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ABSTRACT

The scientific concept of intelligence has been heavily influenced by the technology of measurement. The variables which can be measured have been made the operational definition of intelligence. This approach differs from a deductive approach, in which a theory of cognition in general is used to derive the sorts of measurements that must be taken to describe an individual's cognitive competence. The cognitive science approach to cognition in general can be used as a base theory. This theory generates requirements for individual intelligence measurements which differ from tests used to predict performance in some (perhaps ill-defined) criterion situation. The use of theory-defined measures of individual mental competence is different from the use of measures that are justified in terms of their predictive validity. (Author/GDC)

SCIENCE, TECHNOLOGY, AND INTELLIGENCE

EARL HUNT

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The scientific concept of intelligence has been heavily influenced by the technology of measurement. In a sense, the variables that we can measure have been made the operational definition of intelligence. This approach contrasts to a deductive approach, in which a theory of cognition in general is used to derive the sort of measurements that must be taken to describe an individual's cognitive competence. The "cognitive science" approach to cognition in general can be used as a base theory. The base theory then generates requirements (over)

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on measurements of individual intelligence that are different from the sorts of measures that might be taken if the purpose of testing is to predict performance in some (ill-defined) criterion situation. The use of theory-defined measures of individual mental competence is contrasted to the use of measures that are justified in terms of their predictive validity.

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Science, Technology, and Intelligence #1

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The intelligence test has been cited as psychology's most important technological contribution to society. Whether this is good or ill can be debated (Eysenck, 1979; Kamin, 1974; Herrnstein; 1971; Gould, 1981). Certain facts are not really subject to debate. Psychologists can and have developed 'standardized interviews' that, on a population basis, provide a cost effective technique for personnel classification in industrial, military, and some government settings. However the tests are very far from perfect indicators. Validity coefficents between tests and performance ratings typically range in the .3 to .5 range; i.e. from ten to twenty five percent of the variance in performance is predictable from test scores. While such correlations may be quite high enough to justify testing in many situations, there is a nagging feeling that better tests can be found.

The popular view is that a technology must be rooted in a science; in this case psychological tests must be rooted in a science of mental competence. In fact, the

situation is not quite that simple. Psychology has two distinct sciences of me[illegible]tric study of intelligence (henceforth 'psychometrics' (2) is closely intertwined with the development of testing itself. The other tradition, Cognitive Psychology, has historically stood apart from the study of individual differences. Yet both study the human mind, in the human brain. A number of years ago Chronbach (1957) urged psychologists to unite these two disciplines. At one level the uniting took place. Cognitive psychologists do look at individual variations, and the techniques of Cognitive Psychology are used to study individual differences. The resulting research has had rather little influence on the technology of testing. Is this because there is always too long a lag between science and technology? Or is there a deeper reason? And if there is a deeper reason, is there cause for alarm? Should something be done to accelerate the application of new scientific findings to psychological technology?

These questions are particularly apt today because Cognitive Psychology and a group of related disciplines, collectively called the "Cognitive Sciences", are perceived as being extremely active intellectually. This is in marked contrast to psychometrics, where the questions being debated today are not terribly different from those that were debated over fifty years ago (Hunt, in press). Interest in the technological potential of the Cognitive Sciences has been expressed at as high a level as the Office of the President (Holden, 1984). The interest in Cognitive Science has a strong technological bias. It is hoped that advances in the study of laws of cognition will lead to the development of a technology of intelligent devices. These devices may expand the power of human intelligence. They may also expand the efficiency of our society's very large program of formal education, which is perceived as having substantial defects. It is logical to believe that the development of better methods improving mental competence will be closely linked to better methods of evaluating competence.

This view may be too optimistic. The current fervor in the Cognitive Sciences is based on real changes in our views of the mind. However these changes are derived from theories about cognition that are almost intellectually orthogonal to psychometric theories of intelligence on which modern intelligence testing is founded. Previous writers who have urged that psychometricians and experimental psychologists unite in their study of the mind (Chronbach, 1957; R.J. Sternberg, 1977; Underwood,

1975) proposed that the personal ability measurements of the psychometricians be added to the design variables manipulated by the experimentalists, so that the interactions between the two could be studied. The logic is epitomized by the phrase "aptitude X treatment interaction". The same logic is found, slightly muted, in studies of 'cognitive correlates' between psychometric and Cognitive Science measures.(Pellegrino and Glaser, 1979). In both cases there is an implicit assumption that discovering the correlations between measures that have been developed in different intellectual traditions will further our understanding in both fields. In this paper some questions will be raised about the approach. Two traditions can seldom be rammed together by statistics. What is required is a theoretical synthesis that fuses them. If the synthesis cannot be made the theories will probably co-exist, each covering slightly different domains.

Is the synthesis or the separate theory approach appropriate for the study of individual differences in cognition? This question can only be answered by considering the present status of the psychometric and Cognitive Science views of the mind, and asking whether they are compatible. This question is explored below.

The sort of answer to be expected should be made clear. It is not a question of one approach being right and one being wrong. Neither is it a question of technology versus science. The question is whether psychometrics and cognitive science can be synthesized into a single view. If they can, then the technology can be developed from a uniform scientific basis. If Chronbach's two 'camps of scientific psychology' are inevitably separate camps each may develop its own technology, which may be useful for different purposes.

THE PRESENT STATUS OF PSYCHOMETRICAL THEORY

Since its inception psychometrics has been beholden to technology. Where would test theory be without the number two lead pencil, the mark sense form, and the calculating machine? The digital computer, which came somewhat later, really did little more than cement intellectual trends that had already developed in response to what, collectively, will be called the "paper and pencil technology."

The paper and pencil technology made it easy to record the products of cognition. Note the stress on product. The paper and pencil technology is at its best when large numbers of fairly short questions are presented and when the respondent must choose from a fixed set of alternatives. The paper and pencil technology is not well suited to recording how a person chooses the answers, and is worse suited for situations in which free form responding is required. Perhaps most important, the paper and pencil technology emphasizes counting the total number of correct items or, in more recent applications, determining the most difficult item that a person can consistently answer correctly. Thus the conditions of the measurement procedure rule out observation of some psychologically interesting behavior, and no amount of theorizing can put them back in.

The paper and pencil testing process has also been influenced by the economic constraints imposed on personnel evaluation, largely in military and educational settings. Because the test has been thought of as a one-time only measure on which to base a long term prediction of a vaguely specified criterion, great stress has been laid on measuring traits that are stable over repeated test administrations. Indeed, in many discussions of testing the correlations between test scores taken at different times are regarded as measures of test reliability rather than as measures of the stability of the examinee's ability to do whatever the test requires.

These are reasonable strategies if the goal of prediction is accepted. The decision to concentrate on stable mental traits does rule out of consideration broad classes of behavior that could be considered part of intelligence. In particular, measures of learning and of individual variability of performance will not be measured. However, learning and personal stability could easily be regarded as part of a person's mental competence.

