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Understanding Spatial Ability

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Spatial ability is discussed in terms of psychometric factors and information processing research. Reanalysis of major psychometric studies suggests two major spatial factors — spatial relations and spatial visualization ability. Apparent differences between these factors in speed versus power and cognitive complexity are verified by process analyses of individual differences in spatial relations and visualization ability. Information processing studies suggest multiple sources of individual differences such as process execution speed, quality and capacity of representation, process coordination and strategies for problem solution. Consideration is also given to additional issues for research as well as implications for testing.

The concept of a separate intellectual ability known as spatial ability, which is differentiated from other abilities such as verbal, quantitative or reasoning ability is derived from psychometric research and theory. The effective use of spatial information is one aspect of human cognition, and it is manifest in situations ranging from navigating through one's environment to determining the trajectories of approaching objects. These skills are also required in intellectual endeavors ranging from solving problems in engineering and design to physics and mathematics. Evidence of the importance of spatial ability in these various areas can be found in the recent review by McGee (1979) of the predictive validity of measures of spatial ability. For academic and vocational training programs, spatial ability tests correlate with course grades in mechanical drawing, shop courses, art, mathematics, physics and mechanics. In the area of job performance in industry, spatial ability tests have been proven useful in predicting success in engineering, drafting, design and other mechanically oriented areas. The predictive validity of such tests frequently surpasses that obtained from verbal ability or general intelligence tests.

Given the potential importance of this aspect of intellectual ability and the wide variation among individuals, how might we understand this aspect of cognition? Our goal in this article is first to summarize what is meant by spatial ability from a psychometric or assessment perspective since spatial ability turns out to be composed of several subfactors. This summary serves as the basis for then presenting some of the results from information processing research attempting to isolate the cognitive processes associated with overall ability differences. The final section of this article considers some of the implications of these attempts to understand spatial ability and directions for further research.

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Psychometrics of Spatial Ability

Recently, two reviews of psychometric studies of spatial ability have appeared, one by Lohman (1979) and the other by McGee (1979). Both re-emphasized points made by Smith (1964) in a much earlier review of this ability domain. First, they were clear in noting that virtually all major factor analytic studies have identified mechanical-spatial factors that are distinct from other general and specific factors. However, both also point out that spatial ability is still an ill-defined construct after 70 years of psychometric research. There often appears to be little agreement among major studies as to the number of distinct spatial abilities that exist and how best to characterize each one. Carroll (1983) and Lohman (1979) mention several reasons for such a situation and have stressed the need for reanalyses of data from major psychometric studies. Conflicts in the literature can be attributed to (a) different methods used in the extraction and rotation of factors, (b) differences in the subject populations and composition of test batteries, and (c) differences in the administration, format and content of tests bearing the same label.

In Thurstone's (1938) study of primary mental abilities, he identified a "Space" factor which represented the ability to operate mentally on spatial or visual images. Zimmerman (1953) subsequently re-analyzed Thurstone's data and derived two spatial factors. The first was identical to Thurstone's Space factor and seemed to involve mentally manipulating objects and object relationships. Zimmerman labelled this as the Spatial Relations factor. The second factor was called Visualization and the tests loading on this factor tended to be more difficult and less speeded than those loading on the Spatial Relations factor.

Another major study of spatial ability was conducted by Guilford and Lacey (1947). They identified two strong spatial factors, spatial relations and visualization, and also obtained two weaker spatial factors labelled simply as *S2* and *S3*. The spatial relations and visualization factors were the same as those found by Thurstone and Zimmerman, but the *S2* factor seemed to emphasize tests of right versus left hand discrimination. The *S3* factor was subsequently dropped as irrelevant. In 1952 Guilford, Fruchter, and Zimmerman reported the factor analysis of a 65 test aptitude battery administered to over 8,000 aviation students and reported in part in Guilford and Lacey (1947). This study yielded five spatial factors denoted as Spatial Relations, Visualization, Spatial Orientation, Spatial Scanning, and Perceptual Speed. The first two were identical to the factors discovered earlier. The Spatial Orientation factor was characterized by "empathetic involvement" where spatial judgments were made given a particular orientation of the individual. The Spatial Scanning factor involved the use of planning in order to visually map out a correct route on a test like maze tracing. Finally, Perceptual Speed related to tests involving rapid identification of a letter in a letter string.

Given the diversity of findings in the literature, a necessary step towards understanding spatial ability is the reorganization of psychometric data with the goal of standardization. Lohman (1979) attempted such a reorganization by re-analyzing within a hierarchial framework the data from major American psychometric studies such as those mentioned earlier. The result of his efforts was the delineation of at least two distinct and replicable spatial factors. To help understand these factors it is necessary to examine the types of tasks and performances associated with these factors.

Figure 1 shows examples of four tasks that tap Spatial Relations ability. The problem shown at the top of the figure is drawn from Thurstone's Primary Mental Abilities test. It requires identification of those alternatives identical to the standard on the left. Identity is defined in terms of rotation in the picture plane whereas mismatches involve rotation plus mirror image reversal. The second problem type shown in Figure 1 is the cards test from the French Reference Kit (Ekstrom, French, & Harman, 1976). The format of the problem is identical to the problem from the Primary Mental Abilities test. The third problem type in Figure 1 is the cubes comparison test from the French Reference Kit. The task is to determine if each pair of cubes is logically consistent. This requires one or more 90 degree rotations to bring surfaces into congruence for a consistency check. The final problem type in Figure 1 is taken from a test adapted by Vandenberg (1971) based on stimuli originally used by Shepard and Metzler (1971). The task is to find the two stimuli on the right that are the same as the standard on the left. This requires mental rotation in the depth or picture plane. Tests composed of problems such as those illustrated in Figure 1 define the Spatial Relations factor. This factor seems to tap the ability to engage rapidly and accurately in mental transformation or rotation processes for judgments about the identity of a pair of stimuli.

