies on the relationship between some information-processing tasks and measures of verbal ability, pointing out differences in the adequacy of the approaches of various types of investigation. Second, we provide a similar analysis of studies of the component processess underlying measures of reading ability. Third, we discuss in essentially the same way the nature of the information-processing skills that may be related to spatial ability. Finally, we attempt to synthesize the salient and replicable results of these investigations, and we provide an evaluation of the success of this general approach to studying human intelligence.

Verbal Ability

One rather obvious strategy for exploring the relationships among information-processing skills and ability measurements might involve isolating a sample of subjects that differ in measured ability and then testing these subjects on a series of information-processing tasks. Measures of performance on the information-processing tasks could be derived, and then these performance measures could be correlated with the ability measurements. The hope, using this sort of approach, is that the pattern of correlations among the task performance measures and the ability measures might yield some coherent picture of just what aspects of which tasks are most strongly related to ability differences. Such an interpretable pattern of correlations might, in turn, help to uncover the basic processing skills that underlie ability.

As an example of this sort of research strategy, consider a series of studies by Lunneborg (1977). In these experiments, subjects were tested on a variety of psychometric instruments, and they were then tested on a variety of information-processing tasks, many of which used response time as the dependent variable of interest. Correlations among the processing measures and the psychometric measures were then computed. Of chief concern ~~to~~ Lunneborg was the extent of the possible relationship between choice reaction time (presumably a reflection of processing speed) and the ability measures. Unfortunately, the results are difficult to interpret. In one study, the correlations of choice reaction time with ability measures were reasonably high (between -.55 and -.28, with faster times being related to higher measured ability), but these correlations virtually disappeared in two subsequent experiments. Had the pattern of correlations been consistent across experiments or within an experiment across sets of information-processing and ability measures, then undoubtedly more could have been learned from this study. What seems lacking in this approach is an attempt to specify just what information-processing skills the laboratory tasks are measuring and which such skills might be components common to a variety of the tasks. With a theory of the information-processing components of laboratory tasks as a guide, a selection of tasks with theoretically meaningful and, hopefully, shared components could be made, and predictions could be generated concerning relationships between the information-processing measures and the ability measures. What is clear from this study is that there is no guarantee that such a theory will fall out of the pattern of correlations among many tasks and many ability measures. In a subsequent experiment using much the same approach, Lunneborg (1978) did find more interpretable patterns of relationships among ability and information-processing measures. In this case, significant correlations between performance IQ and visual and nonlinguistic processing measures were found, while vocabulary and verbal IQ scores appeared to be more strongly related to measures of linguistic flexibility and reading time.

A somewhat more satisfying approach to investigating the relation between information-processing skills and measures of ability is illustrated by some of the experiments reported by Hunt et al. (1975; see also Hunt, Frost, & Lunneborg, 1973). Their basic notion was that tests of verbal ability provide direct measures of verbal knowledge (e.g., meaning of words, size of vocabulary, rules of syntax) but only indirect measures of content free information-processing efficiency. Nonetheless, high scoring and lower scoring groups of subjects might differ reliably in the speed and efficiency with which they carry out basic information-processing tasks. The subjects in Hunt et al.'s studies were University of Washington students who scored in the upper quartile ("high verbals") or lower quartile ("low verbals") on a composite verbal ability measure from a standardized test administered to high school juniors. The laboratory tasks on which these subjects were tested involved a variety of more or less "standard" information-processing paradigms. The interesting point about Hunt et al.'s selection of tasks was that they represented an effort by the investigators to specify in advance what the information-processing demands of the tasks might be. Thus, the investigators had a basis for predicting on which tasks the high verbal subjects should excel, and, further, for analyzing the nature of the information-processing skills that might lead to more efficient performance. One might quarrel both with Hunt et al.'s analysis of the information-processing tasks and, particularly with their claims concerning processing skills common to various tasks. For, Hunt et al. provide no external evidence for the relationships among the processing variables which they hypothesize are related. Nonetheless, this approach goes beyond the purely correlational method in attempting to specify in advance the information-processing skills underlying performance on the laboratory tasks.

For purposes of our analysis, only two of the tasks used by Hunt et al. will be considered at length. We describe these experimental paradigms in some detail, as they have been used extensively in the work of others to be discussed in later sections. The first task was based on a procedure orginally intorduced by Posner and Mitchell (1967) and Posner, Boies, Eichelman and Taylor (1969). The paradigm involves presentation of two letters which are identical in both name and type case (A,A), identical in name but not in case (A,a), different in name but not in case (A,B) or different in both name and case (A,b). In one standard version of Posner et al.'s (1969) procedure, subjects are shown such letter pairs and are required to respond "same" as rapidly and accurately as possible if the two letters share a common name. Otherwise, the required response is "different." Of central interest is the difference between the time taken to respond "same" when the letters are identical in name only (A,a) and the time to respond "same" when they are physically identical (A,A) as well. The average difference in response time between name identical (NI) and physically identical (PI), or the NI-PI difference, is on the order of 70 milliseconds when groups of college students are tested as subjects (Posner et al., 1969).

One standard interpretation of this reaction-time difference is as follows: In the case of NI trials, the name associated with each visual pattern must be retrieved from memory in order to respond "same." Thus, the NI-PI difference is a measure of the additional time needed to access the name of a letter code in memory. Variations on the standard Posner procedure--which themselves produce reliable NI-PI differences--include instructing the subject on separate blocks of trials to respond "same" on the basis of physical identity only or name identity only, and measuring the speed with which a deck of cards containing letter pairs can be sorted into "same" and "different" piles under physical identity or name identity instructions. In the Hunt et al. study, both the standard paradigm and the card-sorting modifications were used.

The results that Hunt et al. (1975) obtained for the letter matching task can be summarized as follows: For both the standard reaction-time version of the task and the card-sorting variant, high verbal subjects exhibited a smaller difference between NI and PI trials than did low verbal subjects. The magnitude of the NI-PI difference was about 64 milliseconds

seconds for high verbals, and 89 milliseconds for low verbals. (In subsequent work by Hunt and his colleagues, reviewed in Hunt, 1978, the magnitude of the NI-PI difference has been found to increase substantially when groups spanning a wider range of measured ability are tested, e.g., the NI-PI difference is as large as 310 milliseconds for mildly mentally retarded school children.) Hunt et al. interpret this finding as indicating that high verbals have relatively faster access to overlearned material (letter names) in memory than do low verbals, and that this faster memory access to name codes is a basic information-processing skill that underlies verbal ability.

There are some potential problems with this interpretation, though, that plague not only the Hunt et al. study but also the work of other investigators to be reviewed later. First, although the interaction between level of verbal ability and type of letter-pair identity was indeed statistically significant, it is nonetheless true that high and low verbal subjects differed in mean response times on physically identical trials as well as on name identical trials. (In the case of the standard reaction-time task, high verbals were about 18 milliseconds faster than low verbals on PI trials, and the difference was about 44 milliseconds on NI trials.) The problem here is that the entire NI-PI difference between high and low verbal subjects cannot necessarily be attributed to differences in the efficiency of memory access. In addition, there may be general speed factors or differential speed of pattern-matching processes that contribute both to the differences in measured ability and reaction time.

A second problem with the Hunt et al. (1975) interpretation lies in the empirical basis for their claim that the NI-PI difference is an index of efficiency of memory retrieval of overlearned codes. In order to establish that speed of memory access, and not some other factor, really is an information-processing skill correlated with verbal ability, it would be desirable to show that individuals with small NI-PI differences (fast memory access) also show small reaction-time differences in some component of another information-processing task, where that component is also assumed to be an index of efficiency of retrieval of overlearned material. What this amounts to is establishing construct validity via an individual differences analysis for processing components of tasks for which those components are assumed to be related. If such construct validity can be established, then the meaning of a relationship between processing time and measured ability is more readily interpretable. Hunt et al. do not provide such an analysis of relationships among processing components in similar tasks.

The second task of interest used by Hunt et al. (1975) was a modification of the "sentence-picture verification" paradigm introduced by Clark and Chase (1972). In this paradigm, the subject is first shown a sentence describing a spatial relation between two elements (e.g., "star" or *, and "plus" or +). The relational terms used in the initial description may contain either the words "above" or "below," and the description may or may not contain a negative. This yields four basic sentence types in the initial descriptions--"star above plus," "star not above plus," "star below plus," and "star not below plus." Following presentation of the sentence, a test picture is presented which contains either the configuration $\overset{+}{*}$ or $\overset{*}{+}$. The subject must respond as rapidly and accurately as possible whether the initial sentence is "true" or "false" of the test picture. In the modification used by Hunt et al. (1975), two measures of response time were obtained--the time the subject needed to encode or comprehend the initial sentence and the time needed to verify that the sentence was true or false of the picture, which was presented as soon as the subject indicated that encoding of the sentence was complete.

There are a number of theoretical analyses that have been offered of the processes underlying performance on this task which we will consider in detail later (e.g., Clark & Chase, 1972; Carpenter & Just, 1975; Glushko & Cooper, 1978). For now, let us consider only the general analysis offered by Clark and Chase (1972) and by Hunt et al. (1975). When the initial sentence is presented, the subject encodes it by forming an internal representation that will subsequently be compared with the picture. A number of investigators have suggested that this internal representation is linguistic in nature and that the time it takes to form the representation is affected by the linguistic complexity of the sentence (see Clark & Chase, 1972; Trabasso, Rollins, & Shaughnessey, 1971). Furthermore, both the presence of a negative term and the presence of a "marked" form of a spatial comparative (in this case, "below" as opposed to "above") are thought to increase linguistic complexity and hence to increase encoding time. Clark and Chase propose that the internal representation of the picture to be compared with the representation of the sentence is also linguistic in nature.

Hence, we might expect that the test picture will be converted into a representation similar to that of the initial sentence and that processing time for verifying that the picture is true or false of the sentence will be affected by the same linguistic variables that affect encoding of the sentence. If this analysis of the task is correct, then differences between the times to encode or to verify more or less complex sentence types measure the speed with which a subject can convert the sentence or picture stimulus material into a linguistic internal representation and then perform the comparison.

Hunt et al. found no effects of linguistic markedness, but they did find both a significant effect of negation and a significant interaction between the size of the negation effect and verbal ability. High verbal subjects took about 55 milliseconds longer to encode sentences containing a negative than sentences without a negative, and this difference rose to about 100 milliseconds for low verbal subjects. The size of the negation effect differed across ability levels in the case of decision times also. High verbals required about 70 additional milliseconds to compare a negative sentence with a picture; and low verbals required an additional 120 milliseconds to make the same comparison. The investigators interpret the differential size of the negation effect for different levels of measured ability as follows: The larger difference in time to encode or comprehend negative than affirmative sentences for low verbal subjects could reflect a superior ability in the high verbals to convert a complex sentence into a corresponding internal representation. The difference between high and low verbals in the size of the negation effect for decision latencies could reflect a superior efficiency in comparing a picture against a complex internal representation for the high verbal subjects.

We can question the interpretation of these results along much the same lines as we did the interpretation of the results of the letter-matching task. First, the differential size of the negation effect could simply derive from a general tendency toward faster processing in the high verbal subjects. From the way in which Hunt et al. present their data, it is not possible to determine whether the two ability groups are approximately equivalent in speed of encoding and/or comparing an affirmative sentence or whether the high verbal subjects excel in this base condition as well as in their relative sensitivity to negation. Second, the interpretation of the pattern of differences is tied to a particular theoretical analysis of the operations involved in the sentence-picture verification task. And, Hunt et al. provide no evidence for the validity of the assumed underlying processes in that they do not show that individuals with relatively small negation effects also show small reaction-time effects in other tasks that are presumed to measure the efficiency with which more or less complex internal representations are encoded and compared against test stimuli. The general thrust of this second objection---that an interpretation of performance differences is critically dependent on the adequacy of one's theory of the processes underlying a given information-processing task--will become quite important when we consider later further work that Hunt and his colleagues have done on an analysis of the relationship between patterns of ability and patterns of performance in the sentence-picture verification situation (MacLeod, Hunt, & Mathews, 1978; Lansman, Note 1).

We conclude our discussion with an examination of what we consider two "model" sets of experiments on basic information-processing correlates of verbal ability, one by Chiang and Atkinson (1976) and one by Keating and Bobbitt (1978). The appealing feature of these studies is that the investigators attempt to demonstrate empirically the assumed theoretical relationships among component processing parameters of various cognitive tasks. This is accomplished by correlating individual subjects' values of parameters from models of the tasks across different tasks and within the same task. The pattern of correlations is inspected to determine whether there is adequate support for the theoretical analysis of the tasks (i.e., whether parameters which, theoretically, ought to be related are related empirically). Having established such construct validity for the processing parameters of the tasks, correlations of these parameters with psychometric measures of ability are then obtained to determine which basic information-processing skills relate to differences in ability.

In the Chiang and Atkinson (1976) study, the subjects were Stanford University undergraduates whose verbal and math scores on the Scholastic Aptitude test were available. The information-processing tasks on which the subjects were tested were a memory search task (Sternberg, 1966) and a visual search task. (A test of digit span was also included, but we will not consider the results here.) In the memory search task, the subject is presented a set of from one to five items (letters), followed by the presentation of a test letter. The subject is required to report as rapidly and accurately as possible whether or not the test letter is contained in the set of letters in memory. Generally, the amount of time to make the response increases linearly with the number of items in the memory set (Sternberg, 1969). This linear reaction-time function (along with other aspects of the data usually obtained with this procedure) is taken as evidence that subjects perform the task by sequentially comparing the test item to each item in the memory set before making a positive or a negative response. The slope of this reaction-time function provides an estimate of the time required for each memory comparison, or the rate of scanning items in memory. The intercept of the reaction-time function reflects all other processes not involved in memory search---viz., encoding the test item, determining whether a match has been found, and executing the appropriate response.

The component processing operations in the visual search task are theoretically related to those in the memory scanning task. In the visual search paradigm, a single target item is presented first, followed by a display of from one to five items. The subject is required to search the display set and to determine as rapidly and accurately as possible whether the target is contained in the display set. As in the memory search task, it is generally found that reaction time increases linearly with the size of the set of visual display items (Atkinson, Holmgren, & Juola, 1969; Estes & Taylor, 1964, 1966). The slope of this function is thought to reflect the time for each comparison of the target item with each display set item and also the time to encode each item in the visual display. The intercept parameter in the visual search task is taken as a measure of the time to make the "yes" - "no" decision and the time to execute the response.