While any testing technolgy will be appropriate for some behavior and not for others, the very success of paper and pencil testing has made its shortcomings unusually serious. The behaviors measured on the tests have become the accepted definition of intelligence. The extent of this belief has been shown by reactions to some of the attempts that experimental psychologists have made to establish theories of individual differences in cognition. Although these attempts proceed from a very different tradition, and although attempts to reproduce correlations with traditional tests were specifically disavowed in one of the earliest papers on these attempts

(Hunt, Frost, and Lunneborg, 1973) people still evaluate both their own (Keating, 1984) and other's (R.J. Sternberg, 1984, but for a more balanced view see R. J. Sternberg, 1985) work in terms of correlations with existing tests.

The paper and pencil technology has led to a particular type of theorizing. The volume of data produced by giving batteries of tests to large numbers of people has forced psychometricians to develop sophisticated statistical procedures for data summarization and analysis. The natural way to represent a person's test scores is by a vector, and the natural way to summarize a vector is by a smaller vector. Hence factor analysis, the art of extracting the small factor score vectors from the bewilderingly large vectors of test scores. The summary is well defined mathematically. A person's abilities are represented by a point in a Euclidean space of "mental abilities." The point is then mapped on a line representing the (usually vaguely defined) ultimate criteria. An example is shown in Figure 1. As

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Figure 1 about here

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the figure shows, this is a perfectly respectable way of making classification decisions.

The Euclidean representation has been used as a psychological theory of intelligence, by interpreting the dimensions of the Euclidean space as basic mental traits. The method is well known, so no further description is needed here. (See Nunnaly, 1978, for a good introduction.) This is where the problem lies. Factor analytic based theories do not provide an adequate conceptual basis for thinking about individual differences in mental competence, except for the restricted purpose of classification. Why is this?

The usual objection to factor analytic theories is that the factor analysis as a mathematical procedure does not lead to a unique Euclidean representation of the data. Therefore subsidiary mathematical assumptions are made that, in effect, dictate the psychological theory to be accepted (Gould, 1981). The biggest argument is over whether one should insist that the dimensions, when interpreted as traits, be mathematically orthogonal. The argument is not trivial, because the orthogonality requirement mathematically precludes the discovery of separate but correlated psychological traits. This and

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similar indeterminancies in the mathematical solutions to the data analysis problem set the stage for a confusing play of empirical observations. Different investigators applied different mathematical techniques to different data sets, producing a variety of claims for models that vary from Spearman's (1927) classic "general" theory of intelligence through hierarchial models of "general intelligence" of varying degrees, and finally to the orthogonal specific abilities models espoused by Thurstone (1938) and Guilford (1967).

The trees may have obscured the forest. Carroll (in press) has done the field a considerable service by applying consistent factor analytic procedures to some of the major data sets reported in the literature. Oversimplifying a good deal, what Carroll found is that most of these data sets can be fit by a "hierarchial general factor" model of human abilities. Examples of such models are those espoused by Cattell and Horn (Cattell, 1972; Horn and Donaldson, 1979) or by Vernon (1961). The Cattell-Horn model seems to be the most accurate. It assumes that there are three major classes of abilities. These are the "crystallized", and usually highly verbal, ability to apply previously learned solutions to current problems (Gc), the "fluid intelligence" ability to apply general problem solving methods to new situations (Gf), and a "visualization" ability to deal with problems involving visual-spatial relations (Gv). (There is some evidence for an analagous ability to deal with auditory relations (Stankov and Horn, 1980)). There is ample evidence that these abilities are distinct, although Gc and Gf are correlated in most populations.

One of the most encouraging things aobut the Cattell-Horn model is that it fits reasonably well with neuropsychological analyses of brain function. These are based on quite different sorts of observations about cognition; extensive examinations of pathologioal cases. The match is particularly strong for Gv and for Gc, interpreted as verbal ability, for there is massive evidence that spatial-visual and verbal information processing take place in different physical locations in the brain. (Kolb and Whishaw, 1980). There is also some evidence for selective forebrain involvement in the sorts of planning functions that appear to be involved in the ability to plan and coordinate activities. At least superficially this sounds like Gf, although it should be realized that the sorts of failures of planning described for frontal lobe patients are much more extreme than those

associated wih low Gf.

In summary, hierarchial models provide good summaries of the abilities tapped by paper and pencil testing. To a limited extent, we can make a guess about where some of the information processing that underlies the traits identified in the models takes place in the brain. Clearly there is some reality to the model, as a Euclidean description of human abilities. The problem is that it is difficult to go further with <u>any</u> Euclidean model of cognition, because such models provide relative descriptions of the products of thought without any commitment to a model of the process of thinking.

Since this point is crucial, a hypothetical illustration will be given. Consider the task of predicting how a person might perform on a test paragraph comprehension. A psychometrician could predict the total test score, by using a formula something like

Predicted test score = a x (Examinee's Gf trait score) =

b x (Examinee's Gc trait score),

where a and b are appropriately valued coefficients. But this predicts how well the person will perform, not how . To describe performance on the test one has to have a model of how a person merges his or her general knowledge with the information in the text, in order to construct a representation of the information in the paragraph, and then one has to have a model of how the examinee interprets questions and interrogates the internal representation of the text. These models deal with processes, not relative outcomes.

Psychometricians are certainly aware of this problem. Their approach has been to examine tests that appear, by mathematical criteria, to be relatively pure tests of a trait. The hope is that an examination of such tests will lead to a better understanding of what the trait means. This has worked relatively well for spatial-visual reasoning (Gv), which seems to be composed of several definable actions; holding bits of visual images in one's head, and moving images about "in the mind's eye" (Lohman, 1979; McGee, 1979). The approach has worked much less well in the case of the more general "crystallized" and "fluid" intelligence traits. The relevant findings are very well summarized by recent work by Snow and his colleagues (Snow, in press; Marshalak, Snow, and Lohman, 1984). They used multidimensional scaling methods to construct a space

of various tests in which distances between tests approximated correlations between them. Hence tests that define a factor will be grouped in tight clusters. A graphic summary of some of their results is shown in Figure 2. As the figure shows, there are clusters that define the Gf and Gc factors. However the tests in these clusters tend to be complex ones. Therefore people differ in their interpretation of the behavioral capabilities needed to attack them. The well known Raven Progressive Matrix test (Raven, 1965), which is widely regarded as a good Gf measure, is a good example. The test contains problems that yield to several alternative strategies, each of which utilizes distinct elementary processing steps (Hunt, 1974). Therefore one cannot easily summarize the processes that the Raven Matrix test tests. A summary that one person finds adequate will displease another, and there is no way to resolve the issue.

R.J. Sternberg (1977) has developed an alternative approach to the problem of definition of what a trait means. The technique is called "component analysis." One assumes that an examinee's overall test performance can be broken down into components, where a component is defined as a process that begins with a defined input from previous components and ends with a defined output to be delivered to the next component in line. Consider analogy tests. Each item is of the form

"A is to B as C is to D1,D2,D3,D4"

e.g.

"Cat is to Dog as Wolf is to (Lion, Giraffe, Elephant, Penguin)"

Such a problem can be solved in the following steps.