The second major spatial ability factor is referred to as Spatial Visualization, and it is defined by a variety of problem types. Figure 2 shows examples of some common spatial visualization problems. The problem shown at the top of Figure 2 is drawn from the Minnesota Paper Form Board Test (Likert & Quasha, 1970). The task is to select the completed figure that can be constructed from the set of randomly arranged pieces shown in the upper left corner of the item. The second problem shown in Figure 2 is the punched holes test from the French Reference Kit. The left portion of the problem shows a hypothetical series of folds of a square of paper followed by the puching of a single hole. The task is to determine the number and location of the holes when the paper is unfolded and select the appropriate answer. The third

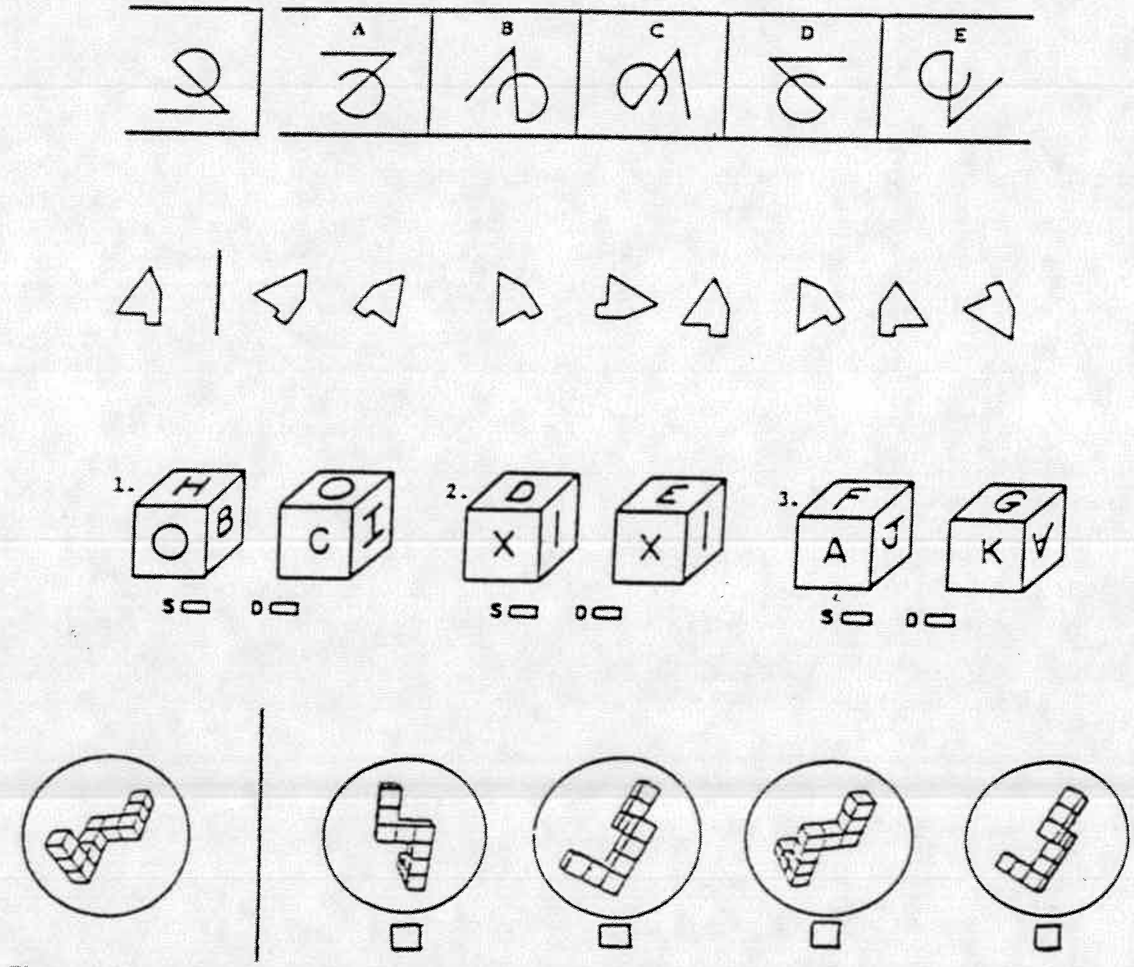

Figure 1. Examples of spatial relations problems (from Pellegrino & Kail, 1982; reprinted with permission).

problem type in Figure 2 is known as a surface development problem and it comes from the Differential Aptitude Test (Bennett, Seashore, & Wesman, 1974). The left portion of the item is a representation of a flat, unfolded object. The right portion of the problem is a series of completed objects. The task is to select the completed object that can be made from the unfolded object. The Spatial Visualization factor is defined by tests that are relatively unspeeded and complex. Such tasks frequently require a manipulation in which there is movement among the internal parts of a complex configuration and/or the folding and unfolding of flat patterns.

Conclusions from Lohman's (1979) reanalysis of factor analytic data are illustrated in Figure 3. Spatial ability is decomposable into at least two major subfactors referred to as Spatial Relations and Spatial Visualization. Each of these subfactors is asessed by specific tests or problem types. The differences between Spatial Relations and Visualization tasks seem to represent two correlated dimensions of performance. One of these is a speed-power dimension. Individual spatial relations problems are solved more rapidly than spatial visualization problems, and the tests themselves are administered in a format that emphasizes speed in the former case and both speed and accuracy in the latter case. Test "speededness" may be measured by the number of items in a test divided by total time allowed. Lohman's (1979) analysis of 14 spatial ability tests indicated a correlation of .75 between "speededness" and factor loadings supporting the hypothesis that the spatial relations vs visualization split partially reflects such