Chiang and Atkinson (1976) estimated the intercept and slope parameters for each of their individual subjects for both the memory search and the visual search tasks. When the individual subjects' parameter values were intercorrelated, a compelling pattern emerged. Correlations between the intercepts of the two tasks and the slopes of the two tasks were high (.968 and .832, respectively). However, there was virtually no correlation between the intercepts and the slopes within each task. That is, subjects who are characterized by rapid search rates manifest this skill in both memory and visual search conditions, and subjects who encode efficiently do so in both experimental situations. Furthermore, the lack of correlation between intercept and slope parameters in the same task shows that the correlation of parameters across tasks is a reflection of more than simple, general processing speed. For, a general speed factor should show up in a correlation of intercept and slope parameters, as well as in a correlation of each of these parameters in different tasks.

Despite the elegance of Chiang and Atkinson's analysis of the relationships among component processing skills, the results of their attempt to relate these skills to psychometric measures of ability are quite disappointing. Unfortunately, they failed to obtain any significant correlations between the information-processing parameters and either the SAT verbal or SAT math scores. When the data were broken down by sex, some significant correlations emerged, but the pattern is extremely difficult to interpret. One possible reason for the failure to find relationships between processing components and ability could be that the range of measured ability of Stanford undergraduate students was rather narrow.

Some more positive evidence concerning the relationship between ability and information-processing skills has been found in a study by Keating and Bobbitt (1978). The ability measure used by these investigators was a composite score on the Standard and Advanced Raven Progressive Matrices (Raven, 1960, 1965). This test is generally regarded as a measure of problem-solving ability in that, unlike measures of verbal ability, general or vocabulary knowledge is not assessed. The subjects in the experiment were children from grades 3,7, and 11. The information-processing tasks used were the Posner letter-matching task (the card-sorting variation described earlier) and the memory search task. In addition, tests of simple and choice reaction time were included. In the simple reaction-time task, the subject had to indicate as rapidly as possible whenever a light turned red. In the choice reaction-time task, the subject had to push one button when a green light appeared and another when a red light appeared, and to push the buttons as rapidly as possible.

The results of these experiments were subjected to a number of different analyses. Analyses of variance generally showed significant main effects of age and ability levels, such that older and higher ability subjects performed each of the tasks more efficiently than younger and lower ability subjects. Of particular interest are some of the interactions between age and ability and certain task variables. For the letter-matching task, significant interactions emerged, such that the NI-PI difference was smaller for older than for younger subjects and also smaller for higher than for lower ability subjects. For the memory scanning task, there was an interaction between memory set size and ability, such that search rate was slower for lower ability subjects.

Like Chiang and Atkinson (1976), Keating and Bobbitt (1978) attempted to provide construct validity for the component operations presumed to underlie the various information-processing tasks. To do this, they proposed a four stage sequence of basic component processes consisting of (1) encoding, (2) operation, (3) binary decision (response selection), and (4) response execution. Various parameters of the information-processing tasks were assigned to one or more of the four sequential stages. Then, individual subjects' values for these parameters were correlated across tasks. The hope was that variables assumed to involve common processing stages would correlate more highly than those that did not have any stages in common. Unlike Chiang and Atkinson, no within-task correlations were computed. The results of this analysis revealed that the intercorrelations among variables having common stages were higher than among variables without stages in common (.66 and .30, respectively). They interpret the pattern of correlations as showing that there are basic information-processing operations that are tapped by the different tasks, but that in addition there exists a general speed factor that is reflected in the lower but often still significant correlations among variables without hypothesized common stages.

In their final analysis, Keating and Bobbitt assessed the relationship among three information-processing parameters and measured ability via multiple regression techniques. The information-processing parameters were measures of decision efficiency (choice reaction time minus simple reaction time), efficiency of memory retrieval of overlearned codes (NI-PI difference), and memory search efficiency (slope of the memory scanning function). With age partialed out, the information-processing measures accounted for only 15% of the variance in the ability scores, but this was a significant amount of added variance. More interestingly, when correlations were computed for each age group separately, the NI-PI difference was always the most effective variable, and it accounted for progressively more variance in measured ability as the age of the subjects increased (17%, 25%, and 32% of variance for the three groups in chronological order).

What, if any, systematic findings have emerged from a consideration of these various studies reflecting different approaches to assessing the relationship between basic information-processing skills and measures of verbal ability? Clearly, the most universal processing difference between the higher and the lower ability subjects in the work reviewed above is the difference between the time for matching letters identical in name only and letters that are, in addition, physically identical. Furthermore, this difference emerges despite procedural variations in the letter-matching task (the discrete trial reaction-time method and the card-sorting technique), and for both children (Keating & Bobbitt, 1978) and adults (Hunt et al., 1975). Thusfar, we have interpreted this NI-PI difference as reflecting efficiency of memory access to overlearned material. In subsequent sections, as the difference appears in still other bodies of work, we shall consider whether this processing skill is specifically one of the letter-code access or whether it may reflect a more general process of memory access or even of flexibility in applying information-processing skills.

Another possible candidate for an operation underlying verbal ability is the speed with which items in memory can be compared with a test item. Keating and Bobbitt's (1978) finding of a decrease in the slope of the Sternberg memory scanning function with increasing ability provides evidence for this notion, but the evidence is mixed at best. On the opposite side, we have Chiang and Atkinson's failure to find a relationship between slope and ability, and the report of Hunt et al., (1975) that the positive relationship that was reported earlier (Hunt et al., 1973) could not be replicated. And, Sternberg (1975) has reported no relationship between scanning rate and measures of intelligence within normal university and high school populations. The relationship of memory comparison efficiency to ability may be a subtle one, however. Hunt (1978, 1980) has reviewed evidence suggesting a rather dramatic difference in memory comparison processes when the groups considered come from more extreme populations than the variation of ability in the normal college sample used by most investigators. For example, groups of subjects suffering from various forms of mental retardation show much steeper slopes in the memory-scanning experiment than do normal high school and college students. Furthermore, Keating and Bobbitt (1978) report an almost significant interaction between age and ability in the slope of the memory scanning function such that the effect of ability on scanning rate becomes less important as age increases. What this may mean is that general memory comparison skills are well developed across ability levels within the normal range, but that these general skills are not available to the younger or the more severely low ability subject.

A third possible skill that may be related to ability is simply overall processing speed. That is, more able people may just be faster at anything they do. We will consider seriously the general speed factor as a source of ability differences in later sections. At present, analyses such as those of Keating and Bobbitt (1978) suggest that although a general speed factor may exist, there are additional more specific processing skills that contribute to differences in verbal intelligence.

Reading Ability

The ability to read rapidly and with high comprehension is a crucial aspect of "intelligent" behavior in any literate society. At a minimum, reading involves picking up visual information from a page of print and processing that information on a variety of levels so as to yield, eventually, understanding of the meaning of a passage. In this section we review and evaluate some of the literature that attempts to isolate the basic processes or components of reading that might differentiate highly skilled from less skilled readers. The recent literature on reading is voluminous, and our review will be highly selective.

We first discuss in detail a series of studies by Jackson and McClelland (1975; 1979; Jackson, Note 2; see also McClelland & Jackson, 1978) that purport to demonstrate a very basic visual information-processing difference between average and very proficient readers. We highlight these studies because they combine elegance and care in experimental design and execution, clarity of exposition, and a consistent and intriguing pattern of results.

It has been known for over seventy years (Huey, 1908) that reading takes place during pauses or fixations of the eye, and that faster readers make fewer fixations per page of text although they spend about the same amount of time on each fixation. This suggests that faster readers may be able to process a larger amount of text per fixation, and a study by Gilbert (1959) supports the suggestion. Gilbert presented single lines of text for very brief periods, and found that faster readers could accurately report more of the text than slower readers. But, precisely what is the nature of the advantage fast readers have that enables them to extract more information from a single fixation? The possibilities are numerous, and Jackson and McClelland (1975; 1979) designed their studies so as to narrow them down.

A word is in order about the measure of reading ability used in these studies. Groups of relatively fast and "average" readers are selected from a university population. These groups have non-overlapping scores on a measure of Effective Reading Speed, which is the speed of reading the text material multiplied by the score on a very strict comprehension test. There is a persuasive rationale for using this measure of reading ability: The best readers should both read quickly and comprehend much. And, in fact, typically their fast effective readers do score higher on both speed and comprehension. The groups are then put through a variety of tasks designed to tap particular processing abilities that might distinguish them.

In their first study, Jackson and McClelland (1975) replicated Gilbert's (1959) results and investigated the possibility that faster readers might pick up more from a single fixation because they have a visual sensory processing advantage. But faster readers actually showed no greater ability to pick up information presented at the periphery of the visual field, nor were their thresholds lower for detecting a single letter under conditions of pre- and post-exposure patterned masking.

At the other extreme from basic sensory processes, fast readers might be better at filling in missing information on the basis of contextual cues. Or, they might have superior understanding of the orthographic constraints of the English language, and thus be more effective at guessing "missing" letters in words. Finally, fast readers might simply be able to hold more material in short-term memory. But, Jackson and McClelland (1975) found that fast readers maintained their superiority over slow readers even when forced to pick between two words differing in but a single letter, both of which fit the context of the previous sentence but only one of which had actually appeared. Contextual cues could not guide such a choice. Furthermore, fast readers could report accurately a larger percentage of a string of briefly presented random letters, so the superiority shows itself even when orthographic regularities are eliminated. This last result also suggests that the fast readers' visual processing advantage is independent of language-comprehension processes responsible for our understanding the meaning of what is read. Finally and relatedly, greater short term memory capacity does not seen responsible for the fast readers' superiority on the tasks described above, for they were not superior on an auditory version of the unrelated letters task (Jackson & McClelland, 1979).

What, then, accounts for the superior performance of more able readers in extracting information from a brief presentation of text or letters? The results thus far point to some relatively central processing capacity that seems visually specific, but attempting to identify what this capacity might be requires specifying a theory of reading. Jackson and McClelland (1979) do not attempt such a theory, but they share the central assumptions of many information-processing theories of reading (e.g., Estes, 1975; Frederikson, 1978; Rumelhart, 1977) that the processing of information in reading occurs simultaneously and interactively at many different levels of analysis, which are loosely hierarchically organized. In constructing a conceptual representation of what is read (understanding the meaning of the text), it is argued, there are subprocesses corresponding to analysis of visual features, letter clusters, words, and semantic/conceptual meanings. The output of each level of encoding and analysis may serve as input to the level(s) above it, and may in turn be influenced by output from these higher levels. The problem becomes one of isolating level(s) of processing at which fast readers have an advantage.

To this end, Jackson and McClelland (1979) utilized a variety of matching tasks, in which the subject responded as quickly and as accurately as possible whether two presented stimuli were the "same" or "different" according to a specified criterion. The stimuli to be matched and the criterion for responding "same" were chosen to reflect different levels in the processing hierarchy leading to reading with comprehension. The primary matching tasks of interest were: letters, where the subject is instructed to respond "same" if the letters have the same name (e.g., Aa) or are physically the same (e.g., AA; after Posner et al., 1969); words, where the subject responds "same" if the words are synonyms; words, where the "same" response is given to homonyms; pseudo-words, with a "same" response to homophones; and simple dot patterns, with a "same" response if the patterns are physically identical. The tasks thus were an attempt to reflect, respectively, the process of forming letter codes, word meanings, verbal (articulatory) word codes, and visual codes. In addition to the matching tasks, the test battery included measures of listening comprehension and of verbal ability.

The results were that fast readers had shorter reaction times on all t matching tasks except dot patterns. This exception is important, for it indicates that the advantage of fast readers does not lie in more rapid encoding or comparison of any visual display. In the matching tasks that did show a fast vs. average reader difference, the magnitude of the difference was generally proportional to overall response time. But again, the dot matching task, which had the longest response times, did not show a difference between readers of varying ability.

Given only these results, the fast reader advantage could lie at any or all of the levels of processing presumably tapped by the various matching tasks. But Jackson and McClelland (1979) subjected their data to a variety of correlational, partial correlational, and regression analyses which clarify considerably the interpretation of the findings. The simple correlational analysis showed that the single strongest predictor of effective reading speed was a measure of listening comprehension, in which the subjects answered a set of questions about a passage which was read to them at normal speaking rate. The listening comprehension measure accounted for about half the variance in effective reading speed. This measure was also statistically independent of the reaction-time measures from the matching tasks. The strongest predictor of reading ability in this study then seems to be a modality-independent set of language comprehension skills for understanding and remembering meaningful discourse. A subsequent stepwise regression analysis, with variables entered in the order of the amount of unexplained variance in reading ability accounted for, confirmed that listening comprehension was the most powerful predictor of reading ability. We will discuss this listening comprehension variable in more detail below.

The correlational analysis indicated that the reaction-time measure which most strongly predicted reading speed was on the letter name-match task, and the stepwise regression analysis confirmed that this reaction-time measure accounted for a significant proportion of the remaining variance when it was entered after listening comprehension. None of the other reaction-time measures accounted for significant residual variance. And the name-match reaction-time continued to account for significant variance in reading speed even when listening comprehension and the other reaction-time measures were partialed out (Jackson and McClelland, 1979; Table 7). Finally, a measure of verbal aptitude (School and College Aptitude Test, Series II, Form 1C) correlated approximately .45 with effective reading speed. However, once the name-match reaction-time variable was entered in the stepwise regression analysis, verbal aptitude failed to account for any of the residual variance.

These results strongly suggest the letter name-match variable is the best measure of the component of reading ability that is picked up by the reaction-time matching tasks. In interpreting the difference on this task, Jackson and McClelland suggest that fast readers have swifter access to letter identity codes stored in long term memory, a claim similar to the one that Hunt et al. (1975) have made for high verbals. This is consistent with the lack of any relationship between the reaction-time tasks and the listening comprehension task (letters were not involved in the latter), as well as with the obtained differences between fast and average readers on the synonym, homonym and homophone tasks, if we make the reasonable assumption that letter identification is a component of fluent word identification (e.g., Estes, 1975; McClelland, 1976).