1. Code the meaning of the terms.
2. Establish the relation between the A and B terms.
3. Apply that relation to map from the C term into an ideal answer.
4. Locate that answer amongst the D terms that most closely approximates the ideal answer.

The time required to answer a test item is assumed to be a linear function of the time required to execute each component process, plus a "junk" term representing "all other processes involved." A similar model can be constructed for estimating the probability of producing the correct answer as a function of the probability of correctly executing each component process. A person's ability to execute individual components can be estimated in two ways; by designing modified test items that isolate

one of the components (as was done in Sternberg's original work) or by constructing a factorial experiment in which the experimental variables are chosen to modify the difficulty of one and only one of the component processes (e.g. Pellegrino and Kail, 1982).

Componential analyses can produce very accurate partitions of variation in performance on different problems within a particular type of test, averaged across individuals. On the other hand, no one of the component process measures seems to account for very much of the variance in individual variation in test performance. The "junk" parameter, which represents "encoding plus everything else" is consistently the most accurate estimate of general performance in other areas. This is disconcerting, for the processes contributing to the junk parameter are not defined by the experimental variations. As a result, componential analysis does provide a better idea of what behaviors are required to take a conventional test, but componential analysis has not related these behaviors to a theory of cognition, nor has it explained why some tests work as predictors in some situations.

The criticisms that have been directed at the hierarchial model are not specific to it. They can be directed at any trait theory of cognition. This does not mean that trait theories are false, just that they have inherent deficiencies. Can these deficiencies be remedied by combining psychometrics with cognitive psychology? To answer this question, let us take a look at what the Cognitive Psychology view is.

THE COGNITIVE PSYCHOLOGY APPROACH

Cognitive psychology is based on an approach to the mind that is markedly different from the Euclidean representation approach taken by psychometrics. The modern (post 1970) approach has been strongly influenced by a variety of other disciplines, notably by linguistics, neuropsychology, artificial intelligence, psychology, and to a lesser extent cultural anthropology. These branches of each of these disciplines that are concerned with thinking have come to be referred to, collectively, as the 'Cognitive Sciences.' This is an umbrella term for a collective movement toward the development of a unified theory of mind rather than to multiple, discipline-specific models. Since modern cognitive psychology is best understood as part of this movement a few words about it are in order. The basic assumption of the cognitive sciences is that there are laws that govern physical symbol manipulating systems, somewhat akin to laws that govern physical phenomena. At a very general level, Shannon & Weaver's (1949) theory of information transmission would be an example of such a law. The term "physical symbol manipulating system" is important. The cognitive science approach assumes cognition is achieved by the manipulation of symbols that represent some external world. However the act of symbol manipulation requires some sort of physical system. What cognitive science studies is the restraints placed on symbol manipulation by the nature of the external world being represented, by the nature of symbol manipulation itse and by the physical character of the system doing the manipulation.

Pylyshyn (1983) has identified three levels of cognitive science studies. The first is the study of the influence of physical mechanisms upon cognitive processing. This can be done by analyzing the one device that we know is capable of thought; the mammalian brain. The cognitive and neurosciences merge here. A complementary approach is to analyze the performance of hypothetical physical devices, to see if they could perform the computations that are required to achieve certain cognitive actions. Examples of such work are the study of the learning and memory capacities of networks of idealized, neuron-like devices (Hinton and Anderson, 1981, Minsky and Papert, 1969) and analyses of the networks that can realize computations required in vision (Marr, 1982).

Pylyshyns's second level of cognitive science research deals with 'pure' symbolic processing

capabilities defined without concern for the external referents of the symbols being processed. An example would be the well known studies of the scanning of information in short-term memory (S.Sternberg, 1969, 1975) or studies of the process of moving visual images "in the mind's eye" (Shepard and Cooper, 1982). At the highest level are studies of thought processes that are controlled by people's understanding of the referents of symbolic processing. Examples of work at this level are studies of problem solving and text comprehension. Johnson-Laird (1983) has described this level of research as research on the mental models that people construct and manipulate in the course of problem solving.

For brevity let us refer to these levels as the physical, information processing, and referential levels of cognition. Clearly the physical level is the most concrete, for an action of the mind must ultimately be an action of the brain. The referential level is what we normally think of as conscious thought. The most abstract of the three levels is the information processing level. Pylyshyn presented the levels as analogically similar to the study of computer circuitry, system design, and programs within computer science. A related, and perhaps somewhat clearer, analogy is to think of studies at the physical (brain) level in humans as being analagous to the study of computer hardware, studies at the representational level as being analagous to the study of the actions of particular programs, and studies at the information processing level as being analagous to studies of the operations permitted in a computer language in which the representational "programs" are written.

To provide a more specific illustration, consider the study of human verbal comprehension. At the physical level there have been numerous studies showing that language processing in the brain takes place largely in the left hemisphere (Kolb and Whishaw, 1980). At the representational level we find studies of how the information a person extracts from a text is from a text, is influenced by their level of knowledge of the topic, the text and their beliefs about the use they will have to make of the text based information (Johnson and Kieras, 1983; Chiesi, Spillich, and Voss, 1979).

The information processing level is the hardest level to define, since it refers to processes rather than to physical structures, but the processes are not open to conscious inspection. Continuing the analogy to computation, unraveling the information processing

elements of cognition is a bit like attempting to infer the basic operations of a computer programming language by observing the performance of programs written in that language. The problem can be illustrated by considering the logic of the sentence verification paradigm developed by Clark and Chase (1972). The procedure will be considered in some detail because it has been the vehicle for a reasonable amount of research on individual differences. The procedure is shown in Figure 3. First a simple sentence is shown. The sentence is followed by a picture. The participant must indicate whether or not the sentence correctly describes the picture. Since errors are infrequent, the dependent variables are the time a person requires to comprehend the sentence ("comprehension time") and the time required to determine whether or not the sentence correctly describes the picture ("verification time"). These can be altered by varying the truth value and syntactic-semantic form of the sentence. For instance, it takes longer to verify negations than affirmations ("Plus above star" versus "Plus not above star") and longer to verify sentences containing marked terms ("below") than unmarked ones ("above"). The time required to carry out basic steps in linguistic information steps can be measured by observing how verification times change when sentence forms are altered systematically. The logo can be extended to individual difference research by determining how (or whether) the time required to execute a specific linguistic process varies across people.

Figure 3 here

There are two major differences between the cognitive psychology and the psychometric approaches. Both are particularly striking in studies at the information processing and representational level. Cognitive psychology is interested in the process of cognition, rather than the product. This can be seen in the studies of verbal comprehension just described, where the emphasis is on building a model of how a linguistic statement is understood, rather than on specifying how likely a person is to understand an arbitrary statement. The second difference, which follows from the first, is that a cognitive psychology theory of individual differences must fit into a process model of the cognitive action being studied. The cognitive psychologist is not particularly interested in determining the dimensions of the Euclidean space adequate to describe individual's ability, relative to each other. The cognitive psychologist is interested in knowing how variables related to the individual impinge

upon the process of that individual's cognition.