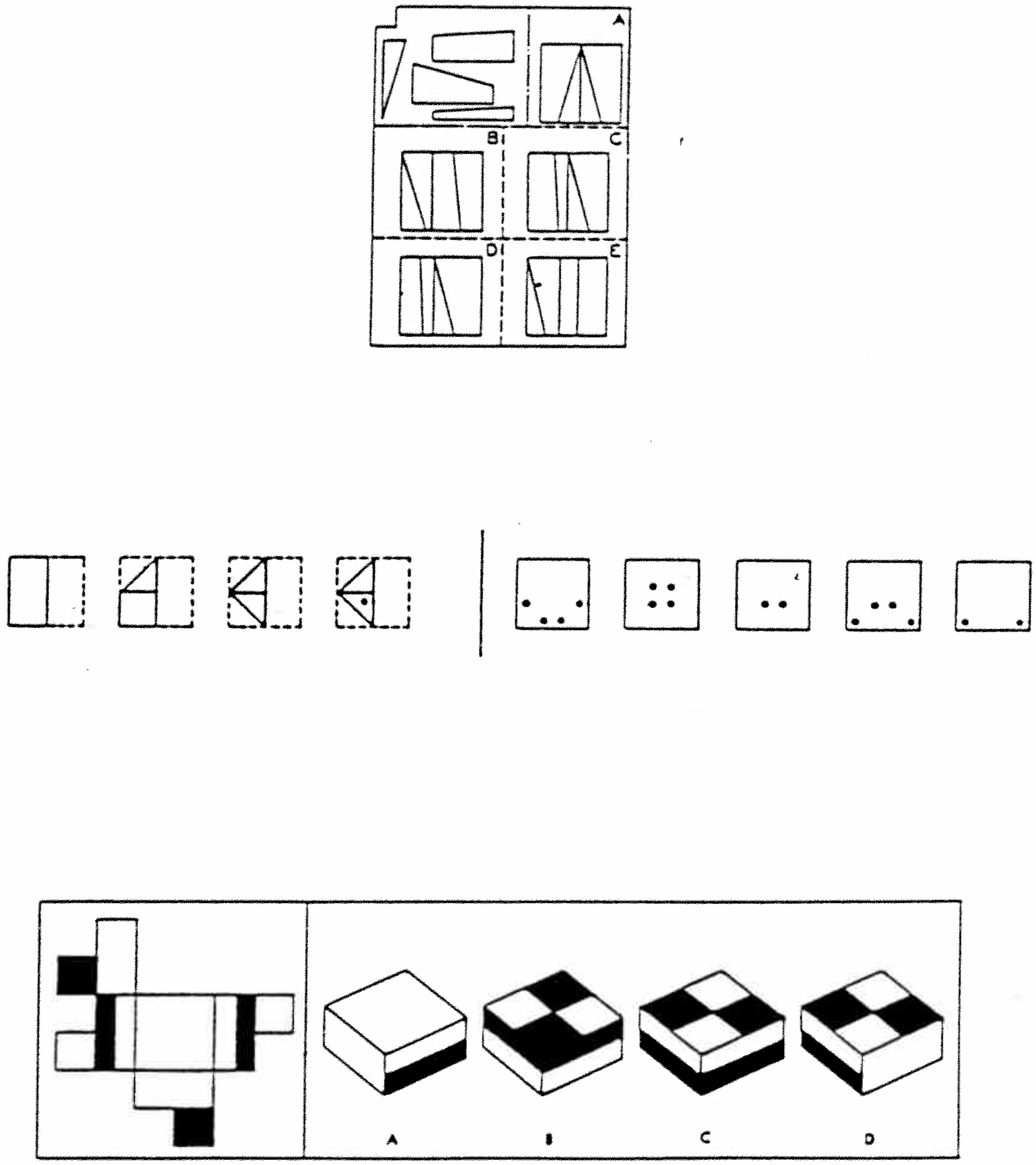

Figure 2. Examples of spatial visualization problems (from Pellegrino & Kail, 1982; reprinted with permission).).

a speed-power dimension. The second dimension shown in Figure 3 involves stimulus and cognitive processing complexity. A gross index of stimulus complexity is the number of individual elements or parts that must be dealt with. Spatial relations problems, although varying among themselves in complexity, involve less complex stimuli than spatial visualization problems. In terms of cognitive processing complexity or effort, an intuitive analysis suggests that more mental operations and coordination are required to solve spatial visualization problems.

The recent re-analyses of psychometric studies of spatial ability have helped impose some order and interpretation on an important set of data about variation in intellectual ability. We know from psychometric studies that

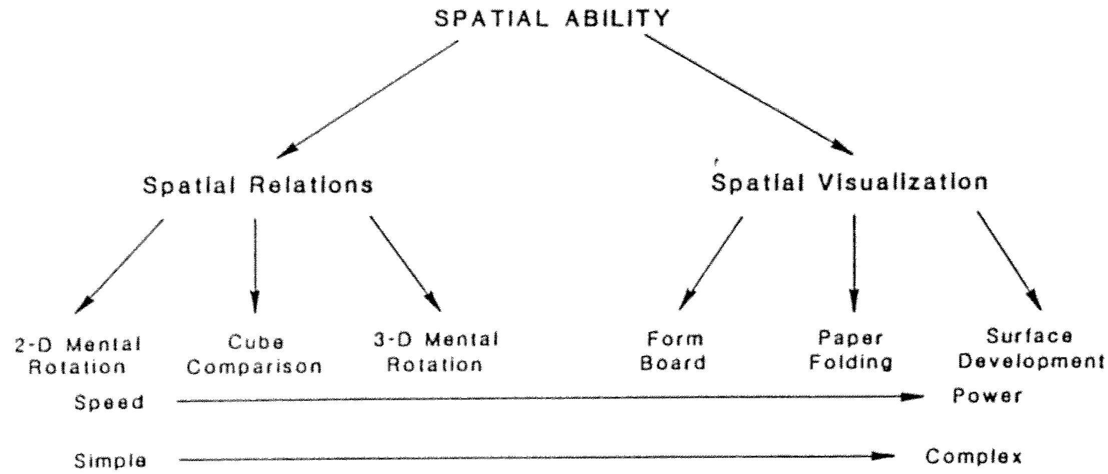

Figure 3. Schematic representation of spatial ability (from Pellegrino & Kail, 1982; reprinted with permission)).

there are substantial variations among individuals in their ability to solve problems involving the manipulation of figural or pictorial stimuli. However, these variations are not uniform over the spatial problem types that have been devised for testing purposes. This lack of uniformity gives rise to a further differentiation of spatial abilities ranging from simple perceptual speed to spatial relations to spatial visualization ability. These abilities are correlated but the pattern and problem forms suggest continua in the number and type of mental processes that underlie performance and individual differences. (See also Zimmerman [1954] for a related discussion of item characteristics and factor loadings.)

Cognitive Process Analyses of Spatial Ability

A principal shortcoming of the factor analytic approach to mental ability is its inappropriateness for discovering the cognitive processes underlying performance on any intellectual task. Factor analysis is limited to analyzing inter-item structure across tasks and individuals. However, the locus of intelligence and aptitude is not between individuals, tests or items. Rather, the source of inter-item and inter-test variance is the dynamic processes that individuals bring to bear on problems presented in tests (see Resnick, 1976). Factor analysis can only identify major categories of mentation and groups of tests that seem to require the same skills. This limitation was noted by Thurstone (1947): "The factorial methods were developed for the study of individual differences among people but these individual differences may be regarded as an avenue to the study of the processes which underlie these differences." (p. 55)

In contrast to factor analysis, information processing analysis has the goal of understanding the basic processes and process coordination involved in solving a specific problem. This theoretical and methodological approach provides a powerful set of "tools" for decomposing item solution into the requisite mental operations underlying overall performance. However, this approach does not directly provide techniques for discovering the ways in which these processes combine to form consistent patterns of individual differences in diverse tasks.

By combining information processing analyses with factor analytic results, a richer understanding of human ability can be achieved. This combined approach has been referred to as cognitive components research (Pellegrino & Glaser, 1979) and componential analysis (Sternberg, 1977). Process analyses of spatial ability have been pursued over the past few years, and they have moved us closer to an understanding of individual differences in spatial ability. These analyses have separately focused on the spatial relations and visualization factors delineated in psychometric research.

Before considering process analyses of performance on tasks representing spatial relations and visualization, it is important to set the theoretical context for conducting such studies.

Cognitive psychologists such as Roger Shepard, Lynn Cooper, and Stephen Kosslyn have vigorously pursued theoretical and empirical issues concerning spatial information processing. As a result of these efforts we now have a reasonably well developed theory of the cognitive structures and processes that underlie the solution of a wide range of spatial reasoning problems, including those found on standardized tests of spatial ability.