In his doctoral thesis, Jackson (Note 2) attempted to clarify the nature of the name-match reaction-time advantage for fast readers by addressing two questions: Is the fast reader advantage restricted to letter codes, or does it appear whenever any meaningful (nameable) visual stimulus is presented? Second, if the difference is found on other meaningful material besides letters (or words), is is attributable to differential practice with the nameable material, or does it occur even without differential amounts of practice? The second question has some implications for the possible beneficial effects of mere practice in identifying letters and words in improving the performance of poorer readers. If better readers come to the reading situation with an already existing superiority in ability to access memory codes for any meaningful pattern, regardless of familiarity with it, one would be less sanguine about the possibility that practice could close the gap between readers of differing ability.

Jackson (Note 2) replicated many of the results of the previous work by Jackson and McClelland (1979). In addition, he found that faster readers were quicker to respond whether two line drawings were or were not members of the same general category (e.g., toy, vegetable, musical instrument). This category-match reaction-time variable correlated -.29 with the measure of effective reading speed (with faster reaction times associated with superior effective reading speed). Name-match reaction time correlated -.35 with reading speed. And category-match and name-match reaction times correlated .42 with each other.

Each contributes significantly to effective reading speed when listening comprehension is partialed out. Most importantly, the two reaction-time tasks seem to be tapping the same component of reading ability, for when either is partialed out, the correlation of the other with reading speed drops essentially to zero. So the name-match reaction-time measure is an index of a very general processing ability to access rapidly a learned code in memory for any meaningful visual material.

That this ability is independent of practice with the particular visual material processed is strongly suggested by a second experiment (Jackson, Note 2) in which the stimuli were an unfamiliar character set constructed by using features similar to those found in letters. None of the characters closely resembled existing letters, however. Fast readers showed no advantage in a physical identity matching task. But when pairs (5 pairs in total) of these characters were given one-syllable nonsense names, and the subjects were required to respond "same" if the two characters shown had the same name, fast readers showed roughly a 100-millisecond advantage over average readers on this task. This difference occurred despite the fact that the two groups did not differ in amount of practice with or prior exposure to the characters, in that both groups learned the names in the same small number of trials.

The upshot of this elegant body of research is that relatively proficient adult readers differ from less proficient ones in the rapidity with which they can execute a basic visual information-processing skill--that is, access from long-term memory to the name for any meaningful visual pattern. Letters appear to be the meaningful visual patterns involved in reading, but the information-processing skill at which proficient readers have an advantage is apparently much more general than the ability to access the names of letters. The results seem to suggest that better readers bring to reading a "talent" independent of practice with the particular material being viewed, and independent of the language comprehension skills that account for the bulk of the variance in reading ability in these studies. Though the results are impressively consistent from study to study, and make a coherent conceptual package, it is perhaps worth remembering that the correlation between reading ability and this processing skill as indicated by the various reaction-time tasks was generally in the .30 range, which accounts for only approximately 10% of the variance in the data. And even this may be an inflated estimate, since the reading groups were selected to be nonoverlapping in ability.

The listening comprehension measure, on the other hand, did account for a very large proportion of the variance (typically about 50%) in effective reading scores in these studies. We might ask what particular skills are involved in listening comprehension that would contribute to reading ability, and the possibilities are clearly numerous. People who can comprehend discourse better may have better knowledge of word meanings, better short term memory capacity (although this seems unlikely; see, e.g., Perfetti & Goldman, 1976), better ability to maintain continuous attention in the task of understanding (Jackson & McClelland, 1979), better ability to utilize structure and context of discourse so as maximally to devote processing resources where most needed, or a variety of other advantages.

This last possibility was investigated in a series of studies by Perfetti and his colleagues (see especially Perfetti & Goldman, 1976; Perfetti & Lesgold, 1978). These authors utilized a variety of techniques to investigate the possibility that good vs. poor readers would be differentially sensitive to aspects of discourse structure that might be related to ease of comprehension of meaningful material. Specifically, they investigated the possibilities (a) that aspects of sentence- and thematic-structure of discourse would affect subjects' ability to comprehend and remember spoken or written material, and (b) that good readers would profit more from discourse organization than poor readers. They performed several experiments, and the findings converged in support of (a) but provided no evidence whatever for (b).

Consider memory for spoken or written material. Perfetti and Lesgold (1978) performed several "probe discourse experiments," in which the subject's task is to read (or listen to) material presented to him or her and to attempt to remember it. Every now and then, a probe word which had occurred recently in the text is presented to the subject, whose task is to report the word (called the target) which had immediately followed the probe word in the text. It is possible to manipulate a variety of aspects of discourse structure between the target's position in the text and the occurrence of the probe test item, and thereby to see whether good vs. poor readers are differentially sensitive to them. Perfetti and colleagues did this in a variety of studies using as subjects, typically, 3rd to 5th grade students of differing reading ability but matched on IQ.

As three examples of this manipulation (reported in Perfetti & Lesgold, 1978), they varied (1) the number of words intervening between target and probe test, and whether these words were within the same sentence or across sentence boundaries, (2) whether the context in which sentences were presented to subjects was normal or scrambled, and (3) whether the material intervening between target and probe test item referred to material already "given" earlier in the text, or introduced "new" material (see Haviland & Clark, 1974). In each of these cases, we would expect a main effect of discourse structure: Memory should be better for material within a sentence than across sentence lines, especially if a large number of words intervened between target and test. It should also be better for material presented in a meaningful context. And it should be better when "given" rather than "new" information intervened between target and test. All of these predictions were confirmed, presumably because in each case the material is easier to process when the discourse is more structured. We should also expect in each case a main effect of reading ability: Good readers should remember more from spoken or written passages than do poor readers. The results clearly supported this prediction as well. But are good readers more proficient because they are better able to take advantage of the structure of discourse? Perfetti and Lesgold's (1978) answer is an emphatic "no". In no case was there a statistical interaction between reading ability and discourse structure. Poor readers' memory for the material was helped (or hindered) by discourse structure (or its absence) every bit as much as that of good readers. Determination of the precise nature of the listening comprehension differences between good and poor readers clearly awaits further investigation.

We turn, finally, to an information-processing approach to reading that retains the assumption that reading can be viewed as a set of interactive component processes, but adopts a different method from Jackson and McClelland for identifying those processes and testing their relationship to reading ability. We highlight this work by Frederiksen (1978, Note 3) because the theoretical approach and research methods clearly have promise, although the data base on which the conclusions rest needs expansion.

The component processes in reading hypothesized by Frederiksen are Perceptual Encoding, Decoding, and Lexical Access. Encoding is divided into two processes--Encoding of Graphemes and Encoding of Multiletter Units. Decoding is also divided into two separate processes--Phonemic Translation, which involves applying letter-sound correspondence rules to derive a phonological/phonemic representation, and Articulatory Programming, which refers to "automaticity in deriving a speech representation, in the assignment of stress and other prosidic features" (Frederiksen, 1978, p. 29). The component processes are assumed to be hierarchically organized, although Frederiksen (1978) explicitly states that the initiation of the "higher" processes need not necessarily await completion of earlier ones. With these assumptions about the nature of reading, Frederiksen's overall research goals were three: (1) to derive information-processing tasks that should be measures of these separate component processes, (2) to show, by factor analysis, that the hypothesized five processes do best represent the pattern of correlations among the tasks, and (3) to show that the factor structure actually is related to scores on standard tests of reading ability.

We do not here consider in detail the tasks selected (see Frederiksen, 1978). But the general idea was to choose tasks such that different conditions of a task (for example, responding "same" to name-identical versus physically-identical letters) should place different demands on one of the hypothesized processing components of reading (in this case, Grapheme Encoding). Then, reaction-time differences were computed between conditions for several such tasks in the expectation that these differences should be highly correlated if the tasks tap the same component process. In certain cases, the reason why a particular reaction-time difference should tap a particular component process was unclear. Nevertheless, Frederiksen (1978) found that his hypothesized five-factor structure (one factor corresponding to each of the five hypothesized component processes) provided an impressive fit to the pattern of correlations among the eleven reaction-time differences computed. Further, he was able to show statistically that simpler, four-factor models did not provide an adequate fit.

Frederiksen (1978) tested the relationship between his component processes, as revealed in the factor structure for the chronometric tasks, and reading ability on a sample of 20 high school sophomores, juniors, and seniors who represented a wide range of reading ability levels. Three measures of reading ability were assessed, and the multiple correlations of the five factors with the reading scores ranged from a low of .73 for the Gray Oral Reading Test, to 1.00 for the Total Score on the Nelson-Denny Reading Test. These multiple correlations are particularly impressive when it is noted that none of the reaction-time tasks defining the factors involved reading anything more complex than a single word or pseudo-word. The factors with the heaviest loading on reading scores in this sample were Encoding of Multiletter Units and Articulatory Programming, but we do not make much of these relative weights because the sample is so small and the findings clearly need to be replicated. For the same reason, we do not make an explicit comparison with the findings of Jackson and McClelland discussed above, save to mention that Frederiksen (1978) did find that the name-identity versus physical-identity letter matching reaction-time difference significantly discriminated between good and poor readers. Also, if the Frederiksen results hold up, it should be possible to tap chronometrically what Jackson and McClelland have called listening comprehension with simple information-processing tasks. But the most attractive feature of Frederiksen's work is the explicit statement of a theory of reading as embodying particular component processes, along with the sophisticated methods for testing for the existence of those component processes and their relationship to reading ability.

On the basis of the work described, we can draw some general conclusions about the information-processing abilities that discriminate between relatively good versus poor readers. The difference is clearly not to be found in low-level sensory capacities (Jackson & McClelland, 1975). Nor does it derive simply from more exposure to or greater familiarity with letters (Jackson, Note 2). At the other extreme, good readers do not seem to different from poor readers in high-level sensitivity to discourse structure (Perfetti & Lesgold, 1978), although this is not to say that good readers cannot more effectively utilize contextual cues in some circumstances (e.g., see Frederiksen, Note 4). All of the extensive work by Jackson and McClelland converges on the point that good readers can more quickly access the name of any meaningful visual pattern, regardless of practice with it. And there is the very intriguing suggestion in Jackson and McClelland (1979) that this ability may totally account for the often-found association between measures of verbal ability and reading ability. Finally, there is the possibility (although we are skeptical) that measures of basic information-processing abilities, if carefully selected and tied to a component-processes theory of reading, may account for much more of the variance in reading ability than the approximately 10% or so generally found in the literature.

Spatial Ability

The term "spatial ability" is often thought to refer to competence in encoding, transforming, generating, and remembering internal representations of objects in space and their relationships to other objects and spatial positions. Psychometric tests providing measures of levels of spatial ability have been available since the time of Thurstone (1938). We will not undertake a review of the psychometric literature on tests of spatial ability here. Rather, we point to two recent reviews of psychometric and correlational studies of spatial ability (Lohman, 1979a; McGee, 1979) that indicate the existence of at least two separable but correlated major spatial facotrs and several minor ones.[2]

The first of these factors--Spatial Visualization--refers to the ability to manipulate mentally representations of visual objects. Tests measuring this ability load on Guilford's (1969) factor labeled Cognition of Figural Transformation

A typical item on one such test might require the testee to image a particular object having undergone a particular spatial transformation (e.g., a 90 degree rotation). The picture showing the result of that spatial transformation must then be selected from a number of alternative pictures. The second major spatial factor--Spatial Orientation--refers to the ability to determine spatial relationships with respect to an imagined orientation of one's own body. Tests measuring this ability load on Guilford's (1969) Cognition of Visual Figural Systems factor. A typical item on such a test might require the testee to determine which of a number of pictures of landscapes accurately shows what he or she would see from the cockpit of an airplane shown in another picture.

Tests of spatial ability have been shown to predict well certain aspects of job performance, technical school success, and success in engineering, calculus, and other mathematics courses (see McGee, 1979, and Smith, 1964, for reviews). From our point of view, tests of spatial ability provide an interesting place to look for attentional and perceptual correlates of intelligence for two reasons: First, the information-processing demands of these tests (e.g., imagining transformations on visual objects) seem, intuitively, to have much in common with ordinary perceptual processing. Second, unlike tests of verbal or reading ability, spatial ability tests do not seem particularly dependent on specific world knowledge. It might be in just this situation--when the contribution of knowledge is minimized--that the contribution of basic information-processing skills to ability measures could be most clearly revealed.

In the discussion that follows, we hope to accomplish several goals. First, we review some of the information-processing studies of tasks that seem to require skills similar to those tapped by items on tests of spatial ability. In particular, we provide evidence for sources of individual and group differences in performance on these tasks. Second, we examine studies which have specifically tried to relate measures of spatial ability to parameters of information-processing models for performance on tests of spatial ability. Finally, we attempt to make sense of the results of these studies, and we point to potential new directions in investigating the nature of spatial ability.

One information-processing task that has received considerable current attention and that bears similarity to visualization items on tests of spatial ability is the "mental rotation" task first studied by Shepard and Metzler (1971). In their initial experiment, Shepard and Metzler asked subjects to determine whether pairs of perspective drawings of three-dimensional objects were the same in shape or were mirror images. In addition to a possible difference in shape, the objects could differ in their portrayed orientations either in the picture plane or about an axis in depth. The most significant result of Shepard and Metzler's study was that the time required to make the "same-different" discrimination increased linearly with the difference in the portrayed orientations of the two objects in the pair. Shepard and Metzler interpreted these results as suggesting that subjects performed the task by imagining one object in the pair rotated into the orientation of the other object and then by comparing the transformed international representation with the second object to determine whether there was a match or a mismatch in shape. Presumably, the slope of the reaction-time function provides an estimate of the rate at which this mental manipulation can be caried out, and the intercept provides an estimate of the time required to encode the two objects in the pair, to compare them following the mental rotation, and to select and execute the response of "same" or "different."