This can be illustrated by looking at a series of studies on the rule of short term memory in reading. There is a positive correlation between measures of memory span and scores on omnibus written tests of verbal ability (Daneman and Carpenter, 1980; Palmer et al., 1985). Daneman and her colleagues (reviewed in Daneman, 1984) asked why this is so. First it was shown that higher correlations can be achieved if the measure of memory span is one that directly reflects the ability to hold information in memory while processing intervening linguistic statements, rather than one that reflects the "passive" capacity to hold words in memory without doing some intervening activity. (The memory span subjects of most intelligence batteries are of the latter sort.) Next, it was shown that the ability to hold information in memory exerts its effect on certain steps in linguistic processing, such as the ability to resolve anaphoric references or to recall previously presented information when some reference to it is required. Instead of stopping with the observation that reading comprehension and short term memory tests load on the same factor, Daneman and her colleagues examined the process of reading in order to determine what produced the loading.

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Because the emphasis of cognitive psychology is on process, experimenters try to construct laboratory situations that isolate process. A cognitive psychologist may find performance in an isolated situation extremely interesting, on theoretical grounds, even though that isolated situation does not draw upon behaviors that are called upon a great deal in the everyday world. Prediction is not the point.

Measures of individual differences that relate to a theory of process are always of interest, in the framework of that theory, even though variations in the measures may not be highly related to variations in performance in any important socio-economic activity. Indeed, from a theoretical view some of the most important measures on an individual may be those measures that reflect constancies. Years ago, Miller (1956) observed that there is very little absolute variation in the human abilities to make perceptual judgments and to hold information in short term memory. The importance of these constancies for perception and language comprehension is immense. Yet measures with low variability are not good predictors.

Given the differences in philosophy, it is not clear

that cognitive psychology and psychometrics can be united. On the other hand, it is not clear that they cannot. The problems are somewhat different at each of Pylyshyn's three levels of the study of the mind.

The functioning of the mind depends upon the functioning of the brain, so questions about the relation between brain processes and mental processes are of interest. The famous issue of hemispheric localization of function is an example. So are studies of the influence of specific chemicals upon mental functioning; e.g. the role of alcoholic intoxication upon memory. A great deal of technological development has gone into the construction of measures of functioning of the physical brain, ranging from neuropsychological observations of behavior to such exotica as tomographic scans. The technology provides an excellent way to study two things; the general physical substrate of the normal mind and aberrations in mind that are produced by specific, usually physical alterations in the brain.

The fact that the dimensions of individual variation uncovered by psychometrics do map reasonably well upon the brain functions discovered by neuropsychology is an important observation. The neuropsychological observations are almost all based upon the study of extreme cases, while the psychometric data rests very largely upon the study of normal variation in mental competence within a normal populaton. This suggests that there are sufficient differences in brain functioning in the normal population to make a difference in at least some of our behaviors, specifically those actions required by a conventional aptitude test. In terms of the Euclidean representation of the psychometrician, the question is whether or not measures of brain functioning are sufficiently close to psychometric measures to fit into the psychometric dimensional representation of the mind. In more pragmatic terms whether or not brain function measures can be related to everyday functioning in normal individuals depends upon whether the measures are related to behaviors shared by test taking and everyday cognitive actions, or whether the brain function measures are mainly associated with cognitive epiphenomena of the test itself.

From time to time there are reports that there are "substantial correlations" between measurements of brain functioning and some extremely complex behavior, such as a general intelligence test. (see Hendrickson, 1982) for the latest such example.) The vast majority of these reports

have simply failed the crucial test of independent replication. This is not to deny that the proposition that individual differences in brain functioning have something to do with individual cognitive behavior. I am sure that they do, especially in extreme cases. As a matter of scientific interest, studies of the relation between brain functioning and cognitive behavior should and will be repeated. However it is not at all clear what will be learned by studies that are confined to reporting correlations between gross measures of brain function and gross measures of mental function; e.g. a correlation between a measure of the variability of the brain's overall response to a repeated stimulus and performance on a general intelligence test. Unless the correlations were extremely high (and again I repeat my caution about independent replication) all this tells us is that the general functioning of the brain is related to general cognitive functioning. Did anyone doubt this?

Brain-cognition questions have a seductive physical concreteness. If tomographic scans reveal metabolic activity in a particular brain region during certain acts of cognition (e.g. activity in the right hemisphere during spatial-visual reasoning) then surely this must tell us how we think. Unfortunately, it does not. It tells us where we think. Brain function measures do not answer the questions posed by the cognitive psychologist unless measures on the brain can be associated with specific processes. To some extent this has been done, especially in the analysis of language comprehension, where the processes of word and sentence comprehension have been diassociated at an anatomical level. It is even possible that physical disassociations between different techniques for word analysis will be discovered (Coltheart, in press). Such work is certainly exciting, but it is probably not g ng to have much influence on the relation between psychometrics and cognitive psychology, since neuropsychology rests upon evidence from pathological cases. One must also remember that a process may be distributed over several anatomical loci. So a failure to identify an anatomical location for a process tells us little. There would be a need for information processing studies even if we knew all there was to know about neuropsychology.

Figure 4 here

Early theories of information processing emphasized

the isolation of stages of symbol manipulation. Figure 4 shows an example, taken from an early paper by Smith (1968), in which the act of selecting a response to a stimulus was broken up into two stages of stimulus analysis and two stages of response execution. In fact, this approach is the historic progenitor of R.J. Sternberg's (1977) component analyses of intelligence tests. The strongest interpretation of Smith's model is that there are distinct stages of information processing, that activity in one stage is independent of activity in the other stages, and that the stages pass information to each other in a serial manner. Thus a model like that shown in Figure 4 is really quite a strong statement about information processing. A more general view is to regard thought as depending upon isoleble subsystems, or modules, of information processing actions that operate independently of each other (Fodor, 1983; Posner, 1978). Each of the modules contains its own view of some aspect of the external world. These views are eventually integrated into an overall representation of what is going on. As an example of modular processing, consider what must happen when an automobile driver is told, verbally, by a passenger, that the passenger would like to stop for dinner at the next restaurant. Figure 5 shows the exchange of information between modules that must go on inside the driver's head if the car is to be maneuvered into the nearest restaurant parking lot.

Figure 5 here

The current "wisdom" is that the integration of modular processing that occurs in cognition can be modeled by the use of a conceptual device known as a production execution system. The basis of production execution systems is the production , a pattern and an action to be taken if that pattern is executed. Figure 6 shows a slightly whimsical set of productions for driving a car. Each module of thought can be conceptualized as the set of patterns and primitive actions that are effected within by that module. Intermodule communication is achieved by allowing modules to place their output either into the pattern area of other modules or (more usually) by assuming a common "blackboard" area that can contain patterns appropriate to any of the separate modules. This is illustrated in Figure 7, which shows the organization of an hypothetical modular system of productions that might be required to execute the logical production system stated in Figure 6.

Figure 6

Thinking of thinking as organized modularity leads to an emphasis upon certain classes of information processing functions. The first is the definition of the modules themselves. Modules should not be thought of as stages in component processes (as described previously in discussing R.J.Sternberg's work), but rather as specialized workshops containing resources to be assembled into component processes. The distinction is roughly analagous to the distinction between a hardware manufacturer, such as the Boeing Aircraft Company, that is capable of doing certain things, provided its shops are not overloaded, and the stages in the process of constructing a specific aircraft, missile, or space vehicle.