For purposes of discussion we will briefly focus on the elaborate theory developed by Kosslyn (1981). Although it is conceived as a theory of mental imagery, it is also applicable to issues concerning the processing of visual stimuli. A central aspect of this theory is the idea that the human mind creates and operates on analogical representations that preserve spatial properties of visual stimuli. The theory distinguishes between structures and processes. One structure is a visual buffer or short term memory. This medium mimics a coordinate space and it supports data structures that depict information. Regions of the buffer are activated and these regions correspond to portions of depicted objects. Relations among activated portions mirror actual physical relations of the object or objects depicted. The visual image or representation resides in the visual buffer and such a representation is derived either from actual visual imput or from information stored in long-term memory. The other major structures in the theory are the types of information stored in long-term memory. This includes both propositional information about the parts of objects and their relations, and information about the literal appearance of an object.

Kosslyn postulates a set of processes that operate on the various structures just described. For present purposes we will focus on those processes that operate on the visual buffer. One major process is Regenerate which refreshes or reactivates the representation which fades over time. Of particular significance are the processes for operating on visual representations for the purpose of transforming them. Several specific transformation processes are postulated, and these include Rotate, Scan, Pan, Zoom, and Translate. Each of these processes involves some manipulation of the representation resulting in a modification of the representation in the visual buffer. Finally, there are processes that inspect and classify patterns depicted in the representation. These include a Find and Resolution process.

Kosslyn's theory is an attempt to address the issue mentioned earlier — namely, the mechanisms underlying specific intellectual performances. The performances of interest are the manipulation of simple and complex visual representations for the purposes of making decisions or solving problems. There are several ways in which we can use his theory to discuss issues about this domain of intellectual ability. First, it emphasizes the fact that the processing of visual-spatial information is composed of many basic processes that interact with information representations of varying detail and clarity. Second, tasks or performances can vary on several dimensions. One such dimension is the number of processes that must be executed to achieve a given result. Another dimension is the types of processes necessary to achieve that result. Third, individuals can vary in their performance depending upon how well they can perform certain processes and the extent to which those processes are necessary for solving different types of problems.

A theory of spatial information processing, such as Kosslyn's theory, not only addresses issues concerning the mechanisms underlying this class of intellectual performance, but it also provides a basis for understanding issues associated with individual variation within this intellectual ability domain. We have a framework for simultaneously analyzing differences among individuals and tasks and for understanding psychometric data on spatial ability.

Earlier we indicated that spatial ability can be broken down into at least two major factors and that these factors seem to vary on two dimensions. One was the speed-power dimension and the other was a complexity dimension. We can treat these dimensions as hypotheses about what we would expect to find as the major sources of individual differences in tasks sampled from these continua. More specifically, we would expect that individual differences in simple spatial relations tasks would be primarily associated with measures of processing speed while individual differences in complex spatial relations and spatial visualization tasks would reflect an increasing contribution of processing accuracy. Similarly, we would expect that the models for describing task performance would reflect a larger number of component processes and/or more executions of individual processes. Both of these expectations have been borne out in our data, and we will now illustrate some of these results.

Spatial Relations Performance

A basic aspect of any process analysis of ability is the development of explicit process models for individual tasks representing an ability factor. The process models provide a basis for examining exactly how individuals differ on specific components of processing such as encoding, rotation, transformation or comparison of visual stimuli. To estimate these processes, laboratory tasks are designed that emulate the problems found on psychometric tests. The laboratory tasks include systematic problem sets that permit model testing and parameter estimation for individuals who are known to vary in the ability of interest.

This approach has been used to examine sources of individual differences in several tasks representing the spatial relations factor. Earlier we illustrated that spatial relations problems are typically presented in a matching-to-sample format with a standard or referent presented along with several alternatives to be individually evaluated relative to the standard. The individual's task for most spatial relations problems is to find those alternatives that can be rotated into congruence with the standard. The distractors or non-matching stimuli are typically mirror image reflections of the standard that have also been rotated. Thus, the individual must make a series of same-different judgments on pairs of stimuli involving different degrees of rotation or angular disparity. Information processing models have been developed for this type of mental rotation task (Cooper & Shepard, 1973; Shepard & Metzler, 1971), and they can be used as the basis of a process analysis of spatial relations ability.

To solve a typical spatial relations problem, the individual must encode, i.e., internally represent, each of the stimuli in the pair. Then, a rotation process must be executed on one of the representations to attempt to bring corresponding features into congruence, i.e., orient the stimuli the same. The individual must then compare the two representations to see if they match and execute a response of same or different. When problems of this type are presented, the time to make a decision is a systematic linear function of the differences in orientation between the two stimuli. As the angular disparity between the stimuli increases, more rotation must be done to bring features into congruence. Thus, the slope of the linear function relating reaction time to angular disparity provides an index of the rate of the mental rotation process while the intercept provides an index of the encoding, comparison and response processes.

The process model applied to typical mental rotation data provides the basis for a process analysis of individual differences in spatial relations ability. Mumaw, Pellegrino, Kail, and Carter (in press) conducted a study exploring this issue. They tested 99 young adults who varied in spatial relations ability as measured by the Primary Mental Abilities spatial relations test. Each individual was presented a large number of individual stimulus pairs that systematically varied in angular disparity.

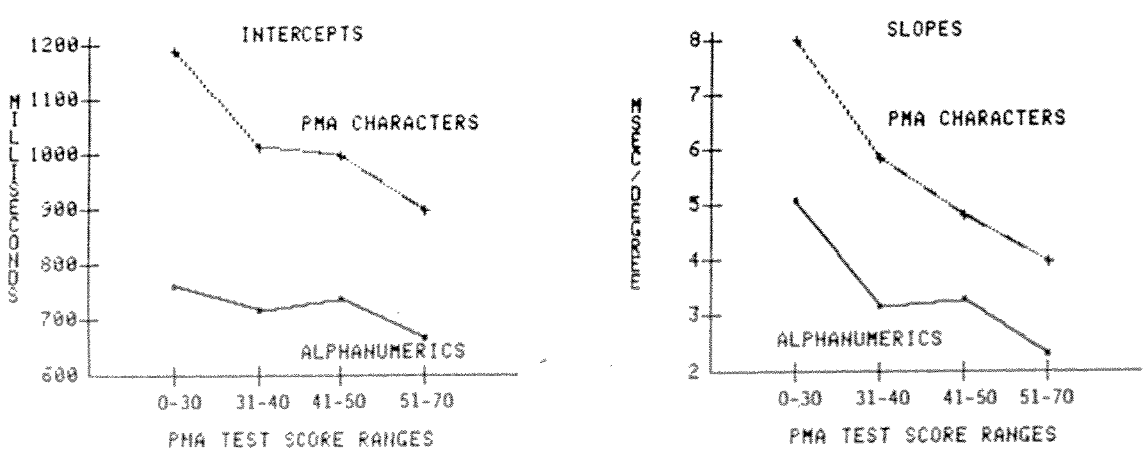

Figure 4. Components of mental rotation performance as a function of stimulus matieral and spatial ability scores (from Mumaw, Pellegrino, Kail, & Carter, in press; reprinted with permission).