Subsequent studies of this process of mental rotation have shown that when familiar visual stimuli (e.g., letters of the alphabet) are shown individually in nonstandard orientations, the time to determine whether they are normal or reflected versions increases monotonically with the extent of their departure from the canonical, upright position (Cooper & Shepard, 1973a, 1973b). In addition, linear reaction-time functions, indicating a process of mental rotation, have been demonstrated for stimuli such as random polygons (Cooper, 1975), and Cooper and Podgorny (1976) have shown that the rate of mental rotation of such polygons is unaffected by the complexity of the visual figures. Orderly relationships between decision time and extent and/or number of spatial transformations have not been limited to tasks in which the transformation is specifically one of rotation. For example, Shepard and Feng (1972) have reported that response time for "mental paper folding" items, similar to surface development items on tests of spatial ability, increases linearly with the number of transformations required to complete the items.

Models of the processes underlying these mental transformation tasks can be considered as characterizations of the operations involved when a given subject solves a given visualization item on a typical test of spatial ability. Is there any evidence from the information-processing literature for individual differences in mental transformation tasks that might ultimately be related to psychometrically measured spatial ability? In fact, in all of the studies cited above, substantial individual differences in both rate of mental transformation and in encoding, comparison, and response processes have consistently been found. For example, in the Cooper (1975) study, slopes of the linear function relating reaction time to angular disorientation (expressed in terms of rate of mental rotation) have ranged from 320 to 840 degrees per second for individual subjects, and intercepts have ranged form 300 to 1000 milliseconds. These differences are difficult to interpret from a psychometric viewpoint, however, because the number of subjects in each study has been small and the subjects have been selected from a population that undoubtedly would score high on tests of spatial ability (generally, university graduate students and faculty). Indeed, in the original Shepard and Metzler (1971) study, subjects were initially screened on the basis of a series of tests of spatial ability. In a subsequent study, Metzler and Shepard (1974) systematically investigated the effects of sex and handedness on mental rotation (again, with a small number of subjects), and no compelling or consistent patterns emerged in the data.

More recently, Kail and his associates (Kail, Carter, & Pellegrino, 1979; Kail, Pellegrino, & Carter, 1980) have used larger samples of subjects to investigate both developmental and sex differences in mental rotation studies. The developmental studies (Kail et al., 1980)--using subjects from grades 3, 4, 6, and college -- indicate that the rate of mental rotation increases with increasing chronological age, and also that the intercept of the reaction-time function decreases as age increases. In addition, these investigators found interactions between age and stimulus familiarity for encoding, comparison, and response processes (the intercept parameter). To the extent that one accepts the view that older subjects are generally more able, these results suggest that mental transformation processes are quicker and more efficient in those of higher ability.

Within a college population, Kail et al. (1979) have examined sex differences in performance on a mental rotation task. To the extent that mental rotation tasks require the same underlying processes that are measured in tests of spatial ability, such an investigation is quite reasonable. For, there is a substantial body of literature documenting the superiority of males over females on psychometric tests of both the Visualization and the Orientation factors of spatial ability (see McGee, 1979, for a recent review of this literature). The Kail et al. (1979) results can be summarized as follows: No differences were found between the sexes in the intercept of the reaction-time function, which presumably reflects the speed of encoding, comparison, and response processes. Somewhat curiously, given the psychometric literature, overall accuracy was also roughly equal for men and women. The extent to which the male and the female data were fit by linear functions was also equal, suggesting that both sexes did indeed use a process of mental rotation in solving these spatial problems. The chief difference between the sexes was located in the slope of the reaction-time functions, with the men overall having a faster rate of rotation than the women. Closer examination of the data revealed that the variability of the slopes was considerably greater for women than for men, with about 30% of the distribution of slopes for women falling outside of the distribution for men.

This study, then, is indirect support for the idea that speed of mental transformation is related to spatial ability. The support is only indirect, because no attempt was made to correlate psychometrically measured ability with parameters of performance on the mental rotation task for this set of subjects. Rather, the argument rests on the assumption that these subjects would show the same sex differences in spatial ability that are characteristic of other populations. In any event, the studies of Kail and his associates and earlier studies of mental rotation provide compelling evidence for individual and group differences in the rate at which mental transformations on representations of visual objects can be carried out.

Several recent programs of research have taken the further step of attempting to relate measured spatial ability to parameters of information-processing tasks. We concentrate primarily on a series of studies by Egan (1976, 1978, 1979, Note 5) although Lohman (1979b) has also reported an extensive if not readily interpretable study along these same lines. Egan's basic approach has been to recast items on tests of visualization and orientation abilities into an information-processing/latency framework. He then examines the relationship between overall accuracy on the psychometric tests and latency on the modified information-processing tasks. He goes on to develop process models of the operations underlying performance on the information-processing tasks, and he seeks to establish relationships between parameters of the process models and psychometric measures of spatial ability.

In all his studies, this subjects have been Aviation Officer Candidates and Naval Flight Officer Candidates. An example of a psychometric test of orientation ability that Egan has used is the U.S. Navy's Spatial Apperception Test. In the standard version, the testee is shown a particular aerial view of a landscape, and he must select from among five airplanes the one oriented appropriately so that a pilot in the cockpit would see that particular aerial view. In the information-processing/latency version of this task, one landscape paired with one airplane orientation is presented on each trial, and the subject must determine as rapidly as possible whether they are or are not correctly matched. An example of a psychometric test of Visualization ability that he has used is the Guilford-Zimmerman Aptitude Survey's Spatial Visualization subtest. In the standard version, the testee must mentally rotate an alarm clock in a specified sequence, and then select which of five depicted clocks matches the final position in the sequence of transformations. In the latency version of this task, only one of the five alternative clocks is shown -- paired with another clock and the specified sequence of transformations-- and the subject must determine as rapidly as possible whether the test clock accurately depicts the result of the set of mental rotations.

In some initial studies, Egan (1976, 1978) found the following pattern of relationships among the accuracy and latency measures on the psychometric tests and the modified information-processing versions. Correlations among accuracy scores both across tests and between the psychometric and information-processing versions of a given test were generally high and positive. Also, latency scores correlated positively across information-processing tasks. However, the correlations between accuracy and latency measures were generally low and negative.[3] This failure to find a correlation between the accuracy and the reaction-time measures is not due to an unreliability in the reaction times; for, reliability of the latency measures was generally as high as for the accuracy measures. Further evidence for the independence of the accuracy and the reaction-time indices derives from a factor analysis of the matrix of intercorrelations, in which the latency tasks and the accuracy measures clearly loaded on separate factors (Egan, 1978).

This pattern of results is puzzling, because the psychometric tests---on which overall accuracy is measured---are nonetheless taken under speeded or time-limited conditions. Thus, the speed with which the mental operations underlying completion of individual item can be performed should presumably be reflected in the overall accuracy scores. There are several possible reasons for this lack of relationship between reaction time and accuracy. First, the two measures could be indices of separate aspects of spatial ability. Second, the latency measure could have nothing to do with spatial ability, as measured on psychometric tests, but could rather reflect nothing more than some "general" speed factor. (We will consider this second possibility in some detail in a later section of this paper.) The third and most interesting possibility is that while accuracy and overall latency are not correlated, it still could be that measured spatial ability correlates with one or more components of the reaction-time measure which reflect the time required for different mental operations.

To evaluate this third possibility, Egan (1978, 1979, Note 5) developed process models of the mental operations in the reaction-time tasks and attempted to find relationships between spatial ability measures and different parameters of the models. We consider first his process model of the reaction-time version of the orientation task. Briefly, the model proposes that the subject first encodes the orientation shown in the aerial view and the orientation of the observer in the cockpit of the airplane in terms of a number of different spatial dimensions (in the case of items on this task, the dimensions would be extent of rotation about three different axes in space). The values of the two encoded representations on these spatial dimensions are then compared sequentially. As soon as a mismatch is found, the response "no" can be executed, and the "yes" response can be executed only after all three dimensions have been compared and found to match. This model clearly predicts that the time taken to respond will increase as the number of dimensions on which the two pictures match increases. The slope of the reaction-time function should provide an estimate of the time for a single dimensional comparison, and the intercept should reflect the time needed for encoding and response selection and execution.

Egan (Note 5) found that the group data generally fit the model well, in that latency scores increased linearly with the number of matching spatial dimensions. But to what extent might accuracy scores, or measures of spatial ability be related to either the rate of comparing spatial dimensions or to speed of encoding and response processes? Correlations of intercepts, slopes, and degree of linearity of the reaction-time functions with spatial ability measures revealed only two significant relationships. First, the degree to which the latency functions were linear was positively correlated with measured spatial ability. Second, for a subset of the subjects, the intercept parameter showed a significant negative correlation with ability measures. What these results suggest is that the basic information-processing skill contributing to high scores on spatial ability tests is efficiency or speed of encoding and response processes, rather than the efficiency with which spatial dimensions can be compared! The degree of linearity of the reaction-time functions may reflect the extent to which subjects were consistent in using the dimensional comparison strategy, and this, too, was positively related to measured spatial ability.

A similar and somewhat disappointing picture emerges from an analysis of the relationship between hypothesized information-processing parameters in the Visualization task and psychometric measures of spatial ability. Egan's (1976, 1978, 1979) information-processing/latency version of the Visualization test is basically the mental rotation task discussed above. The intercept of the reaction-time function can be thought of as the time required to encode the two visual objects in the pair, to compare them following the mental rotation, and to select and execute the appropriate response. The slope provides an estimate of the speed of the actual process of mental transformation. (The model that Egan, 1976, 1978, 1979, proposes for this task is slightly different from the above account of the component processes in mental rotation. It derives from Just and Carpenter's, 1976, analysis of patterns of eye fixations while subjects perform a mental rotation task.)

As in his analysis of the Orientation task, Egan (Note 3) found support from the group data for his information-processing analysis of the Visualization task, in that reaction time increased approximately linearly with the angular difference between the portrayed orientations of the two visual objects to be compared. However, correlations between the slopes of the functions for individual subjects and measures of spatial ability were generally quite low, while the correlation between intercept and accuracy (the ability measure) was a statistically significant -.30. Once again, it appears that efficiency of encoding and comparison processes--not rate of mental transformation--is a basic information-processing skill underlying spatial ability. One further aspect of Egan's data deserves mention. In addition to the latency versions of the psychometric tests, he included a two-choice reaction time task. Latency scores on this task had generally low correlations with accuracy measures. This suggests that the significant correlation between intercept and ability in the mental rotation task really does reflect efficiency of visual coding and comparison operations, rather than response processes or a general speed factor, both of which are measured in the choice reaction-time task.

In summary, the Egan studies provide little support for the appealing notion that the speed with which mental transformations such as rotation or comparison of spatial dimensions can be carried out underlies measures of spatial ability. Rather, speed of encoding operations is weakly though statistically significantly related to the ability measures. A similar conclusion can be drawn from the work of Pellegrino, Glaser and their associates on the operations involved in the solution of geometric analogies (see Glaser & Pellegrino, 1978 - 1979; Mulholland, Pelllegrino, & Glaser, 1980; Pellegrino & Glaser, 1980). In these studies, latencies for solving geometric analogies varying in difficulty---both in terms of the number of spatial transformations required and the number of visual elements that must be transformed--have been examined, and components of the latency measures have been correlated with psychometric measures of ability. A full consideration of this impressive body of work is beyond the scope of the present paper. Two of their findings, however, are relevant to the present discussion. First, measures of the rate of transformational processing were not significantly correlated with ability measures. Second, there was a significant negative relationship (r = -.44) between ability scores and intercepts of the reaction-time functions (see, also, Sternberg, 1977).

Our tentative conclusion that basic processes of visual coding, representation, and comparison may contribute more to spatial ability than seemingly more complex operations such as efficiency of mental transformation does not go unchallenged. One obvious problem with this analysis comes from the studies of developmental and sex differences in rate of mental rotation that were discussed earlier (Kail et al., 1979; Kail et al., 1980). Recall that in those studies both older subjects and, within an adult sample, male subjects were found to have shallower reaction-time functions (faster rates of mental rotation) than younger subjects or females. These findings suggest that spatial ability and transformation rate are related, in that adults are generally more able than children and females tend to score lower on tests of spatial ability than do males. The argument is not conclusive, however, because no psychometric measures of spatial ability were available for the subjects in these studies, so a direct correlational analysis of mental rotation rate and ability score could not be performed.

A much more problematic finding comes from a recent study by Lansman (Note 1). In the portion of this study that is relevant to the present discussion, Lansman found a strong correlation between scores on a Visualization factor and slopes of reaction-time functions from a mental rotation task. (The correlation was -.50, with faster rotaters scoring higher on the ability measure than slower rotaters.) Furthermore, no significant correlations were obtained between this slope parameter and other ability factors, thus strongly implicating efficiency of mental transformation as a component of specifically spatial ability. Lansman also reported a significant correlation (-.25) between the spatial ability measure and the intercept parameter. Finally, in marked contrast to Egan's (1976, 1978) results, a high negative correlation emerged between overall latency on the rotation task and accuracy on the spatial ability measure. It is difficult to interpret Lansman's results as reflecting an overall speed component in ability, because the reaction-time measures on the mental rotation task correlated almost exclusively with the Visualization factor, and not with other ability factors. We conclude, then, that there is reasonable evidence for a relationship between visual encoding processes and measured spatial ability, in that the correlation between ability and intercept is ubiquitous.[4] Any evidence for a relationship between mental manipulation speed and spatial ability needs to be established more firmly, however.

In concluding this section on spatial ability, we would like to point briefly to two potentially fruitful directions for research on basic information-processing skills underlying spatial ability measures. One research avenue might involve assessing the relationship between spatial ability and components of information-processing tasks not specifically derived from items on psychometric tests. In most of the studies reviewed above, the information-processing tasks have been adaptations in a reaction-time framework of individual items on psychometric tests of spatial ability. Our understanding of the component processes underlying spatial ability might benefit from research in which other kinds of tasks that provide more general measures of visual encoding and comparison operations (e.g., "same-different" visual matching) are examined in terms of the relationships of the processes in these tasks to measures of spatial ability. (See Lansman, Note 1, however, for an unsuccessful attempt to relate parameters of a model of the sentence-picture verification task to spatial ability.)

A second research direction might involve exploring the relationship between the cognitive processes underlying more "ecologically valid" spatial information-processing tasks and psychometric measures of spatial ability. A topic of considerable current interest in cognitive psychology concerns the way in which information about the relationships among objects and locations in an environment is acquired, represented internally, and accessed for purposes of making judgments about that environment or for purposes of actual locomotion through the environment from one place to another (see, for example, Baum & Jonides, 1979; Loftus, 1976; Kosslyn, Pick, & Fariello, 1974; Stevens & Coupe, 1978, to mention but a few recent studies).