Information processing research attempts to identify the modules and the actions of which they are capable. This is done by inferring the existence of a module, or of a process within a module, by observing the selective action of variables on certain types of performance. An example is a widely cited study by Biederman and Kaplan (1970) which demonstrated selective effects of stimulus discriminability and response compatibility upon visual encoding and motor response production systems. An alternative technique for inferring the existence of separate modules is to show that action within one module does not interfere with action in another module. This sort of reasoning is exemplified by dual task studies, in which people are asked to do ostensibly independent tasks. If the tasks are done by separate modules it should be possible to time share the tasks without interference. A good illustration is a study by Kerr et al. (1983) in which maintaining one's posture was found to interfere with visual but not with verbal memory tasks.

Once modules have been identified one can investigate the extent to which each module displays variation across individuals. Similar studies can be made of processes within a module. Logically, individuals are treated as factors in an experiment, and one observes when differences associated with individuals (e.g. age, sex, or sometimes simply individual identity) make a difference in the performance of a task that is already known to involve a particular module. The fact that the modules have been defined independently is what distinguishes the experimental psychology of individual differences from psychometric investigations. In psychometric theory a

"good" measure is defined by the pattern of correlations involving it and other tests. In cognitive psychology the meaning of the testing procedure will already have been defined, with respect to a particular theory of cognition, and will have been justified by the nomothetic experiments done to validate that theory. The pattern of individual differences is something to discover, but the pattern does not validate the measure.

The approach can be illustrated by a further consideration of linguistic information processing. The modular character of linguistic processing has been established by psychometric, neuropsychological, and experimental psychological criteria. In order to process language one has to know words. This is reflected in the well known fact that (at least in young adults) vocabulary size is an excellent indicator of one's general ability to deal with language. This is the reason that vocabulary tests are often used as "markers" for verbal ability. Tests of the speed of retrieval of the meaning of common words identify a reliable dimension of individual differences. Furthermore, this dimension of ability is distinct from the ability to manipulate strings of words, as tested in the sentence verification paradigm (Hunt, Davidson, and Lansman, 1981; Palmer, MacLeod, Hunt, and

Davidson, 1985). These findings indicate that the language processing module contains two somewhat separate mechanisms, one for retrieving word information from long term memory and one for manipulating information after it has been retrieved. The conclusion is buttressed by neuropsychologicl findings indicating that different brain structures are involved in retrieval of word meaning and sentence analysis (Kolb and Whishart, 1980). Since sentence and word processing are not perfectly correlated they evidently make a distinct contribution to the psychometrician's verbal comprehension trait. Note the implied causality. Sentence and word processing measures are not regarded as loading on an underlying trait of verbal comprehension ability, they are thought of as producing that ability. On the other hand, from the point of view of someone interested in prediction, a test that mixed sentence and word processing into a general test of the ability to comprehend language might be far more useful than isolated tests of the separate processes.

Verbal comprehension depends on the integration of word information into sentence strucutre, and sentence structure into discourse structure. Detailed models for both processes have been proposed (Schank, 1975; Kintsch and van Dijk, 1978). Both assume that what a comprehender

does is to construct a structure representing the meaning of the message being received. This is not a trivial task, since the meaning of words and sentences will often be determined largely by context. Substantial individual differences in the ability to define words in context have been observed, indicating that variation in fitting semantic meaning to pragmatic context is a major source of variation in verbal comprehension. (hunt, 1984)

Positive findings such as these fit well into hierarchial psychometric models because they suggest that broad dimensions, such as "verbal ability", can be broken down into more tightly defined traits. But what about negative finding? One of the processes that facilitates the integration of words into sentences is a non-selective "priming" process, in which topics that have already been identified increase a person's sensitivity to the recognition of related words (Foss, 1982). The usual example is that people shown the word "Doctor" are quick to recognize the following word "Nurse." There is no doubt about the existence of this mechanism or about its role in the processing of normal discourse. However the priming mechanism appears to show little variation across individuals, and therefore measures of it are poor predictors of <u>relative</u> verbal comprehension ability

(Hunt, 1984).

From a cognitive science view, findings showing that there is a linguistic information processing module, that it has subprocesses, and that the subprocesses sometimes show individual variation represent a start towards an information processing theory of verbal ability. Mapping the distribution of individual differences, per se, (i.e. constructing the appropriate Euclidean representation) is not a high priority next step. Studies that relate theoretically defined measures to specific individual characteristics are far more interesting. For instance, it appears that adult aging harms linguistic information processing at the level of sentence and text integration (Cohen, 1979; Light, Zolinski and Moore, 1982). This is somewhat contrary to the psychometric observation that "verbal ability", as defined by certain psychometric tests, is relatively impervious to aging (Botwinick, 1975). How is this discrepancy to be resolved? Questions such as this are central to a scientific understanding of individual differences, but may be much less central to prediction of performance in wide-ranging situations.

The discussion of verbal comprehension illustrates how cognitive psychologists think about individual

differences within an area of information processing module. Cognitive psychology also stresses the process of integration of information across different modules, or across different sources of input. The distinction is important. Studies of the exchange of information between processes deal with the passage of information from one representation to another. Studies of the way in which people deal with multiple sources of information focus more upon people's ability to control the way in which attention highlights first one, and then another, aspect of the current situation. Both concerns present challenges for the psychometric approach, but for somewhat different reasons.

Virtually everyone who has examined problem solving has stressed the importance of forming a good problem representation. Perhaps the clearest example is in high school geometry. Strictly speaking, solving geometric problems is an exercise in syntactical analysis; well formed strings of symbols are to be written into other well formed strings using a finite set of rules. Problem diagrams are not logically necessary, but they certainly help. It is quite easy to show that people differ in the representations that they use. Consider the sentence verification task. Most people solve this problem by comparing the meaning of linguistic descriptions of the picture to the meaning of the sentence. These are people who will use the sentence to construct an image of the picture they expect to see and then compare it to the picture that they are actually shown (MacLeod, Hunt, and Mathews, 1978). Regularities in representation use can also be shown across cultures. Children raised in a western European culture will attack an object memorization task similar to the game "concentration" by developing a verbal strategy of where the objects are. Desert dwelling Australian aboriginal children treat the same task as one of memorizing a visual image (Kearins, 1981).

The fact that different people use different representations poses a major problem for any trait model of cognition. Changes of representation may change the type of information processing that is required to take a particular test. This challenges a basic assumption of all psychometric methods; that the same linear combination of abilities can be used to predict the test score of every examinee. More colloquially, if representations change

then there will be "representation optional" tests that are verbal tests to some people and visual-spatial tests to others. When representation optional tests are included in psychometric batteries they will give erratic results, since their loadings will depend on the frequency of use of different representations in the population being tested. (Sentence verification tests provide mixed results when used with college students, but seem to be purely verbal tests in populations of older people (Hunt and Davidson, 1981).) By a sort of Darwinian logic, representation optional tests drop out of intelligence testing, because they do not fit well into the Euclidean model of ability description. But, from a cognitive science view, knowing the sort of representations a person likes to use is one of the most important pieces of information that you can have about problem solving ability.