Two types of stimuli were used, familiar alphanumerics such as F, P and 4, and unfamiliar shapes such as those found on the reference test (see Fig. 1). For each individual they derived four measures of processing speed. Differences between individuals in these measures of processing speed are shown in Figure 4. The left panel shows the data for the two intercept measures which reflect encoding, comparison and response speed. Three things are of interest. First, it takes longer to encode, compare and respond to unfamiliar than familiar stimuli, and this is true for all individuals. Second, there are minimal differences among high and low ability individuals in the time to execute these processes for familiar stimuli. In contrast, there are large differences among individuals in the time to encode, compare and respond to unfamiliar stimuli, and these differences are a systematic

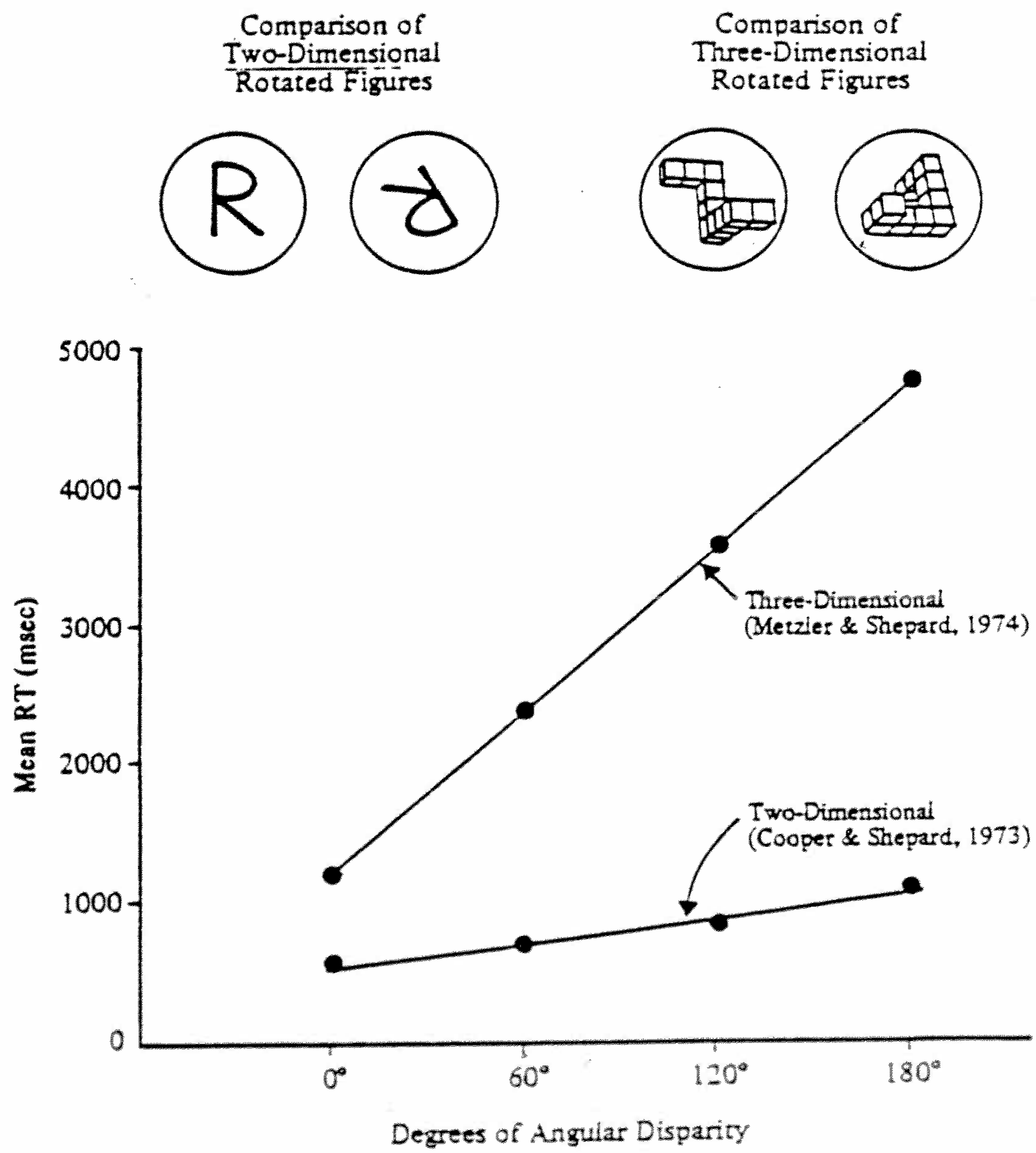

Figure 5. Effects of stimulus complexity on mental rotation performance (from Pellegrino & Glaser, 1979; reprinted with permission).

function of spatial relations ability. The right panel shows similar data for the two slope measures. Again, it takes longer to rotate unfamiliar than familiar stimuli and for both types of stimuli, rate of rotation is related to spatial ability. Ability differences are also larger for the rate of rotating unfamiliar stimuli.

In addition to measures of the speed of executing specific processes, Mumaw et al. (in press) also recorded error rates. However, errors were generally low and unrelated to ability. Thus, ability differences in simple spatial relations tasks are associated with speed rather than accuracy measures, and this is consistent with the evaluation of spatial relations and visualization tests presented earlier.

Similar analyses of individual differences in spatial relations ability have been conducted with more complex three-dimensional stimuli. One interesting aspect of performance in mental rotation tasks is that it takes considerably longer to solve problems using three-dimensional stimuli than those using two-dimensional stimuli, and this is illustrated in Figure 5. Both types of stimuli yield the typical linear function relating reaction time to angular disparity, but the intercepts and slopes are considerably higher for the three-dimensional block structures. A further difference is that errors are more frequent in the rotation of three-dimensional block structures. Data such as these suggest that as stimuli become more complex in spatial relations tasks, both speed and accuracy measures will be related to individual differences in spatial relations ability.

Pellegrino and Mumaw (1980) conducted an analysis of individual differences in spatial relations ability as assessed by tests of three-dimensional rotation. A large number of individual problems were presented to these individuals permitting the derivation of slope and intercept measures for both same and different judgments as well as accuracy measures. Systematic ability differences were obtained for all the measures of processing speed consistent with results obtained by Egan (1979) and Lansman (1981). In addition, the low ability individuals exhibited significantly more errors in solving such problems.

Results from process analyses of spatial relations ability can be summarized as supporting the general hypothesis that individual differences are a function of both the speed and accuracy of executing specific mental processes. When spatial ability is defined by scores on simple spatial relations tests involving two-dimensional rotation, speed of processing is the primary contributor to overall differences in reference test scores. As one moves along the continuum of stimulus complexity, accuracy of process execution, as well as speed of process execution underlie ability differences on reference tests. The results of several studies are consistent in showing that high ability individuals are faster in encoding and comparing unfamiliar stimuli and in the execution of a mental rotation or transformation process that operates on the internal stimulus representation.