This research effort to understand the nature of the mental operations and representations underlying "cognitive mapping" has proceeded by and large without a concern for determining possible relationships between the processes involved in generating and using cognitive maps and the processes contributing to measures of spatial ability. There are several exceptions to this general statement. For example, Kozlowski and Bryant (1977) have successfully correlated self reports of "sense of direction" with performance on a task related to learning to locomote through an actual environment. Even more relevant for our purposes is a preliminary set of studies by Thorndyke and Stasz (1980). These investigators have been examining the factors that make particular individuals more or less adept at learning to read maps of fictitous environments. On the basis of an initial study, they identified a variety of processing strategies that appeared to underlie effective map learning. In a subsequent experiment, Thorndyke and Stasz demonstrated (a) that certain of the learning strategies were trainable, and (b) that both map-learning performance and success in the use of learning strategies were positively related to a psychometric measure of spatial ability. These initial results are suggestive, and they underscore the potential utility of examing the relationship between the operations involved in learning and using representations of the environment and psychometric measures of spatial ability.

Summary and Evaluation

Thusfar we have considered in some detail a number of studies designed to uncover relationships between information-processing skills and measures of ability. The goal of this approach to studying individual differences is to provide a theoretical framework for the analysis of human intelligence. That is, rather than viewing ability as some "thing" or trait that is reflected in a global test score, the effort has been to isolate basic perceptual and cognitive processes that distinguish higher from lower ability persons. To the extent that this effort is successful, we should be able to provide an account of the nature of the mental operations that make individuals intelligent. But how sucessful has this effort actually been? Below we briefly review the central findings from experiments on individual differences in verbal ability, reading ability, and spatial ability. We then point to problems in the interpretation of the results of these experiments, as well as to more general problems with the information-processing approach to an analysis of ability. Detailed and subtle methodological criticisms are beyond the scope of our discussion. However, several excellent methodological papers have recently appeared (see, for example, Baron & Treiman, 1980; Carroll, 1978, Hunt & MacLeod, 1978; McClelland & Jackson, 1978).

Despite the relatively large amount of experimental work, few consistent findings have emerged from studies of the relationship between information-processing tasks and verbal ability. The one clear result, obtained by virtually all investigators, is that high verbal subjects show a smaller difference than do low verbal subjects between the time needed to determine that two letters of different cases share the same name and the time needed to determine that two physically identical letters are the same (the NI-PI difference). The general interpretation of this result is that high verbal subjects enjoy faster access to overlearned codes in memory (letter names) than do low verbal subjects. High verbal subjects may also have more rapid and efficient memory scanning and comparison operations, particularly when the reference group is very low ability subjects (Hunt, 1978) or children (Keating and Bobbitt, 1978).

Related to the NI-PI difference between high and low verbal subjects, studies of reading ability have consistently found that good readers can more quickly access the name of a letter code in memory (the Posner task). This ability, which accounts for about 10% of the variance in reading ability, is not restricted to letter codes. Better readers can more efficiently access the name of any meaningful visual pattern, even when practice with the pattern is held constant (Jackson, Note 2). Though many investigations have indicated that modality-independent language comprehenion skills account for the bulk of the variance in reading ability, Frederiksen (1978) has offered a component process model of reading and devised simple reaction-time tasks for isolating those processes which in one study accounted for nearly all the variance in reading ability in a sample of high school students.

In the area of spatial ability, the picture is complicated by conflicting findings. However, one result that tends to emerge quite consistently is that the intercept of the function relating reaction time to extent of spatial transformation is significantly negatively correlated with spatial ability. An interpretation of this negative correlation is that high spatial subjects are faster at visual encoding and comparison operations than are low spatial subjects. It may also be that high spatial subjects are faster at performing mental transformations (measured by the slope of the reaction-time function), but the evidence is mixed (see, in particular, Egan, 1978, and Lansman, Note 1).

Even for the few information-processing differences that have been found to relate to individual differences in ability, there are problems of theoretical interpretation. We divide these problems into two general categories--

problems relating to the possibility of a general speed factor and problems deriving from the adequacy of the theoretical analysis of the information-processing tasks. With regard to the possibility of a general speed factor, we should note that in virtually all of the information-processing tasks discussed above, response time has been the chief dependent variable of interest. And, correlations between reaction time and ability level or the magnitude of reaction-time differences that relate to ability have constituted the evidence for basic information-processing factors in intelligence. But, could it not be the case that the efficiency of component processing operations--presumably measured by the cognitive tasks--have little or nothing to do with measured ability? Rather, more able individuals could simply be faster at hitting response buttons than less able individuals, and hence the correlations between performance on reaction-time tasks and ability level could emerge.

It is very difficult to eliminate this possibility of a general speed difference between high and low ability subjects in the case of many of the experiments that we have discussed. However, in some of the studies, there is at least indirect evidence that overall speed is not the sole determinant of the relationship between performance on information-processing tasks and ability. For example, Jackson and McClelland (1979) failed to find a statistically significant reaction-time difference between fast and average readers in either a dot-pattern matching task or a physical-identity letter matching task, but the times for the two groups did differ reliably on a name-identity letter matching task. Presumably, if the chief difference between the fast and average readers is one of general speed, then the time required for visual pattern matching (measured by the dot pattern and the physical-identity letter pattern tasks)--as well as the time needed for name-identity letter matching--should have been less for the high than for the lower ability subjects. Another example of a finding that argues against a general speed factor comes from Egan (1978). Recall that he obtained very low correlations between choice reaction time and spatial ability while obtaining considerably higher correlations between ability and other reaction-time parameters from his information-processing tasks. Similarly, Keating and Bobbit (1978) found higher correlations among reaction-time parameters which were theoretically related than among parameters that were not hypothesized to be related. Again, if overall response speed--rather than the efficiency of particular processing operations--~~underlies~~ underlies differences in ability, then all of these correlations between ability and reaction-time parameters and between the reaction-time parameters themselves should have been roughly equal.

There is evidence, though, that strongly suggests that a general speed factor may contribute substantially to the relationship between performance on information-processing tasks and ability. Jensen (Note 6) has amassed considerable evidence for correlations between various parameters from reaction-time tasks and general measures of ability. Indeed, by combining certain parameters in a multiple regression equation, Jensen shows that about 50% of the variance in measured ability can be accounted for. Perhaps more relevant to the issue of a general speed factor are Jensen's (Note 6; Jensen & Munro, 1979) own studies on the relationship of reaction time and movement time to intelligence. In this paradigm, the subject must lift a finger from a home key when 1,2,4, or 8 lights, arranged in a semicircle around the home key, go(es) on. The subject must then turn off the light by touching a microswitch directly below it. The time taken to lift the finger off the home key, once the light has appeared, is defined as the subject's reaction time. The time taken actually to turn off the light, once the finger has been raised, is the subject's movement time. Jensen and Munro (1979) have reported a -.39 correlation between reaction time and scores on the Raven Standard Progressive Matrices (Raven, 1960) and a correlation of -.43 between movement time and Raven scores. Note that these correlations are as high as those obtained between ability measures and reaction-time parameters from information-processing tasks. Furthermore, it is difficult to argue that the same operations that theoretically underlie performance on the information-processing tasks (encoding, memory access, etc.) are involved in the simple task that Jensen is studying. Jensen and Munro's (1979) data strongly suggest a relationship between overall speed and ability scores. However, the theoretical interpretation of this relationship between speed and intelligence is not clear. From these data, Jensen concludes only that intelligence tests "tap fundamental processes involved in individual differences in intellectual ability and not merely differences in specific knowledge, acquired skills, or cultural background" (Note 6, p. 1).

If one accepts the notion that relationships between processing parameters in cognitive tasks and ability measures reflect more than a general speed factor, then problems with the interpretation of these relationships still remain. This second set of problems concerns the theoretical adequacy of the analysis of the component processes required by the information-processing tasks. Stated simply, any interpretation of a reaction-time difference between groups in an information-processing task or a correlation of reaction time with ability will only be as good as the theory of the component operations underlying performance on the information-processing task. This is why, throughout, we have praised studies in which an attempt has been made to establish construct validity for processing operations in various cognitive tasks.

As an example of the relationship between theory in cognitive psychology and the interpretation of sources of individual differences, consider the sentence-picture verification task (Clark & Chase, 1972). Hunt et al. (1975) found that high verbal subjects had a smaller effect of negation than did low verbal subjects on reaction times for both encoding an initially presented sentence and for comparing the sentence with a subsequently presented picture. Their interpretation of this difference was tied to then-current theory of the nature of the mental operations and representations involved in the sentence-picture verification situation. In subsequent work, Lansman (Note 1) has explored further possible relationships between ability factors and performance on this task. She found that both the information-processing model proposed by Clark and Chase (1972) and a modification of this model introduced by Carpenter and Just (1975) accounted for about 97% of the variance in the group mean reaction-time data. She went on to perform an invididual differences analysis of the sort suggested by Underwood (1975) as a test of the adequacy of the information-processing models. This was accomplished by deriving parameters from the reaction-time data that, according to the two models, provided measures of essentially the same underlying mental processes, and then correlating these two parameters across individual subjects. The results of this analysis and the derivation of the model parameters are too complex to be considered in detail here. What Lansman (Note 1) found, essentially, was that two of the parameters which theoretically provided measures of the same mental process, according to both of the models, correlated only .03 across individuals. And, if the cognitive models of the sentence-picture verification task were indeed accurate, then these measures should have been highly correlated across individual subjects.

What Lansman's analysis suggests is that neither the Clark and Chase (1972) nor the Carpenter and Just (1975) model gives an adequate account of the processes underlying performance in the sentence-picture verification task. In the absence of an adequate theory of an information-processing task, any interpretation of individual differences in performance on the task becomes virtually impossible. (In Lansman's study, only weak relationships between ability factors and reaction-time parameters were found.) It should be noted that the sentence-picture verification paradigm is particularly vulnerable to this criticism. In addition to the Lansman (Note 1) study, MacLeod Hunt and Mathews (1978) have reported substantial individual differences in strategies used to compare sentences with pictures. Glushko and Cooper (1978) have also demonstrated that seemingly minor variations in temporal parameters of the task can lead to gross changes in strategies within individual subjects. The general point, however, which extends beyond the sentence-picture verification task, is that interpretation of information-processing differences and their relation to differences in ability is only as powerful and adequate as current theory in cognitive psychology.

There are several issues in the interpretation of processing differences that are related to the general point of the adequacy of models of cognitive tasks. One of these issues concerns the specificity of the processes that distinguish higher from lower ability persons. That is, when we find that a particular parameter of performance on a reaction-time task distinguishes high from low ability subjects, are we to attribute the underlying processing difference to some aspect of the task or to the efficiency of some more basic, general mental operation? Often, this is a difficult question to resolve. Consider, for example, Jackson and McClelland's (1979) finding that good and poor readers differed more, in terms of reaction-time performance, on a homonym matching task than on the standard Posner name-identity letter matching task. At first blush, this result suggests that phonological processes---presumably tapped by the homonym task---contribute more to differences in reading ability than does a general factor of access to overlearned codes in memory. However, when Jackson and McClelland partialled out the contribution of name-identity matching to effective reading speed, the relationship between the homonyn task and ability became negligible. So, the more general operation of memory access, rather than phonological processing per se, was responsible for the differences in reading ability. Another obvious example of this issue of general versus specific information-processing skills comes from the work of Jackson (Note 2) showing that retrieval of general conceptual categories, rather than specific access to letters names, mediates the difference between good and poor readers on performance in the Posner letter-matching task situation..

A second issue in interpreting the relationship between reaction-time and ability differences concerns the precise location of the source of individual variation in the information-processing sequence. To the extent that we adopt the view that component information processes are interactive and interdependent---rather than strictly serial or parallel and independent--then it will be difficult to determine just which processes contribute to individual differences in ability. For, differences in lower-level processes, such as accessing learned information from memory, will influence the efficiency of operation of higher-level processes as well. McClelland and Jackson (1978) elaborate this point, with respect to the particular example of information-processing determinants of reading ability. Quoting them,

> It is also worth noting that accessing information in memory may well influence other important components of the reading process as well. Within the context of models in which all components of the process are strongly interdependent (e.g., Rumelhart, 1977) it is clear that accessing syntactic, semantic, and lexical information in memory must be an

> important determinant not only of comprehension itself, but of the actual process of picking up information from the printed page. Faster access to the semantic and syntactic properties of words picked up in one reading fixation will leave the faster reader in a better position to use contextual information to infer letters and words he has not fully processed from the page, and to guide the movements of the eye to an advantageous position for picking up information on the next fixation. Indeed, if we adopt an interactive model of reading, there is hardly any aspect of the reading process which will not be facilitated by more efficient access to information in memory. (pp. 200-201)

The final issue that we mention concerning interpretation of information-processing skills underlying individual differences in ability is the temporal stability of the demonstrated or hypothesized processing differences. The studies reviewed above are essentially silent on this matter. While certain reaction-time differences (e.g., the difference between the times for name-identity and physical-identity letter matching) have been shown to be stable correlates of verbal and reading ability acorss different variations of the matching task, different groups of adult subjects, and different developmental levels, there has been virtually no attempt to show that given groups of subjects that differ in ability also continue to differ in the magnitude of an information-processing difference over time. The demonstration of such temporal stability of processing differences--alleged to constitute sources of individual differences in ability--would seem important to establish.

In concluding this section, we must note that, despite the initial promise of the attempt to combine psychometric and information-processing approaches to the study of individual differences, the magnitude of the relationships between ability measures and basic processing parameters appears to be small. Correlations between psychometric measures of ability and information-processing operations have hovered around .30. Why might it be that component information-processing skills fail to account for much of the variance in ability scores? There are several possibilities, all of which could be contributing to the weakness of these relationships.