Finally, let us consider the other sense of "integration", the ability to control attention during problem solving. This ability is usually tested by giving people several tasks to do in a short time period, and seeing how well they are able cope with streams of information from different tasks. The tasks involved are almost always very simple ones, such as detecting whether or not a particular word has occurred in a string of words presented to the right or left ear (dichotic listening), or determining whether a signal has been presented at a particular location in the visual field. These simple tasks are studied because they are believed to be key components in a variety of very complex machinery operating tasks, such as flying an airplane.

Early research suggested that there are no reliable individual differences in the ability to do several things at once, apart from the ability to do each of the tasks singly. The early work has been criticized on methodological grounds, though, and a reanalysis of key studies indicates that the ability to share one's attention across several tasks ("time sharing ability") is a reliable dimension of individual differences (Ackerman, Schneider, and Wickens, 1984; Stankov, 1983). Research identifying just what time sharing ability is is in its infancy. However we do have some indications of it nature.

Time sharing must involve some capacity for controlling attention. People who are good either at focusing attention on one <u>auditory</u> channel (e.g. listening to a speech against a background of

conversation) or splitting attention across two auditory channels (listening to a conversation while talking on the telephone) are not necessarily the people who can focus or split attention across the visual field, but there is a substantial (.60) correlation between measures of control of attention within each modality. This suggests that there are both inter and intra modality mechanisms involved (Lansman, Poltrock, and Hunt). There also seems to be a reliable dimension of individual differences in the ability to shift attention from one stream of input to another. Examples are the task of shifting from listening to one ear in a dichotic presentation to listening in another, or shifting from following one sequence of visual symbols to following another (Hunt, in press; Hunt and Farr, 1984). We do not know the relation between "attention shifting" ability and the "attentional control" ability identified by Lansman et al.

Studies of the control of attention are quite outside the present range of abilities tested by conventional psychometric procedures. There are two reasons why psychometricians have avoided this field. One is that the motivation for studying individual differences in the control of attention is based partly on a desire to predict how well people will operate machinery in highly

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demanding, time limited situations. Again aircraft operation is the best example. The sorts of processes being tapped in attentional control studies are simply not an issue in the educational and business settings applications that fuel many psychologcal studies of intelligence. There is also an intentionally practical reason for avoiding studying attention in a psychometric framework.

The procedures required to evaluate the control of attention are, to put it mildly, not easily included in the usual testing situation. The tasks are complicated and the participants must receive a careful explanation. In some cases up to several <u>hours</u> of practice may be needed before a person's performance is stable enough so that he or she can be tested. All of these considerations mitigate against the "large N" studies that psychometric technology depends upon. However, there is no way to shortcut the precautions. As was pointed out earlier, cognitive psychology develops procedures that are justified by their relevance to a theoretical model. Any use of these procedures must contain internal checks to make sure that the model still applies. In the case of studies of attention, the procedures and the internal checks will often be so onerous as to preclude their use in

conventional personnel evaluation settings. This pragmatic fact does not diminish the theory, nor does it diminish our scientific interest in individual differences in attention.

Previous remarks have focused on the conceptual limits of the psychometric approach. It is worth noting that in the case of studies of attention cognitive psychology has also been myopic. "Attention" has been conceived of as something that a person throws from one place to another, in response to an environment that demands an instantaneous response. This is a realistic model for skateboarders, all the time, and for airplane pilots some of the time. In most human endeavors, though, the cognitive environment demands responses within minutes, hours, or even days. The person doing the thinking usually has a good deal of freedom in scheduling the order if different cognitive tasks are to be done. This is a very difficult situation to study within the technologies of both psychometrics and cognitive psychology, because it means giving control of the situation over to the participant. And once this is done, the examinee has control over what is to be measured. Understandably both psychometricians and experimental psychologists avoid such situations. But the ability to structure one's environment may be the key to success. This becomes apparent when we consider the topmost level of cognitive psychology, the study of conscious, specialized problem solving.

Complex problem solving is very much influenced by the representations that problem solvers choose to use, so understanding the process by which representations are developed, selected, and chosen for use has become a central goal of cognitive psychology. Since the choice of optional representations is very heavily influenced by learning, any theory of representation in problem solving has to be, in effect, a theory of how a person acquires and uses knowledge. The effects of representation owning on representation having are multiplicative, not additive.

This point has been illustrated in a striking way in studies that show how the information that a person extracts from a situation depends upon the person's representation of the situation itself. Chiesi, Spillich and Voss (1979) offered a good illustrative study in a rather trivial field, recalling an account of a baseball game. People who were familiar with baseball could construct a representation of the plays being described. This caused them to focus on game relevant information,

which they were subsequently able to recall. People not familiar with baseball were not able to do this, although they were able to recall game irrelevant informaton contained in the broadcast.

At one level, such an observation is hardly surprising. "Everyone" knows that people recall more about events that they understand. But this is precisely the point. Understanding and learning are problem solving situations, in which a person's current knowledge is used to structure new knowledge. The topic of Chiesi et al. experiment may have been trivial. The principle was not. Exactly the same point can be made (after a much more complicated analysis) by studying the way in which students acquire knowledge of plane geometry, or of computer programming (J.R. Anderson, et al., 1984). And consider a still more detailed analysis of a very important activity. Carbonnell (1978) was able to simulate conservative and liberal interpretations of political events using a program that applied identical information processing mechanisms to merge the statements with different representations of political and social forces. What one gets from experience depends very heavily upon one's interpretation of it.

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The psychometric view is quite unsatisfactory here. Saying that people differ in their ability to use common, culturally defined solution methods (the definition of Gc) hardly captures the process of representation use. Amplifying the statement by saying that content knowledge extends Gc in specific fields is only a small step forward, for the psychometrician is still operating within the Euclidean representation of cognition. Regarding 'applying knowledge' as a trait does not discriminate between the possession of knowledge and the ability to see that a particular piece of knowledge is relevant to the problem at hand. It is fairly easy to demonstrate that the two are not synonymous. People can be given exactly the appropriate knowledge to use in problem solving, but in a slightly different context, and be unable to apply it. Some people see connections where others do not (Gick and Holyoak, 1983), but why? What processing differences are there between people who do and don't make generalizations? This is another example of a question that is central to a science of individual differences but not particularly crucial to a technology for prediction.