The differences in encoding, comparison and rotation processes favoring high ability individuals are of even greater magnitude with three-dimensional block stimuli. The complexity of such stimuli also leads to substantial errors on three-dimensional spatial relations problems with greater error rates exhibited by low ability individuals. We will provide a more detailed discussion of the implications of such results after considering results from process analyses of spatial visualization ability.

Spatial Visualization Performance

In contrast to spatial relations tests, all of which involve mental rotation problems, spatial visualization tests are more heterogeneous, and no single process model can be applied to all tasks or problems. In addition, problem types such as form board or surface development have received considerably less attention in the information processing literature. This neglect has necessitated the development and testing of models to explain performance on individual problem types, in contrast to the application of an existing model in spatial relations (mental rotation) problems. We will consider two cases where process analyses have been conducted with spatial visualization tasks. Before doing so, it is important to note some general expectations about sources of individual differences in spatial visualization ability. Lohman's (1979) analysis of spatial relations and spatial visualization tests suggests that individual differences in these more complex spatial processing tasks are likely to be a function of both the speed and accuracy of executing mental processes with a strong possibility that accuracy will be more important than speed.

A related hypothesis is that these problems require the execution and coordination of several separate processes with more information stored in a visual buffer. Thus, the greater cognitive complexity may lead to strategy differences in problem solution, as well as potential breakdowns of solution strategies with increased problem complexity. These expectations have been borne out in studies of individual differences in spatial visualization performance.

Mumaw and Pellegrino (in press) studied performance on problems modeled after those found on the Minnesota Paper Form Board Test which was illustrated in Figure 2. Rather than the multiple choice format of the standard test, they developed problem types requiring same-different judgments so that latency and accuracy of solution could be systematically analyzed. Figure 6 contains examples of the problems that were used. Each item contains a completed "puzzle" and a set of individual elements. The task is to determine as rapidly and accurately as possible if the completed object can be constructed from the set of elements, i.e., whether the completed object and the set of elements are the "same" or "different".

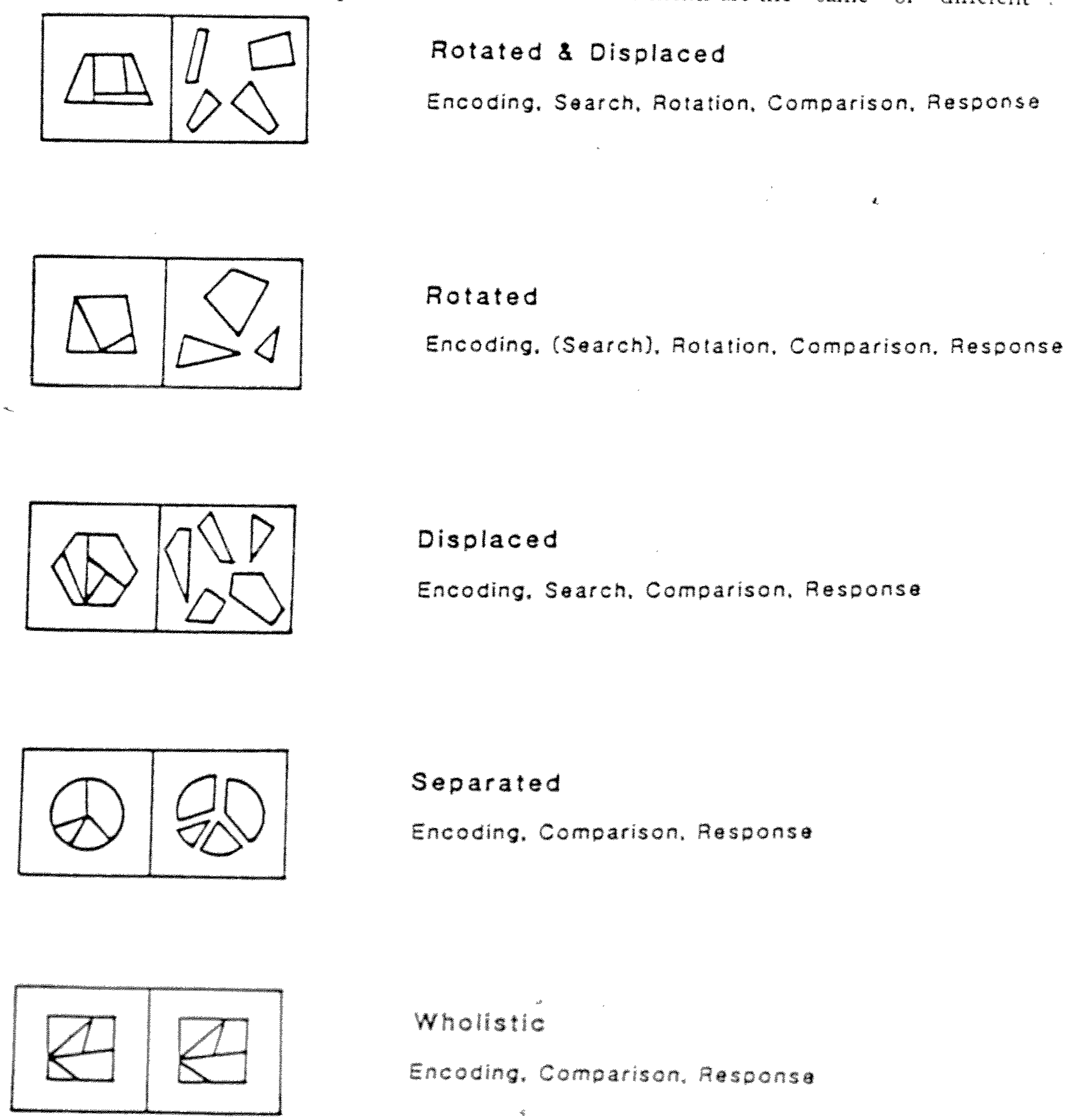

Figure 6. Problem types used in the analysis of form board performance (from Pellegrino & Kail, 1982; reprinted with permission).

The problems used by Mumaw and Pellegrino (in press) had several systematic variations. One variation, which is shown in Figure 6, was the manipulation of the elements themselves ranging from rotation and displacement in the picture plane, the most difficult condition, to a holistic identity match, the easiest condition. A second variation with each condition was the number of elements in each type of problem, ranging from 2-6. A third variation was whether the completed puzzle and the elements matched. Mismatches were of two types, either one element was incorrect or all the elements were incorrect. These item manipulations were designed to test a process model which included encoding, search, rotation, comparison, decision and response processes and provide estimates of the time associated with each process.

Performance in this spatial visualization task was a systematic function of problem type and processing complexity. This is illustrated in Figure 7. The top panels of Figure 7 show performance on problems where the completed puzzle and the elements match, i.e., same judgments. The left and right panels show performance of individuals with high and low spatial visualization ability. For both groups of individuals, the time for problem solution increased as a function of overall problem (processing) complexity and within each problem type as a function of the number of times each process needed to be executed. Error data showed a similar pattern. As shown in Figure 7, there were systematic latency differences between the high and low ability individuals.