One possibility is that the ability measures that have been correlated with performance differences on information-processing tasks are simply too global and that higher correlations could be obtained between processing parameters and more refined subscales of ability. Another possibility is that the information-processing tasks that have been studied are not sensitive enough to reveal sources of individual differences. A related idea (discussed in more detail above) is that models of these cognitive tasks are inadequate, leading to the selection of inappropriate processing parameters for correlational analyses with ability differences. Still a third possibility is that basic information-processing skills in fact are weak determinants of individual differences in ability. In the case of verbal ability, in particular, it is quite conceivable that general knowledge factors influence test scores more heavily than do component content free perceptual and cognitive factors. At a more general level, it could be that while differences in basic information-processing skills provide a reliable (if small) contribution to individual differences in ability, strategies for selecting component perceptual and cognitive operations and flexibility in attentional factors provide an even greater contribution. We consider this final possibility in more detail in the following section.

The Role of Strategies and Attention in Individual Differences Ability

The generally low correlations between basic information-processing parameters and individual differences in ability have led to the suspicion that other, more flexible aspects of cognitive functioning may make more substantial contributions to intelligence than do low-level processing skills. These additional aspects may include strategies--the methods that one selects for approaching a task or solving a problem--and general attentional factors. This point is certainly not a novel one. Hunt (1974), for example, has distinguished between two quite different strategies for completing items on the Raven Progressive Matrix Test of general intelligence. One strategy is based on an algorithm that relies on Gestalt-like perceptual factors, and the other strategy is more analytic in nature. Sternberg (1977), too, has emphasized the importance of strategies, or the order in which component processing operations are combined, in the solution of analogy items.

Recently, both Baron (1978) and Hunt (1978, 1980) have pointed to several sources of individual differences in intelligence. The basic distinction that Baron makes is between capacities, or unmodifiable information-processing limitations, and strategies, or modifiable procedures for organizing cognitive processes in acquiring knowledge and solving problems. Hunt's distinction is basically the same, but to the list of sources of individual differences in competence he adds general attentional resources or "cognitive energy." Baron (1978) argues vigorously for the importance of strategies in ability differences, and he marshalls considerable empirical evidence--primarily from developmental studies and work on human memory--in support of his argument.[5] He concludes this provocative paper by speculating about the nature of central strategies (those which transfer to both novel and familiar situations) that might make some people appear more intelligent than others. The central strategies that Baron considers most important include: relatedness search, the strategy of searching memory for items related in some way to an item that is presented; stimulus analysis, the strategy of processing a stimulus in terms of its component parts of dimensions; and checking, the strategy of suppressing an initial response in order to evaluate other possibilities. In the section below, we too emphasize the contribution of strategies to individual differences in performance. Our discussion has two parts. In the first, we provide evidence for a relationship between strategies and differences in measured ability. In the second, we selectively review evidence for qualitative individual differences in strategies whose relationship to intelligence is less clear. We conclude this section with a brief consideration of individual differences in attentional resources and mechanisms.

Strategies

One reason why it is difficult to study strategies experimentally is that we rarely have a clear notion of what sorts of strategies are available for performing cognitive tasks until we observe compelling individual or group differences in patterns of data. Once we have isolated different strategies in this fashion, we can ask further questions concerning their trainability or manipulability by performing experiments in which different groups of subjects are instructed to use one strategy or another. A very nice set of studies following essentially this line of reasoning and, further, providing evidence about the relationship of strategies to ability, has recently been reported by MacLeod, Hunt, and Mathews (1978) and by Hunt (1980). In the initial experiment, MacLeod et al. had two aims. They were interested both in testing alternative models of the sentence-picture verification task and in relating performance on the task to psychometric measures of verbal, reading, and spatial abilities. Both of the models, one proposed by Clark and Chase (1972) and the other proposed by Carpenter and Just (1975), assume that subjects use a linguistic strategy in performing the task, in that they encode both the initially-presented sentence and the subsequently-presented picture into propositional representations for purposes of comparing the two. The models differ primarily in the nature of the matching operation, but both models predict that the variables of negation and linguistic markedness should increase the time taken to perform the verification operation.

In MacLeod et al.'s procedure, the time taken to encode or comprehend the initial sentence and the time taken to perform the subsequent verification were measured separately. The fit of the Carpenter and Just model to the group mean verification-time data for different sentence types was impressive. The model accounted for 89.4% of the variance in reaction times. However, correlations for individual subjects between model predictions and verification times were quite variable, ranging from .998 to -.877. In order to investigate these individual differences in more detail, they divided their subjects into groups that were "well fit" and "poorly fit" by the model. The data from the "well fit" group showed strong effects of the linguistic variables (captured in the difference sentence types), while the data from the "poorly fit" group showed virtually no effect of the linguistic variables.

The failure to find linguistic effects in the "poorly fit" group suggests that they may use a fundamentally different strategy in comparing sentences and pictures. One such strategy--primarily spatial in nature--would involve generating a visual image of the relationship between the elements described in the sentence during the comprehension interval and then directly comparing this generated visual image against the picture during the verification interval. Contrast this with the "linguistic" strategy of converting the picture into a propositional representation for purposes of comparison with the linguistically-encoded representation of the sentence. The use of these different strategies suggests several hypotheses concerning group differences in the pattern of reaction-time results. Specifically, the spatial strategy should require considerable processing time during comprehension--when a visual image of the elements related in the sentence is being generated--and little processing time during verification--when the generated image is being directly compared with the picture. The linguistic strategy should yield just the opposite pattern. During comprehension, the sentence is being linguistically encoded, and this encoding should be relatively rapid. During verification, however, the picture must be converted into a linguistic representation, and it must be compared with the interal representation of the sentence. The MacLeod et al. data confirm these predictions nicely. The "poorly fit" group had longer comprehension times than did the "well fit" group, as they should were they using a spatial/imaginal strategy. And, the "poorly fit" group also had shorter verification times than did the "well fit" group, which is again consistent with the proposed differences in their strategies.

Even more intriguing are the relationships that MacLeod et al. found between strategy use and psychometric measures of ability. Partial correlations between verbal ability (with spatial ability held constant) and verification time were -.44 for the "well fit" group and -.05 for the "poorly fit" group. Similar correlations with spatial ability were .07 for the "well fit" and -.64 for the "poorly fit" groups. There was a significant correlation (.55) between sex and verification time for the "poorly" fit group, but not for the "well fit" group. This provides additional evidence that the "poorly fit" subjects were using a spatial strategy, in light of the relationship between sex and spatial ability. Finally, inspection of the actual test scores of the two groups of subjects revealed that they did not differ with respect to verbal ability, but the "poorly fit" group had considerably higher spatial ability scores.

In conclusion, this study presents a variety of converging evidence concerning the use of alternative strategies in a "simple" information-processing situation. If strategy choice can alter performance so markedly on this sentence-picture verification task, then the potential impact of strategy selection on the solution of more complex problems, undoubtedly including items on tests of intelligence, may be great indeed. The relationships between strategy use and psychometric measures of ability are some of the most intriguing of the MacLeod et al. results, particularly the finding that subjects with high spatial ability tended to rely on a visual strategy. Does this mean that strategy "selection" is in some sense automatic--dictated by one's relative ability and not under conscious control? The results of a recent study by Mathews, Hunt, and MacLeod (cited in Hunt, 1980) suggest quite the opposite. These investigators replicated the pattern of data from the original MacLeod et al. experiment, this time predicting (correctly) in advance on the basis of psychometric scores which subjects should adopt spatial and which should adopt linguistic strategies. In later phases of the experiment, the same subjects were instructed concerning use of the two strategies, and it was found that they could behave in accord with either of the strategies when instructed appropriately. Thus, while an individual's choice of the type of strategy to apply--when optional--may be related to relative ability, there nonetheless appears to be considerable flexibility and trainability in strategy selection.

This conjecture is supported by recent studies by Sternberg and Weil (1980). These investigators presented subjects with linear syllogisms of the form, "X is taller than Y, Y is taller than Z, who is tallest?". They hypothesized that the strategies used by subjects to solve these problems would be related to their levels of verbal and spatial abilities. The hypothesis was confirmed, with response times of subjects who used a linguistic strategy being correlated with verbal ability, but not with spatial ability scores. The reverse correlational pattern was obtained for subjects identified as using a spatial strategy for solving the syllogisms. Of additional interest in this study is the finding that instruction as to which of several alternative strategies to adopt led to clear differences in the nature of the models that best fit the data.

There are other sources of evidence for qualitative individual differences in the perceptual and cognitive operations that are used to perform a given task. One of these sources comes from the literature on "cognitive styles." Detailed consideration of this large and complex literature is beyond the scope of our discussion (but, see Messick, 1976, for a recent review). We mention this literature only because there are suggestions that certain cognitive styles may reflect strategy differences, and that these differences are related to intelligence. Witkin (1964) presents evidence that the "field independence-field dependence" dimension of cognitive style correlates with intelligence, with more intelligent subjects being more field independent. Zelniker and Jeffrey (in press) suggest that the "impulsive-reflective" dimension of cognitive style in children derives from strategies for attending to global versus detailed aspects of visual stimuli. And there is some evidence, though conflicting, that reflective children (those who process stimulus details) score higher on nonverbal intelligence tests (Messer, 1976).

Another source of evidence for individual differences in perceptual and cognitive strategies comes from recent experiments in the information-processing tradition. In these experiments, strategy differences have typically not been related to psychometric measures of intelligence. We consider these experiments important, though, because they purport to demonstrate qualitative processing differences between individuals in relatively simple perceptual and cognitive tasks--tasks often similar to those used in the search for basic information-processing correlates of ability. To the extent that individual differences in strategies are apparent in even basic information-processing situations, we have reason to believe that they must operate as well in more complex forms of intellectual behavior. Below, we review some of these experiments in more detail.

One set of studies on individual differences in modes of perceptual processing comes from the work ~~of~~ Cooper and her collaborators on visual "same-different" pattern matching (see, in particular, Cooper, 1976, 1980a, 1980b; Cooper and Podgorny, 1976). In the basic paradigm in which the processing differences were first discovered, subjects were required to determine as rapidly as possible whether two successively presented random polygons were the same or different in shape. The second (test) polygon presented was either identical to the first (standard) or it differed by a random perturbation in shape. Further, the "different" probes varied in their rated similarity to the standards.

Inspection of the data of individual subjects revealed two distinctly different patterns. For the larger subset of subjects, "different" reaction time descreased monotonically as dissimilarity between the standard and the test shape increased. "Same" reaction time was intermediate in speed-faster than the slowest (most highly similar) "different" response, but slower than the fastest (most dissimilar) "different" response. For the smaller subset of subjects, "different" reaction time was unaffected by similarity of the test shape to the standard, and average "same" reaction time was faster than any average "different" time. This second group of subjects was also considerably faster overall than the first group. Furthermore, despite the marked differences in their reaction-time performance, the two groups of subjects did not differ in either the magnitude or the pattern of their errors. For both groups, error rate decreased monotonically with increasing dissimilarity between the standard and the test shape.

The constellation of differences in patterns of performance--involving overall response time, sensitivity of reaction time to similarity, relative speed of the "same" and the "different" responses; and the relationship between reaction time and error rate--led Cooper (1976, 1980a; Cooper & Podgorny, 1976) to argue that the two types of subjects used quite different mental operations in comparing a memory representation of a visual shape with another, externally-presented visual test shape. The subjects who were affected by similarity could be using an analytic comparison strategy, comparing the memory representation of the standard and the visual test shape feature by feature. This would explain the decrease in reaction time with increasing dissimilarity, because the more features that distinguish the memory representation from the test stimulus, the earlier will the comparison process succeed in finding one or more of those differences. The subjects who were unaffected by similarity could be using a more holistic comparison strategy, performing a parallel, template-like comparison, in an attempt to verify that the memory representation and the test shape are the same. This holistic "sameness" comparison would explain both why the "same" responses of these subjects are faster than their "different" responses and why the "different" responses are not affected by similarity. For, the "different" response could be made by default if the "same" comparison fails, requiring no further stimulus analysis. (For more details concerning the nature of these hypothesized comparison strategies, see Cooper, 1976, 1980a.)

Having isolated these performance differences in a number of independent experiments, Cooper (1980a; 1980b) went on to consider the related questions of (a) whether additional evidence for the nature of underlying comparison strategies could be obtained, and (b) whether a given individual's comparison strategy could be changed by various stimulus and judgmental manipulations. Unlike the Mathews et al. results, informal observation suggested that in the visual comparison task subjects could not modify their natural strategies by mere instruction as to the nature of the alternative strategy.

On the other hand, Cooper was successful in a series of experiments in causing some subjects to change to an alternative strategy by creating information-processing demands that naturally drew upon one strategy type or the other. Some of the central findings can be summarized as follows: When the "same-different" task is modified to incorporate the explicit detection of differences between the standard and the test shapes (by requiring subjects to determine the approximate location of a differing feature), some "holistic" subjects will switch to an "analytic" strategy. Presumably, this is because the detection of differing features is a natural part of the analytic strategy, but this information is not available to the holistic comparison operation. When the visual materials used in the comparison task are multidimensional stimuli (two alternative shapes of two alternative colors and sizes), then all subjects show results consistent with an analytic mode of processing. Presumably this is because stimuli composed of such separable dimensions (c.f., Garner, 1974) cannot be integrated into a holistic internal representation and used as a basis for visual comparison. On the other hand, when the visual materials used in the comparison task are photographs of human faces varying in their rated similarity, almost all subjects give results consistent with a holistic mode of processing. This finding is suggestive in light of the current belief that configural properties of faces make them difficult to analyze in terms of their component parts or features (see, e.g., Carey & Diamond, 1977). So, these and other findings (Cooper, 1980a, 1980b) indicate that individual subjects approach even this very simple visual information-processing task with different preferred strategies which are, to some extent, manipulable with changes in judgmental requirements and variables of stimulus structure.