The issue being raised here is quite a broad one, for it has to do with the way in which "culturally acquired knowledge" is used. While some knowledge consists of

ready-made answers to questions of fact e.g. much cultural knowledge consists of ways of representing problems so that their solution can be achieved. The representations form skeletons that guide thought, directing one's attention to key aspects of the problem at hand and suggesting particular solutions. Different theorists have used the terms "schema", "frame", and "script" to describe this process. These terms all reflect what seems to be a universal characteristic of human thought. The world is often ambiguous or overwhelmingly complicated. People bring order into this chaos by assuming that the world satisfies the constraints implicit in their world view. Successful problem solving is largely a process of trying out one or another constraining representation until one is found that works. To give a concrete example, consider the problem solving process of expert physicists. They recognize specific problems as instantiations of a generalized class of problems (e.g. balance of force problems). Once recognition has been achieved problem solving methods associated with the general class can then be applied to solve the specific problem. Novices are likely to focus on aspects of a problem that is not relevant to the general classification principles (e.g. is a sliding block involved?), leading to the use of general, but clumsy problem solving methods. (Chi, Glaser, and

Reese, 1981; Larkin et al. 1980).

The realization that most problem solving is achieved by context specific methods marks a major change in Cognitive Science. Early work on artificial intelligence and human problem solving placed great emphasis on the discovery of general problem solving methods (Hunt, 1975). More recent studies have emphasized area specific knowledge (Feigenbaum, 1977; Hayes-Roth, Waterman, and Lenat, 1983). The same trend has been evident in cognitive psychology, where research has shown the extreme importance of topic specific schemata as guides in problem solving.

If this trend were to be taken to its extreme, generalized psychometrics would be, if not impossible, at least greatly changed. The whole idea of "intelligence" is that there is some mental characteristic of the individual that applies to many problem solving situations. An emphasis on the use of schema in problem solving does not completely deny this notion, for some schema will have wide applicability, especially in educational settings. Arguing again by illustration, Van Dijk and Kintsch (1983) have shown that understanding of a text is driven by schema that specify the form of argument in different

types of text (stories, scientific reports, etc.). It is obviously possible to design tests to see whether or not people possess these general schema. Such tests are likely to be useful predictors of ability to function in places where general schema are used. Educational settings immediately spring to mind. Tests of general schema use are not likely to be of much use in predicting performance in situations in which effective local schema operate. People appear to be able to function quite well with a local schema even though they are not terribly comfortable with a related, more general problem solving procedure.

Some recent studies of the learning and use of mathematics and logic provide excellent examples of this point. Mathematics and logic are often thought of as the purest, most abstract, and most general problem solving methods. At least in academic circles, an argument can be justified solely by appealing to its logical purity. When children learn mathematical problems they learn them as schema (Riley, Heller, and Greeno, 1983). Much of the difficulty in mathematics appears to be in translating from a non-mathematical statement of a problem into the appropriate schema (Kintsch and Greeno, 1985). At a grander level, the abstract schema of mathematics are so hard to learn that the ability to do so is often considered in itself a hallmark of intelligence.

If mathematical reasoning is so difficult, how does the modern world function? To take a specific example, how do people calculate the price of products in a supermarket? People are quite good at doing so, even though pricing information is not always presented in the most straightforward way (Lave, Murtagh, and De La Roche, 1984). The same people are not good at solving simple arithmetic problems, when those problems are presented outside of the shopping context. Lave et al. found that shoppers made errors on only 2% of the pricing problems presented in an actual shopping context and on 41% of the problems presented in an abstract arithmetical context. This was true even though the same arithmetic operations were used in each case. Furthermore the two tests were not reliably correlated! Further probing showed that the shoppers had a variety of problem solving procedures that were specialized for shopping and that were quite adequate for problem solving in that context.

Shopping is not the only place where people exhibit context-specific specializations of a logic that, in some abstract sense, they really do not understand. Ceci and

Liker (1985) have reported a study similar to Lave's using an even higher order skill, statistical decision making. Inveterate horse race bettors have to determine whether the odds offered by the track are actually a good estimate of whether or not a horse will win. (The racetrack odds are determined solely by the amount of money bet on each horse, and do not reflect an explicit analysis of the horse's ability vis a vis its competitors.) Some individuals can "beat the odds" reliably. It is possible to formulate what they do as a complicated statistical estimation problem. But the racetrack handicappers were far from being untutored, brilliant mathematicians. In fact, their formal intelligence test scores were well below undergraduate norms. The skilled handicappers had developed complicated, race-track specific techniques for handling an unusually complex problem in decision making.

None of these remarks will be new to those familiar with studies of cross cultural cognition. Specialists in this field have long pointed out that the Western emphasis on "intelligence" emphasizes the ability to do problem solving in the abstract. The very idea of abstract problem solving seems to be related to Western European schooling (Cole and Scribner, 1974). While this may be true in an abstract sense, it does beg a very important point. The

Western European schooling situation, with its emphasis on abstract problem solving, may indeed be a cultural phenomenon. However, it is an important, useful phenomenon. Logic, mathematics, and general problem solving methods do indeed provide an important part of our society, even if they are then specialized as people find their niche in society. Therefore identifying people who are likely to be able to learn to use these methods is a reasonable endeavor.

This is where the concepts of Gc and, to a lesser extent, Gf, are likely to be useful. Let us accept the fact that high scores on Gc tests identify those people who have acquired the problem solving schemata of our society. Those are the very schemata that are going to be used in the classrooms, to aid people in acquiring further decontextualized knowledge. Perhaps we could design better tests if we had a better idea of how the educational process proceeds, because we would then know what schemata are going to be required, when, and (perhaps) how they should be learned. Furthermore, at least in theory Western schooling is supposed to develop an ability to generalize; i.e. to see how problem solving schemata learned in one setting can be applied in another. It may be that tests of Gf <u>identify</u> people who can make such

generalizations. If we had a better understanding of the process of schemata generalization we would know what it is that these people are doing, and then could develop better tests for their identification.

THE UNION OF THE CAMPS

Chronbach (1957) sought a uniting of two camps of <u>scientific</u> psychology; the study of individual differences and the study of nomothetic influences on cognition. The prospects for uniting <u>these</u> camps is excellent. However, the study of individual differences is not identical to the use of a Euclidean representation of mental abilities. The prospects for uniting psychometrics and cognitive psychology are mixed, and for perfectly good reasons.

The paper and pencil testing technology and its accompanying Euclidean representation are hard to beat, so long as one's criteria are cost effective evaluation, and the prediction is to be to a situation that involves very general behavior that depends upon decontextualized reasoning processes. Eduction and, to a lesser extent, military life are examples of such situation. Traditional psychometric evaluation has not, and probably will not, be extended successfully to the prediction of performance in more specific situations, where adequacy depends upon the ability of an individual to execute situation specific, schema based, and perhaps complex information processing sequences. Note that the problem here is not that the paper and pencil technology is inadequate to construct such situations. The problem is that the underlying Euclidean representation of mental abilities cannot be used to formulate a process model of cognition.