As problem complexity increased, ability differences in solution time and errors also increased. This was also reflected in correlations based on measures of process execution speed derived from fitting the information processing model to the data of individuals. The bottom two panels of Figure 7 show performance differences on problems with a complete mismatch between the completed puzzle and the array of elements. High ability individuals were very fast and accurate in detecting these mismatches while low ability individuals were exceedingly slow and inaccurate. To adequately model the data, Mumaw and Pellegrino (in press) had to incorporate an assumption of processing inefficiency in detecting differences which then accounted for both the latency and error rates. Individual differences in visualization ability were predicted by a combination of both speed and accuracy measures from this processing task. However, the accuracy measures made a more substantial contribution to the prediction of individual differences in ability level.

Thus, with more complex spatial tasks such as the form board, it is not simply a matter of how quickly one can execute mental processes but how accurately they can be executed and how well they are coordinated when multiple processes and cycles of processing are required. A subsequent study of performance in this type of processing task, showed that high ability individuals also exhibited a more systematic and "analytic" solution strategy in solving form board problems (Pellegrino, Mumaw, & Shute, in press).

An additional spatial visualization task that has been studied is solution of surface development type problems (see Figure 2). Shepard and Feng (1972) examined performance in a task where individuals were presented representations of flat, unfolded cubes. Two of the squares had marked edges and the task was to determine if the marked edges would be adjacent when the pattern was folded to form the cube. The items varied in the number of 90 degree folds required to bring the marked edges together. Items were also classified by the number of surfaces that had to be mentally carried along with each fold. Decision times for items were a linear function of the total number of folds and surfaces that had to be processed to solve a problem. The slope of this function provides an estimate of the time required for each mental transformation while the intercept reflects other processes such as encoding, decision and response.

Alderton and Pellegrino (1984) used a variant of this task to study individual differences in spatial visualization ability as defined by performance on the surface development test from the Differential Aptitude Test. Each problem consisted of two unfolded cubes presented successively. Each cube had shaded surfaces and the individual's task was to determine for each cube the relationship(s) of the shaded surfaces and whether the two cubes were therefore the same or different in shading pattern. Ability differences were not associated with the speed of solving these problems, the correlation between mean response latency and reference test scores was almost zero. Ability differences were associated with the accuracy of solution, and high ability individuals could solve problems involving more complex folding patterns.

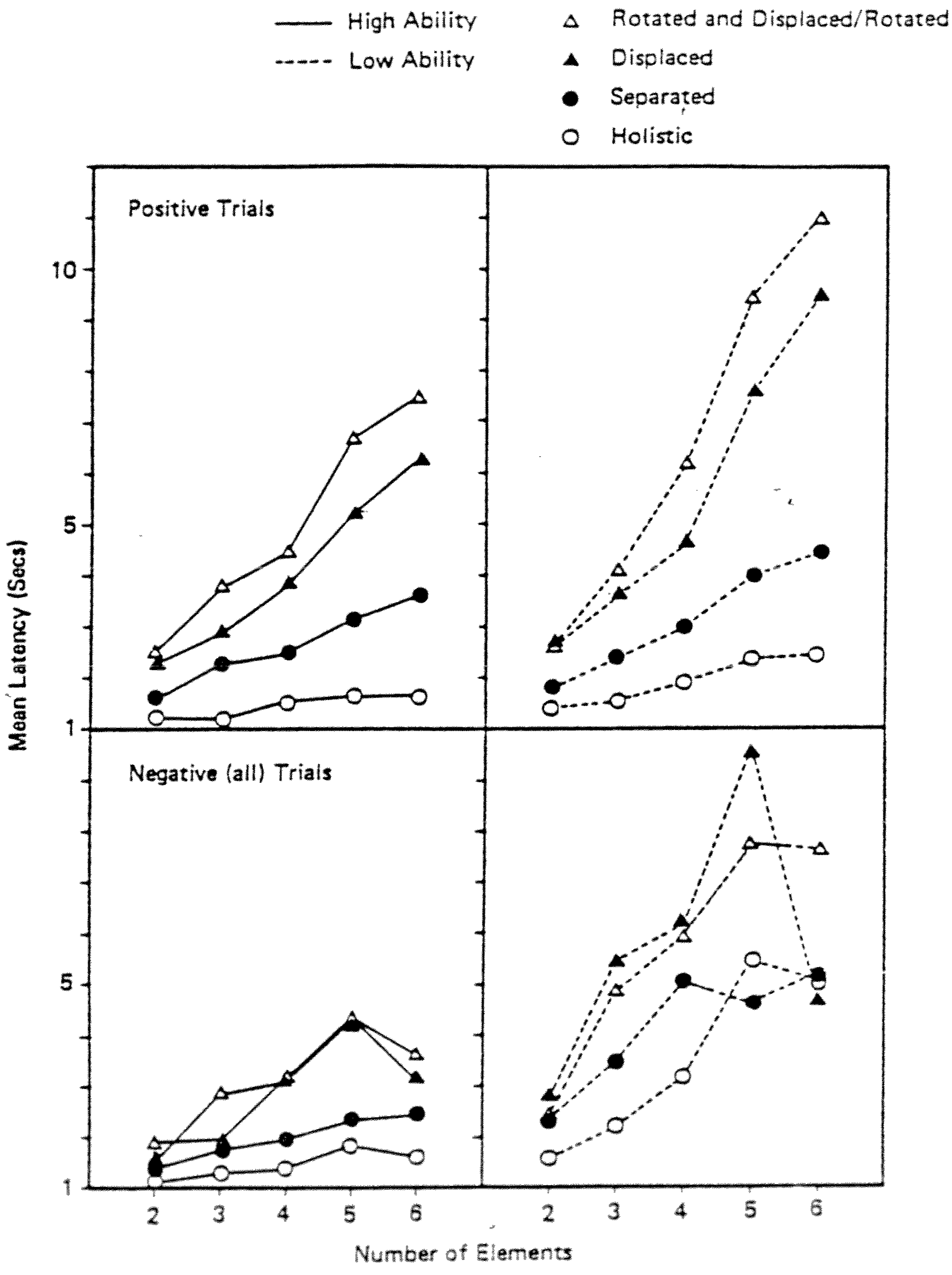

Figure 7. Solution latency for form board problems as a function of problem type and ability level (from Mumaw & Pellegrino, in press; reprinted with permission).