To what extent might there be a relationship between ability and choice or use of a holistic or analytic comparison strategy? It is very difficult to evaluate this question, because in Cooper's studies the sample sizes were quite small, and no psychometric measures of ability were avilable for these subjects. It is worth noting, however, that the subjects were drawn from a population which most likely is relatively honogeneous with respect to ability scores. Many (in some studies, the majority) of the subjects were graduate students and faculty at universities. It is also the case that the two types of processors did not differ in their overall mangitude or pattern of error rates, so neither strategy type produced more success at the task as indexed by the error rate measure. It could be argued that in terms of optimizing all aspects of performance, the holistic strategy is superior to the analytic strategy. For, the holistic subjects have faster response times than the analytic subjects, they fail to show effects of similarity, and they do this with no detectable cost in errors. The holistic subjects also seem more flexible in adopting alternative strategies than do the analytic subjects (Cooper, unpublished data). But this account is merely speculative, going beyond the data. While any relationship between these processing strategies and ability remains elusive, the existence of marked individual differences in preferred modes of processing visual information seems relatively clear.[6]

Hock and his associates (Hock, 1973, Hock, Gordon, & Marcus, 1974; Hock, Gordon, & Gold, 1975; Hock & Ross, 1975) have proposed an information-processing dichotomy in "same-different" visual pattern matching tasks which, superficially, seems related to the "holistic"-"analytic" distinction proposed by Cooper (1976, 1980a, 1980b; Cooper & Podgorny, 1976). Basically, Hock's research strategy consists of manipulating some aspects of stimulus structure in a "same-different" comparison task. For example, Hock (1973) presented pairs of dot patterns for "same-different" comparison, and those dot patterns could be either symmetrical or asymmetrical and familiar or unfamiliar (manipulated by both pretraining and by rotating pretrained patterns 180 degrees from their familiar orientation). Mean "same" reaction-time differences attributable to the stimulus manipulations are then computed for each subject. In the case of the Hock (1973) study, this consisted of determining, for individual subjects, the difference between reaction time to asymmetrical and symmetrical patterns and the difference between reaction time to familiar and unfamiliar (rotated) patterns. These reaction-time differences are then correlated, and when a statistically significant positive correlation is obtained, it is argued that there are individual differences in strategies for processing visual information. (Additional stimulus factors that Hock and his associates have investigated in essentially the same way include physically-identical versus name-identical letter pairs, Hock et al., 1975, and intactness versus embeddedness of familiar visual figures, Hock et al., 1974.)

Hock characterizes these putative individual differences as emphases on "structural" versus "analytic" modes of processing visual stimuli. The "structural" subjects are those who are affected by the stimulus manipulations, and they are thought to process visual material on the basis of configural information. The "analytic" subjects are relatively unaffected by the stimulus manipulations, and they are claimed to process visual material on the basis of component parts or features. There are two central questions that can be raised concerning Hock's classification of individuals as "structural" versus "analytic" processors of visual information. First, is there any reason to believe that this "structural"/"analytic" distinction corresponds to the "holistic"/"analytic" distinction proposed by Cooper? Second, and more important, just how compelling are Hock's evidence and arguments for individual differences in modes of perceptual processing?

With respect to the first issue, there are several reasons for questioning a possible relationship between the processing differences proposed by Hock and those proposed by Cooper. First, the differences that Hock reports are quantitative--inferred from correlational evidence--and are found for "same" response times only. The differences that Cooper reports are more qualitative--based on patterns of performance--and are obtained for both "same" and "different" response types. Second, the "structural" subjects in Hock's experiments (presumably corresponding to the "holistic" subjects in Cooper's experiments) are generally slower overall than the "analytic" subjects. Cooper finds just the opposite, with "holistic" subjects considerably faster than "analytic" ones. Third, and perhaps most conclusively, Cooper (unpublished data) performed an experiment using groups of "holistic" and "analytic" subjects in which the same stimulus factors manipulated by Hock et al. (1975)--orientation of letter pairs and physical versus name identical matches--were used. There was no systematic difference in the sensitivity of the reaction-time performance of the two groups of subjects to these stimulus factors.

With respect to the second issue, inspection of the data from Hock's experiments reveals that the evidence for group differences in performance is surprisingly weak. Arguments for the "structural"/"analytic" processing dichotomy derive from correlational evidence, and these correlations are generally based on a small number of subjects and frequently achieve only marginal levels of statistical significance (e.g., in Hock, 1973, $r=.60$, $p<.05$, $N=24$; in Hock, Gordon, & Marcus, 1974, $r=.73$, $p<.001$, $N=32$ for Experiment 1, but $r=.40$, $p<.05$, $N=32$ for Experiment 2; in Hock & Ross, 1975, $r=.41$, $p<.05$, $N=24$). Even more disturbing, in some cases these correlations appear to be the result of the presence of a small number of extreme observations (see, in particular, Carroll's (1978) reanalysis of the Hock, 1973, data after elimination of these extreme cases). There is another quite different, reason for questioning Hock's division of subjects into "structural" and "analytic" groups. This is the lack of a theoretical basis for predicting which type of information processor should be relatively more affected by which sorts of stimulus manipulations. That is, the performance difference that Hock and his associates report is between subjects who are relatively more or less affected by stimulus manipulations. But they provide no independent reason for predicting that lack of sensitivity to stimulus variables should necessarily imply "analytic" as opposed to "structural" processing. We conclude, then, that the evidence and arguements for the "structural"/"analytic" processing difference are inconclusive, and that even if valid, this difference bears little relation to the individual differences in modes of visual comparison reported by Cooper.

As a final candidate for possible qualitative individual differences in perceptual and cognitive processing--rather unlike the visual comparison differences discussed above--we consider the work of Day (1970, 1973a, 1973b). Day (1970) has reported that when presented with components of words to the two ears at approximately the same time (e.g., "lanket" to one ear and "banket" to the other), people differ markedly in what they report hearing. Some individuals report the two components as fused (i.e., they report hearing the word "blanket"), while other individuals report the two components separately (i.e., they report hearing "lanket" and "banket" individually). When number of individuals is plotted against fusion rate, the distribution is strongly bimodal (Day, 1970), suggesting the possiblity of qualitative individual difference in perceptual processing. Furthermore, individuals who tend to fuse items in this dichotic listening task are also poor at determining which of two items, presented separately to the two ears, arrived first (Day, 1970). They also have shorter digit spans than do non-fusers (Day, 1973a), and they are less successful at learning a "secret language" in which the "r" sounds in words must be pronounced as "l" sounds, and vice versa (Day, 1973b).

Day has attributed the source of individual differences to the way in which the two types of subjects encode information from the environment. The people who tend to fuse in the dichotic listening task, or the "language-bound" subjects, are thought to encode information through a linguistic filter. That is, they are unable to disregard rules of the language in processing external stimuli. Hence, they tend to perceive separate inputs as forming English words, and they have difficulty with tasks such as the "r" - "l" reversal, in which the integrity of familiar linguistic material is destroyed. The individuals who report the two inputs separately are characterized as "stimulus bound," or "language optional." They are able to encode external stimuli quite accurately, and they are not affected by linguistic constraints except in situations in which using those constraints will actually improve their performance.

The "language-bound"/"language-optional" distinction has received considerable attention because the individual differences seem striking, and they may be arising from very basic differences in strategies for perceiving external information. But, how well has this dichotomy held up under systematic replication and various procedural modifications? Keele and Lyon (1975) undertook a study designed both to replicate Day's individual differences and to determine to what extent various tasks involving fusion were interrelated. The three tasks selected were. (1) accuracy of judging which of two inputs to the individual ears, separated by 80 milliseconds, occurred first (temporal order judgments), (2) accuracy with which inputs to one ear could be reported while inputs to the other ear were to be ignored, and (3) accuracy of discriminating whether the inputs to the two ears were the ~~same~~ word, or two word-component inputs, where the component inputs formed a word when fused. Presumably, the tendency to fuse inputs to the two ears should hurt performance on all three tasks.

Somewhat surprisingly, Keele and Lyon found that accuracies on the three tasks were only weakly related, with a maximum correlation of .38 between accuracy on temporal order judgments and accuracy on judgin inputs from one ear only. In addition, they found that the three tasks gave very different estimates of the frequency of subjects fusing, with very little fusion (high accuracy) in the word-components discrimination task. Finally, distributions of number of individuals against error scores for each of the three tasks showed no evidence of the bimodality reported by Day (1970).

In an even more conclusive set of experiments, Poltrock and Hunt (1977) attempted a systematic replication of Day's findings using a large sample of subjects (in Experiment 1, N=60; in Experiment 2, N=100).

Their results were clear: Neither dichotic fusion rates nor temporal order judgments showed evidence of bimodality. However, these two measures were significantly correlated, suggesting that individuals may differ in their tendency to use linguistic rules in judging aspects of perceptual input. These findings lead us to conclude that the "language-bound"/"language-optional" distinction originally proposed by Day does not represent a qualitative difference between individuals in modes of processing perceptual information. Most likely, individuals do differ in the extent to which they rely on linguistic rules in interpreting sensory input; however, this individual difference variable appears to be continuous and quantitative rather than discrete and qualitative in nature.

In summary, the general argument for a relationship between strategies and intelligence seems promising, though there are as yet few sources of relevant or conclusive data. Future, additional demonstrations of qualitative individual differences in modes of perceptual and cognitive processing will be welcome, and it will be important to show whether and/or how these strategy differences distinguish more from less able people. We regard as particularly significant the question of: (a) the extent to which relative differences in ability determine both strategy choice and effectiveness in the use of a particular strategy, and (b) the extent to which strategies can be modified through instruction or by changing information-processing demands. This latter question has obvious implications for training individuals to perform more effectively. And, studying this question will require research techniques rather different from those used to study basic information-processing contributions to ability differences.

Attention

Yet another possible source of individual differences in ability might involve general attentional factors. The intuitively appealing notion that brighter people pay attention more effectively has been alive in psychology for a considerable period of time. Indeed, William James (1890) speculated at length about the relationship between attention and intelligence, taking the position that "what is called sustained attention is the easier, the richer in acquisitions and the fresher and more original the mind" (p. 423).[7] Surprisingly, however, very little empirical work has been done on individual differences in attention and their possible relationship to ability. When we consider this relationship, two possibilities suggest themselves. One is that more able people can more effectively direct or sustain attention where required. Such people could be said to have greater "attentional flexibility." The other possibility is that more able people simply have more attentional resources, capacity for processing information, or cognitive energy (see Kahneman, 1973). We briefly consider some empirical work directed toward each of these possibilities below.

Kahneman and his colleagues (Gopher & Kahneman, 1971; Kahneman, Ben-Ishai & Lotan, 1973) have reported two provocative studies on individual differences in attentional flexibility and their relationship to various measures of ability. Their strategy was first to devise a test of subjects' ability to sustain or direct attention in response to a cue, and then to relate performance on the test to measures of complex psychomotor skills in the natural environment--piloting airplanes and driving buses. The test, which involved dichotic listening, consisted of two parts. In the first, messages were presented to both ears, and subjects had to report target items only when they occurred on the cued ear. Immediately following and continuous with part one, subjects were cued as to which ear was relevant for part two. Effectively, the cue instructed the subject whether to maintain attention on the same ear, or switch to the other ear. The task again was to report target items which occurred on the cued ear only. Correlations were computed between each of three test scores--omissions in part one (failure to report a target on the attended ear), intrusions in part one (reporting a target on the irrelevant ear), and total errors in part two--and the flying ability of pilots in the Israeli Air Force (Gopher & Kahneman, 1971) as well as accident ratings of Israeli bus drivers (Kahneman, Ben-Ishai & Lotan, 1973). Total errors on part two correlated most highly (approximately .36) with each of these criterion variables. The authors suggest that this relationship reflects individual differences in an ability common to both the requirements of the attention task in part two and those of normal driving or airplane piloting. This is the ability rapidly to shift or maintain already directed attention in response to an external signal.

There are some problems with this interpretation of the data, however. We mention two. First, measures of both intelligence and errors on part one were significantly (though more modestly) associated with the criterion variables and with errors on part two. And, there was no attempt to establish (via partial correlation or other statistical techniques) the independent contribution of part two errors to the behavioral criteria. Thus, the relationship between part two errors and the criterion variables could reflect some (perhaps motivational) factor much more general than attentional flexibility. Second, the argument that part two errors provide a measure of attentional flexibility is based only on a logical analysis of the task, with no additional converging evidence. The idea of meaningful individual differences in attentional flexibility gains credence, however, from the results of a recent study by Keele, Neill and de Lemos (1978). These investigators devised three tests of attentional flexibility (in addition to using a version of the Kahneman part two test). The pattern of intercorrelations among performance on the various tests was somewhat complex, but there were suggestions of significant relationships among most of them. Thus, while further work is needed, it may be that there is a general trait of attentional flexibility on which individuals varying in ability differ.

Finally, we turn to the idea that individuals differ in the extent of their attentional capacity or resources. Both Baron and Treiman (1980) and Hunt (1980) have suggested that resource differences may be strongly related to intelligence. Indeed, Hunt (1980) has proposed that differences in attentional resources may make at least as large a contribution to differences in ability as does the efficiency of basic information-processing skills. He also suggests that a general factor of attentional capacity could account for the reasonably high correlations among various measures of intellectual ability. The concept of attentional resources is similar to Spearman's (1927) notion of "mental energy." According to Norman and Bobrow (1975), "resources are such things as processing effort, the various forms of memory capacity, and communication channels. Resources are always limited" (p. 45). The basic idea is that more able people have more resources, and thus will perform more competently when multiple demands are placed on those resources.

What empirical evidence is there for individual differences in attentional resources? In investigating this question, the "dual task" method is most frequently used. (See, for example, Posner, 1978, and Norman & Bobrow, 1975, for details.) In this method, multiple demands are placed on the information-processing system, and the extent and nature of performance breakdowns are observed. The multiple demands are in the form of two tasks that must be performed simultaneously or nearly so. The relationship between performance on the two tasks as one of them is made more difficult is frequently the dependent variable of interest. The application of the method to the question of individual differences in attentional resources is illustrated by two studies reported in Hunt (1980).

In the first, subjects did a hard or easy memory task while simultaneously performing a simple probe reaction-time task. There was a significant correlation across individual subjects of -.40 between probe reaction time while performing the easy memory task and proportion correct on the hard memory task. The logic for interpreting this correlation as due to individual differences in attentional resources is as follows: The memory task and the probe reaction-time task compete for fixed resources. The more limited a subject's resources, the longer the probe reaction time will be even under the relatively undemanding conditions of the easy memory task. When the memory task becomes hard, more limited subjects (identified by the long reaction times in the easy memory condition) will have few resources left to do this difficult task, and their error rate will be high. Hence the correlation. In a second study more directly related to ability differences, subjects simultaneously solved increasingly difficult problems on the Raven Progressive Matrices Test and performed a simple psychomotor task. By the same logic applied above, there should be a correlation between performance on the psychomotor test while doing relatively easy Raven items and the point at which the subject makes his first error as the items become more difficult. The correlation was -.30.