Enter the computer. My frequent references to "paper and pencil technology" may have sounded archaic to those who are already programming computer presentations of the Wechsler Adult Intelligence Scale, the Armed Services Vocational Battery, and any number of other intelligence tests. Doing so will certainly make testing more efficient, as witnessed by current developments in "item banking" and latent trait theory (Green, et al 1982). Furthermore, computer presentations are more flexible than paper and pencil presentations, so the Euclidean model can be extended to new domains. Some possibilities are extensions of spatial-visual testing to the situations involving moving visual displays (Hunt and Pellegrino, 1985) and the development of practical tests of auditory information processing (Stankov and Horn, 1980). We may

have to add a few dimensions to the Euclidean model, or we may not. Either way, the expansion of the traditional model via computerized testing will be a useful exercise. In itself, though, computerized testing will not address the conceptual issues that have been raised here. There is every reason to believe that a theory of individual differences can be developed as a subtheory of a general theory of cognitive psychology will result in better understanding of how individual variables such as age, education, sex, and genetics influence the processes of problem solving. To what extent will or will not this theory influence the technology of testing?

It is now technically possible to develop automated laboratories, so that the experimental psychologist can collect data on enough individuals to study individual differences at all. In the abstract, one could conceive of the development of even larger laboratories devoted to assessment and prediction. Such laboratories would immediately encounter another economic limit; the expense of the evaluation to the examinee. The sorts of measurements required by cognitive process theories are often extremely time consuming. The equipment is relatively complex, so that the examinee must spend considerable time learning to use it before any data can be collected. This and several related problems are very well discussed in Longstreth's (1984) excellent critique of the misuse that has been made of choice reaction time paradigms in order to fit them into an evaluation setting. A point that was made earlier is more than worth repeating. The measures developed from cognitive process theories are only valid when the boundary conditions for measurement are met. This requirement may forever prevent developing cognitive psychology analogs to the ten to twenty minute tests so common in psychometric batteries.

These remarks apply with particular force to any testing program based on the information processing aspect of cognitive science. Because such tests are likely to be expensive, testing itself will of necessity be limited to those situations in which prediction is important and in which performance is limited by a person's information processing capacity, once that person has acquired the specific knowledge required to perform at all. This suggests two guidelines for applied research. If information processing models are to be useful, then the test constructor must have a good idea of how information processing limits performance in the situation to be predicted. Two cases can be imagined. In one the key information processing requirements are not situation

specific, and hence may be tested using some manageable testing paradigm. In the other case the information processing limits may only be definable in context, and hence can only be tested in the actual situation or an adequate simulation of it. If this is so it may not be possible to test examinees who do not already have a good understanding of the job for which they are applying. In either case the test constructor cannot proceed without a situational model. One can imagine such a model for specific situations, such as aircrew or radar operation. A detailed model of the information processing required in high school is unlikely.

At first glance a theory of the use of representations might seem to be of little use in personnel evaluation because, by definition, representations are used by people who have already acquired expertise in some field of endeavor. Ergo they must have already been permitted entry to the field. Fortunately this logic can be reversed. If "becoming an expert" means acquiring certain problem solving schema, why not evaluate a student by determining the extent to which the expert's problem solving schema have been internalized? Developments in Artificial Intelligence have led to at least the claim that we can represent expert knowledge inside a computer (Hayes-Roth, Waterman, and Lenat, 1983; but see Dreyfus, 1984 for questions about some of the evidence on which the claim is based.) "All" that needs to be done is to apply the interview methods used to extract knowledge from an expert to extract (faulty) knowledge from a student. To aid teaching, the evaluation process can be made the basis for further specialized instruction.

Efforts are underway to develop just this sort of intelligence computer aided instruction system (J.R. Anderson, 1984 et al.). The teaching goals appear to be in reach in non-trivial fields (computer programming and geometry). Whether or not the evaluation goal is feasible remains to be determined. The present intelligence tutoring programs seem to make a rather general guess at the student's current state of knowledge, and use that guess to select problems that are most educational for that student. Whether or not the program's guess about the student's representation is sufficiently accurate to be predictive remain to be seen.

CONCLUSION

Chronbach thought that general theories of

psychological processes ought not to ignore individual differences, and vice versa. He was right, and in a general sense the union of the camps is well underway. In my opinion (and here there may be a violent difference of opinion!) the way to achieve the scientific union is to concentrate on understanding how individual differences variables, such as age, sex, genetic constitution, and education, influence the processes of cognition. It does not seem particularly fruitful to try to derive the dimensions of the psychometric Euclidean representation of abilities from an underlying process theory.

This does not mean that the Euclidean model is wrong, within the context in which it has been developed. Consider an analogy to what we know about expertise. Experts develop local schema that apply to their local problems. The psychometric Euclidean model is an excellent way to deal with personnel prediction and classification. But it does not generalize well to understanding cognitive actions. Einstein was certainly intelligent, in the psychometric sense. However he did not develop a single one of his intellectual conceptualizations because he was high on Gc or Gf. He developed them because he had certain schema for problem solving and because he had the information processing capacity to apply these schema.

Eventually there may be a "Grand Unified Theory" of psychology, similar to those now being developed for physics. But will we understand it? There seems to be a role for Newtonian mechanics even after quantum theory..engineers use the limited Newtonian notions all the time. Psychometric and cognitive process theories may similarly co-exist for a long time. Practical application and power of conceptualization are both worthwhile goals. They are not necessarily synonymous.

Footnotes

1. The preparation of this paper was partially supported by the Office of Naval Research, Contract N00014-84-K-5553 to the University of Washington. The opinions expressed are the author's and do not reflect policies of the Office of Naval Research or any other U.S. government agency.

2. The term 'psychometrics' will be used throughout this paper to refer to the psychological theories of mental competence that have been developed by applying correlational analysis methods to test scores. The alternative meaning of psychometrics, as a branch of applied mathematics, will not be used.

Figure Legends

1. The Euclidean model of mental ability. A person is conceptualized as a point (X) in a space of mental traits (y1,y2,y3). Each point on the space can be mapped into an acceptance or rejection interval on a one-dimensional criterion variable.

2. An abstraction of the two dimensional space of mental tests developed by Marshalek, Snow, and Lohman (1983). Tests were located by a multidimensional scaling in which the distance between tests in the space is roughly proportional to the correlation between them; the higher the correlation the less the distance between test points. Some of the tests shown in this figure are 1-Raven Matrices, 2-Letter Series, 3-Hidden Figures, 4-Paper Form Board, 5-Object Assembly, 6-Vocabulary, 7-Information, 8-Comprehension of verbal statements, 9-Arithmetic problem solving, 10-Digit span, and 11-Locating A's in a line of text.

3. The Sentence Verification paradigm. A phrase is displayed. When the participant indicates that the phrase is understood the picture is displayed. The participant then determines whether or not the phrase correctly

described the picture. The dependent variables are the times between phrase display and comprehension (comprehension time) and picture display and verification (verification time).

4. Smith's (1968) stage model of stimulus classification and response production. Each box is assumed to represent a distinct psychological process. The processes take place in series, progressing from the top downward.

5. A modular approach to cognition. Each box represents a class of mental processing, analagous to a specialized work shop. In integrated thinking information is passed back and forth between the different modules, and finally represented as a coherent internal picture of the external world. Processing is not necessarily serial.

6. Fragments of a set of production rules for driving an automobile.

7. The organization of an information processing system for executing productions. The productions reside in long term memory. Information is presented to the system on auditory and visual channels that are connected to the external world. The system can "keep notes for itself" by

placing temporary information in working memory, and using this information to guide production selection.

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