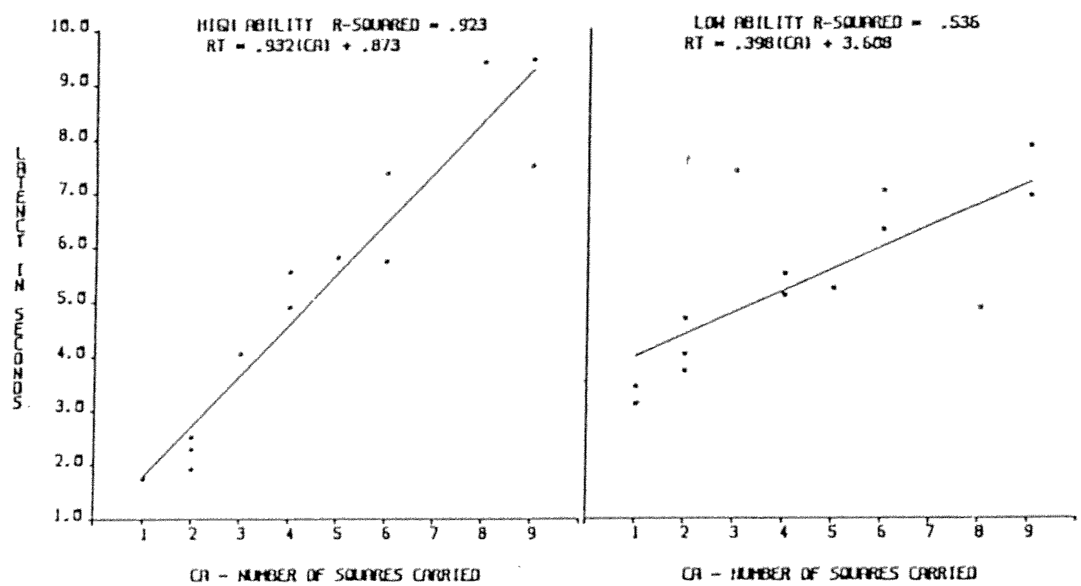

Figure 8. Solution latency for surface development problems as a function of problem complexity and ability level (from Alderton & Pellegrino, 1984).

A detailed analysis of the latency data revealed an interesting difference between the high and low ability individuals and helped explain why mean solution latency was unrelated to ability. Figure 8 shows the relationship between problem solution time and problem complexity. The high ability individuals showed a very systematic latency pattern consistent with Shepard and Feng's (1972) data. Problem solution time increased with each additional surface to be manipulated for final solution. In contrast, the low ability individuals showed a much less systematic latency pattern suggesting an erratic solution procedure and/or a breakdown in the ability to coordinate the image beyond a certain level of complexity. The erratic latency pattern coincides with their lower overall accuracy of solution.

Process analyses of individual differences in spatial visualization ability provide results complementary to those obtained from analyses of spatial relations ability and support interpretations of differences between these subfactors of spatial ability (Lohman, 1979; Michael, 1954; Zimmerman, 1954). First, more individual processes are required for problem solution leading to a longer average solution time and a greater likelihood of error. Second, while individual differences are partly attributable to speed of process execution, as in spatial relations tasks, they are more associated with accuracy or power. The latter may reflect three differences in cognitive capacity between high and low ability individuals: (a) assembly, coordination and monitoring of a complex solution procedure, (b) amount of information that can be retained and coordinated, and (c) quality or precision of the information represented and subsequently transformed. More precise and detailed process research must be done to evaluate these possiblities.

Conclusions and Implications

We have provided an overview of efforts to understand spatial ability (see also Cooper & Mumaw, in press, Pellegrino & Kail, 1982). One element of doing so involves the reorganization and interpretation of psychometric studies of this domain of intellectual performance. Lohman's (1979) extensive examination of psychometric studies has helped identify two major subfactors and some of the relevant differences between these subfactors. The correlated dimensions of speed-power and cognitive complexity as bases of task and individual differences are supported by process oriented research.

Process analyses of individual differences in spatial problem solving have provided a more detailed picture of the cognitive mechanisms tapped by this domain of intellectual tasks. Individual difference data obtained from spatial relations and spatial visualization tasks can be considered together to formulate a preliminary answer to the question of what constitutes spatial ability. By looking across tasks and studies, one might initially conclude that spatial ability is a function of several capacities such as those included in Kosslyn's (1981) theory of mental imagery. One is the ability to establish precise and stable internal representations of unfamiliar visual stimuli. Such representations can then be operated on or transformed with minimal information loss or degradation. It appears that individuals high in spatial ability are often faster at representing and comparing unfamiliar visual stimuli and what is ultimately represented and compared is more precise.

Differences in the quality of representation may also give rise to other speed differences such as superior rotation and search rates observed in spatial relations and visualization tasks. Problems of representation are most apparent in the more complex tasks that require the representation and manipulation of stimuli having several interrelated elements. If we assume that stimulus representation and processing involve a visual short-term memory or buffer (Kosslyn, 1981), then ability differences may also be a function of capacity and resolution within this system.

Differences between spatial relations and visualization tasks may partially reflect a difference in the importance of coding versus transformation processes within this system. Another difference between the two factors appears to involve single versus multiple transformations and the coordination and monitoring of the latter.

A number of issues and details necessary for understanding spatial ability still need to be considered and resolved. One such issue is the use of different strategies in solving complex spatial problems. Both between- and within-individual differences can involve the use of different strategies and processes in item solution. Cooper and Mumaw (in press) and Lohman and Kyllonen (1983) have explored this possibility. It appears that individuals change strategies as a function of the complexity and difficulty of problems. An interesting issue is whether the selection and use of strategies is optimally matched to problem characteristics and whether ability differences result from the strategy repertoire available and/or the optimality of the decision rules for strategy application.

Given that there are differences in the speed and accuracy of executing spatial processes and in the selection and use of strategies for problem solution, another important issue is whether these differences are fixed or modifiable. Can individuals of low ability acquire skill in spatial processing as a function of experience, practice, and/or training? A preliminary and guarded answer to this question is yes. Pellegrino (1984) reported data showing that low ability individuals improved substantially in components of spatial processing and in measured abilities as a function of extended practice in spatial processing tasks. Such data suggest that abilities are modifiable, but it is unclear at present whether the improvements are task or situation specific versus more general. Additional studies are needed of near and far transfer of processing skills following practice and training.

A final, pragmatic issue also bears consideration. It concerns the assessment of intellectual ability and the uses of mental tests. For some time there has been consensus among psychometricians that the predictive level of mental tests has reached an asymptote given the typical constraints of the testing situation. The emphasis on prediction partly reflects a view that intelligence and ability are relatively stable and inert. If we adopt the view that ability is malleable, as suggested by information processing and developmental research, then the value of a test becomes its diagnostic value for instructional decision making and planning.

Current mental tests are not terribly useful for such purposes. One could hope that by combining process analysis with existing psychometric procedures, instruments and testing situations could be developed that, although they may be no more predictive than their predecessors, will provide more extensive diagnostic information regarding an individual's cognitive assets and liabilities. This would include testing situations sufficiently extended so that changes in performance could be observed, including the capacity to adapt to novel situations and automate performance (Sternberg, 1984).

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