Both of the results from the Hunt (1980) paper are consistent with the position that people differ in general processing capacity, and that this difference is related to ability. But there are other interpretations of the data as well. It is possible that there are multiple, separate, minimally-correlated pools of resources for performing different types of tasks. Demonstrating general capacity differences across individuals would seem to require showing within-subject consistencies (and across-subject differences) in the point of breakdown in performance, if any two tasks are used that compete for attention. Recently, Sverko (19--) has attempted such a demonstration. He tested subjects on four quite dissimilar information-processing tasks, administered both singly and in all possible pairwise combinations. The four tasks involved rotary pursuit, digit classification, mental arithmetic, and an auditory discrimination.

In order to assess whether the data provided evidence for the notion of a general capacity (in Sverko's terms, a "unitary time-sharing ability"), two analyses were done. First, the performance of subjects in each experimental condition (individual tasks and task pairings) was correlated with performance in all other conditions. This intercorrelation matrix was then subjected to a factor analysis. Sverko reasoned that if there was a general time-sharing or resource-related ability, then five factors should emerge in the analysis. Four of these factors should correspond to the four specific tasks, and the fifth should represent the more general ability. Instead, only four task-specific factors were found. In a second analysis, Sverko computed a total performance decrement score for each task pairing by adding the proportionate performance change for the tasks when paired, relative to when they were undertaken individually. Correlations were computed between the decrement scores for the three task pairings that did not contain overlapping tasks (i.e., tasks 1 and 2 versus tasks 3 and 4, tasks 1 and 3 versus tasks 2 and 4, and tasks 1 and 4, versus tasks 2 and 3). If the various tasks were drawing on a common, limited resource pool, then the correlations should have been substantial. In fact, all correlations were extremely low, ranging from .060 to .068. These results provide rather compelling evidence against the notion of a truly general, unitary, transsituational time-sharing ability or resource pool.

How, then, are we to account for the findings reported in Hunt (1980) and those of others who have argued for general attentional resources from experiments using the dual-task method? One possibility is that the notion of individual differences in attentional resources, processing capacity, or an ability like "time-sharing" still makes sense, but only if we view the idea of capacity in a less general way. That is, there could exist multiple, separate pools of resources each limited in capacity and only minimally intercorrelated. (See Hawkins, Church & de Lemos, 1978, for a clear statement of this view as it relates to individual-differences research.) Capacity limitations, and hence performance decrements in the dual-task situation, will only be observed when two tasks compete for the same pool of resources. This is a difficult position to evaluate experimentally, for we have little in the way of a priori notions as to which tasks should tap common, as opposed to separate, sources of capacity. At a minimum, this view is consistent with research on "structural interference" (e.g., Brooks, 1968) which suggests that limited resources may be specific to spatial and verbal processing.

Another possibility is that the attentional contribution to ability is a skill, dependent on practice, rather than a limited-capacity resource. According to this view, individuals could differ in their levels of performance on concurrent tasks primarily because of the extent of their relative practice at doing two things at once. Some provocative findings of Damos and Wickens (1977) suggest that at least some portion of differences in time-sharing performance--presumably reflecting capacity limitations--are indeed dependent on practice at combining any two activities. In this study, three groups of subjects were tested in a situation that involved combining two independent psychomotor tasks. Prior to the testing, one group had been trained on performing a short-term memory task and a digit classification task simultaneously, a second group had been trained on performing the tasks sequentially, and a third group had received no training at all. Somewhat surprisingly, the group that had had previous training on the concurrent information-processing tasks showed superior performance on the concurrent psychomotor tasks. This result suggests that practice at combining any two tasks will transfer to other multiple-task situations. Note that this does not necessarily imply that there are no skill- or practice-independent individual differences in resources or processing capacity. Rather, these findings suggest that an individual's level of practice at a given point in time may contribute to just how effectively limited resources may be utilized.

In conclusion, we find the idea of individual differences in attentional factors as possible determinants of ability differences to be an intriguing possibility. As we have noted, however, the relevant data base examining this relationship is meager indeed. Furthermore, interpretation of the sources of individual differences--particularly in the dual-task experiments--is problematic at best. But this should not be surprising. Quite apart from any concern for understanding attentional contributions to individual differences in intelligence, the question of the nature of capacity or resources is currently quite a controversial one in cognitive psychology more generally. Some theorists argue that a general, limited-capacity resource pool underlies attentional phenomena (see, for example, Norman & Bobrow, 1975), while others argue for multiple, independent sources of capacity (see, for example, Navon & Gopher, 1979). Still others (see Neisser, 1976; Spelke, Hirst & Neisser, 1976) have argued that the entire notion of capacity limitations is misguided, and they have emphasized instead the role of practice in developing skills at performing combinations of tasks. Perhaps the study of the relationship between ability and attentional factors--as promising as it might appear to be--should await further theoretical resolution within cognitive psychology concerning the nature of attention and processing resources.

Concluding Remarks

Having reviewed a considerable body of literature on relationships between attentional and perceptual processes and intelligence or ability, what can we conclude? Our tentative answer is "surprisingly little," but there are some firmly established findings and some promising research directions. Our quest to relate these three concepts in cognitive and in differential psychology began with a consideration of the extent to which quantitative differences among individuals in basic information-processing skills correlated with differences in ability. Some of the research in this area is elegant indeed (see, for example, the studies of Jackson, Note 2, and Jackson & McClelland, 1979). And, we distinguished among approaches that we viewed as more or less adequate. In particular, we found congenial those studies that, in addition to showing evidence for a relationship between information-processing parameters and ability, also provided construct validity for the information-processing components that were being correlated with the ability measures.

Nonetheless, the findings from this recent and substantial research effort have often been disappointing and sometimes conflicting. In the areas of verbal and reading ability, it seems clear that efficiency of memory access (for any conceptual category) differentiates more from less able people. In the area of spatial ability, encoding speed is related to proficiency, but speed of mental manipulation may or may not predict performance on psychometric measures.

In addition, the few differences in information-processing skills that distinguish higher from lower ability subjects tend only to account for a small portion of the variance (typically about 10%) of performance on intelligence tests (though they discriminate more effectively between extreme groups on any intelligence dimension). Finally, interpretation of correlations between information-processing skills and ability is plagued with the problem of developing adequate theoretical accounts of the cognitive tasks that are being related to the intelligence measures.

We view as promising the idea that attentional and strategic factors may contribute substantially to ability differences, particularly in view of the low correlations between basic information-processing parameters and individual differences. With respect to individual differences in strategies--or procedures for selecting, combining, and executing information-processing operations--there are several important questions that beg for more empirical research. They include: At what levels can qualitative differences in processing modes or strategies be isolated? (Some of the work that we have reviewed suggests that strategy differences can be found in rather low-level information-processing operations, as well as in higher-level problem solving situations.) To what extent do strategy differences relate to ability or derive from relative ability differences? To what extent are strategies trainable or manipulable by varying task demands? Again, with respect to the relationship between strategies and intelligence, to what extent is initial strategy selection--as opposed to the efficiency in using a strategy, once selected--correlated with ability?

Studying individual differences in strategies and their relationship to intelligence is difficult, and we mentioned earlier that it may require research approaches somewhat different from those standardly used in cognitive psychology. This is because we rarely know in advance what strategies will be more or less effective in what situations. Rather, we infer strategic differences from quantitative or qualitative differences between individual subjects in patterns of data. In two of the cases discussed earlier, evidence for strategies emerged initially from post hoc individual-differences analyses of performance on simple cognitive tasks. In the MacLeod et al. (1978) study, strategy differences were inferred from the wide range of individual subjects' correlations between reaction-time performance on the sentence-picture verification task and predictions of a particular model of the cognitive operations required by the task. In the Cooper (1976, 1980a) studies, differences in processing modes were inferred from qualitative differences in individual subjects' patterns of reaction-time and error performance in a visual comparison task.

But, isolating strategy differences via such "trial and error" post hoc individual differences analyses is hardly likely to be an effective research strategy. We need, in addition, to provide an analysis of the nature of the alternative strategies and to determine in advance which subjects are likely to use which strategies in which situations. In the case of both the MacLeod et al. and the Cooper studies, such a second step was taken. Mathews et al. (reported in

Hunt, 1980, and following up on the MacLeod et al. experiment) were able to predict--on the basis of verbal and spatial ability scores--which subjects would use which strategies, and they were further able to manipulate strategy use through instruction. Cooper (1980a, 1980b) was able to gain independent evidence for qualitative strategy differences by, first, providing an analysis of the nature of the hypothesized strategies, and, next, by constructing information-processing tasks whose demands naturally drew on one strategy type or another. To the extent that these new tasks forced certain subjects to change their patterns of performance (and, by inference, their visual comparison operations), evidence for differential strategy use was obtained. In the case of studies like Cooper's, it remains to relate strategy selection to intelligence, ability, or some criterion measure.

There are other ways in which strategies could be studied, and they depart somewhat from the standard information-processing tradition. One method might involve isolating groups of subjects that differ extensively on some criterion measure of interest (e.g., people who learn to get around in new environments easily versus people who habitually and continually get lost). We could then query these individuals concerning their strategies for learning spatial layouts. From the verbal reports, we could attempt to analyze the strategies in terms of more basic information-processing skills. We could then perform laboratory experiments in which subjects were instructed to use alternative strategies, and performance differences could be assessed. This approach is similar to that of Thorndyke and Stasz (1980), based on protocol analysis of a map learning task. The method has distinct potential, but it suffers from two rather obvious problems. The first is that some strategies that we might wish to study--particularly those involving basic perceptual and cognitive processing--might not be available to conscious introspection and hence verbal report. The second is the possible difficulty of translating verbal reports of strategies into experimental manipulations. Still another method for studying strategies is essentially the one advocated by Baron (1978). This involves generating logical hypotheses concerning the nature of strategies that might lead to efficient, intelligent behavior. We could then design tasks that tap these strategies, or train subjects in the use of these strategies and observe relative changes in performance. The success of this approach depends, of course, on having the proper intuitions concerning the nature of the strategies that contribute to intelligence.

Finally, we wish to comment on the idea that attentional flexibility and/or amount of processing resources make important contributions to individual differences in abilty. This is an intriguing possiblity, and there already exists some relevant and suggestive research. We predict that the relationship between attentional factors and intelligence will be a very active research area for the next several years--particularly in light of the mixed success in establishing correlations between basic information-processing skills and ability. As promising as this direction might seem, we nonetheless have some misgivings.

The approach to studying this question appears to involve translating a task currently fashionable within cognitive psychology--in the case, of attentional resources, the dual-task method--into an individual-differences framework. This approach is reminiscent of the effort, reviewed above, to establish correlations between basic information-processing tasks and psychometric measures of ability. As we have seen, interpretations of these relationships have sometimes suffered from an inadequate theoretical analysis of the cognitive operations underlying the information-processing tasks. In the case of tasks measuring demands on attentional resources, controversies over interpretation are even more apparent at this point in time (see, for example, Kantowitz & Knight, 1976; Navon & Gopher, 1979).

What we fear is that research on attentional contributions to intelligence could experience a fate similar to that of some of the research on basic information-processing determinants of ability: Namely, establishing that individual differences exist, but not knowing what those individual differences really mean. The general point that we make, in concluding, is that progress in research on individual differences in ability must parallel the adequacy of theory and of understanding of experimental paradigms in cognitive psychology. Any effective unity between cognitive and differential approaches must be grounded in a clear understanding of the nature of general mental operations, and the experimental tasks and situations suitable for isolating and investigating them. One thrust of this paper has been that we do not expect such unity to emerge from investigations of how people of varying ability perform on tasks that are themselves inadequately understood. What this implies is that meaningful work on the contributions of attention and perception to intelligence must await a clearer conceptualization within cognitive psychology itself of the nature of those mechanisms.

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Footnotes

[1] Preparation of this chapter was supported in part by NSF grant BNS 76-22079 to the first author. We wish to thank Robert Vallone for his unstinting help in all phases of the preparation of this chapter.

[2] Lohman (1979a) presents an impressive array of evidence for the existence of three major spatial factors--Space Relations, Visualization, and Orientation--as well as a host of minor factors.

[3] This finding may puzzle cognitive psychologists who consistently find relationships between speed and accuracy in information-processing tasks. Indeed, even in Egan's (1976, 1978, 1979) data, reaction time and error rate are positively correlated across experimental conditions. That is, for the group data from, for example, the mental rotation task, both reaction time and error rate increase monotonically with angular difference in the orientations of the two visual objects being compared. It is only in the individual-differences analysis of overall accuracy on tests of spatial ability and latency on the information-processing versions of these tasks that virtually no correlation is found.

[4] There is one exception to this generalization in the studies reviewed in this section. Kail et al. (1979) found slope differences between the male and female subjects, but they found no reliable intercept differences between the sexes.

[5] Beyond the scope of our discussion is the considerable body of research on memory and retrieval strategies, some of which is reviewed by Baron (1978). We will also not consider some recent and intriguing work on developmental changes in strategies for attentional and perceptual processing (see, for example, Kemler & Smith, 1978; Smith & Kemler, 1977, 1978).

[6] Recently, Agari (Note 7) has attempted to replicate Cooper's (1976) individual differences in visual processing using a larger sample of subjects and a slightly shortened version of Cooper's task. While Agari found that the processing parameters used to identify the different subject types were highly correlated, evidence for the sharp dichotomy reported by Cooper was not obtained. The reasons for this discrepancy remain obscure.

[7] This quote does not really do justice to James' position on the relationship between attention and intelligence. To James, highly intelligent people were able to attend more effectively because of their superior mental abilities. Quoting him, "Geniuses are commonly believed to excel other men in their power of sustained attention--But it is their genius making them attentive, not their attention making geniuses of them" (James, 1980, p. 423). Contrast this with the view that we are considering--viz., that individual differences in attentional factors may constitute determinants of ability differences.