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Beyond Difference Scores: Testing Models of Speed of Information-Processing Using Confirmatory Factor Analysis

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This study has two parts: Part I discusses the limitations of difference scores and exploratory factor analysis for representing speed of information-processing stages in the context of a reanalysis of a study by Vernon (1983). Vernon interpreted the differences between

objectively measured reaction times on various simple cognitive tasks as components of speed of information-processing. Correlations were calculated among these differences and subjected to exploratory factor analysis. The factors obtained from this analysis were interpreted by Vernon in terms of short-term and long-term memory processing constructs. The use of difference scores, however, implies an additive model that does not make allowance for random error, which leads to spurious correlations between these differences. The application of exploratory factor analysis to uncover latent variables among these differences compounds the problem because it admits many alternative interpretations which cannot be tested against one another for goodness-of-fit to the data. Confirmatory factor analysis addresses these problems. This thesis demonstrates that the correlations between the difference scores can be accounted for in terms of factors obtained from factor analysis of the original reaction time data. These factors lead to an alternative interpretation of the results which is contrasted with Vernon's interpretation.

Part II of this study illustrates the use of confirmatory factor analysis with this kind of data. An attempt to test the assumptions of Vernon's difference score model with confirmatory factor analysis did not succeed because the implied model was too constrained for the statistical program we were using; consequently, the program could not find a starting solution. In order to demonstrate how confirmatory factor analysis can be used to test models of speed of cognitive processing, Part II partially replicates a study by Lansman, Donaldson, Hunt, & Yantis (1982). This research analyzed a simple cognitive reaction time task that was examined in detail by Vernon. Donaldson (1983) used the Lansman et al. data to compare difference scores and part correlational techniques with a general approach based on analysis of covariance structures to demonstrate how the components of cognitive processes can be explicated using confirmatory factor analysis.

One hundred and one undergraduate psychology students were presented with a computerized version of the Posner letter-matching task (Posner, Boies, Eichelman, & Taylor, 1969; Posner & Mitchell, 1967). Four models of speed-of-processing were formulated to represent this data and were tested. Examination of several goodness-of-fit indices revealed one model that fits the data very well. This model includes two factors, one for perceptual speed in making a match based on physical identity and one for access to lexical codes required for making a match based on name identity. The model also suggests that the perceptual speed factor is identical across matching conditions. This replication supports the results obtained by Donaldson's analysis of the Lansman et al. data.

BEYOND DIFFERENCE SCORES: TESTING MODELS OF SPEED OF INFORMATION-PROCESSING USING CONFIRMATORY FACTOR ANALYSIS

by

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CHAPTER I

INTRODUCTION

In the past decade, the rapidly growing interest in establishing ties between new models of cognitive functioning and the more established Psychometric tradition in the study of human abilities (Carroll & Maxwell, 1979; Carroll, 1980; Sternberg, 1985a) has led to an increase of correlational studies with information-processing variables and psychometric tests (Chiang & Atkinson, 1976; Egan, 1978; Jensen, 1980; Hunt, Frost, & Lunneborg, 1973; Hunt, Lunneborg, & Lewis, 1975; Pellegrino & Glaser, 1979; Smith & Stanley, 1983). A commonly used method involves taking the difference between two observed information-processing variables, typically reaction times, which are postulated to be related in some fundamental way and correlating the difference score with some psychometric measure such as verbal ability (Hunt, et al., 1973; Hunt, et al., 1975; Lansman, Donaldson, Hunt, & Yantis, 1982; McClelland, 1979; Schwartz, Griffin, & Brown, 1983; Vernon, 1983; Vernon, Nador, & Kantor, 1985). Often, a matrix of similarly derived correlations is then subjected to a factor analysis and the resulting factors used as evidence for models that are postulated to account for the structural relations between the variables (Lansman, et al., 1982; Schwartz, et al., 1983; Vernon, 1983; Vernon, et al., 1985).

The goal in using difference scores in the manner described above is to isolate a mental processing stage from one or more other stages in a reaction time task. An example of this approach is typified by the basic paradigm used by Vernon (1983) which examines the relationships among a number of measures of speed of information-processing. Imagine a mental process that can be reflected by a reaction time task that, for theoretical reasons, is assumed to be composed of two stages. One of these stages is directly measurable but the other is not. If the reaction time for the directly measurable stage is subtracted from the reaction time for the entire task, then what remains is the reaction time for the unobservable postulated stage. In this way the processing time for the unobservable stage can be indirectly measured.

A fundamental assumption of this method is that the total response time required for a given task is the simple sum of the response times for the component stages, with no terms included to allow for random error. This assumption is usually violated (Donaldson, 1983). If this assumption is not valid then interpretation of the indirectly measured stage is difficult. In other words, the quantity reflected by the difference score includes error terms, in addition to the difference in underlying factors, $y = F_2 - F_1$.

Donaldson (1983), in a comparison of several methods of modeling information-processing stages, argues that there are inherent difficulties with the difference score (also called change or gain score) approach. The presence of error in the difference scores, for example, tends to produce spurious correlations between these differences and other quantities with related error components. This is because the same errors of measurement are shared by both quantities (Cronbach & Furby, 1970). He questions the widely used practice of taking difference scores as appropriate measures of time required for information-processing stages and is concerned with the theoretical implications. It is not uncommon to take variables that have prima facie value, then arrange, combine, and transform them in a way that appears reasonable, next subject these transformed variables to some standard analysis such as exploratory factor analysis, and finally attempt to interpret the results in a meaningful fashion. This is essentially the approach employed by Vernon (1983). But if the method of combining the variables is questionable then the resulting data structure is at best difficult to interpret and at worst, meaningless. Donaldson suggests that if the structure of information-processing stages is indeed additive in nature, then it is more appropriately represented by a factor analysis model.

There are two aspects to this thesis, both aimed at better understanding the components of speed-of-processing on simple cognitive tasks. The first is an illustration of the consequences of indiscriminate use of difference scores by performing a critical analysis of and reinterpretation of results obtained in a study by Vernon (1983). The second part of this thesis is a demonstration of the advantages of the confirmatory factor analysis approach advocated by Donaldson for the formulation and testing of models of speed-of-processing.

This thesis takes issue with two aspects of Vernon's study. First, Vernon is not explicit about the model he purports to be testing. Secondly, he compounds this problem by using exploratory factor analysis on the difference scores to uncover latent variables. Exploratory factor analysis does not allow for detailed specification of a particular model which can then be tested for goodness-of-fit to the data. It admits too many alternative interpretations and does not allow competing models to be tested against one another.

If Vernon is seeking to identify the best model to represent speed-of-processing, the best approach is the use of confirmatory factor analysis instead of exploratory factor analysis. This technique does not necessarily assume a common factor model with uncorrelated factors, as does the exploratory factor analysis model. It demands that an explicit model be formulated a priori and it encourages the testing of this model against competing models for goodness-of-fit to the data. Vernon's research utilizes difference scores and exploratory factor analysis, both of which are inadequate to provide testable models to represent the relationships among the reaction time variables.

Confirmatory factor analysis is a particular case of the more general covariance structure model. There are two components to the covariance structure model, the measurement model and the structural model. The measurement model specifies the latent variables in terms of the observed variables; the structural model causally relates these latent variables. Confirmatory factor analysis is the measurement model component of the covariance structure model.

The essential difference between exploratory factor analysis and confirmatory factor analysis lies in the fact that exploratory factor analysis decides for itself which measured variables go with which latent variables; in confirmatory factor analysis, the researcher specifies a model in advance which stipulates what the relationships between measured variables and latent variables ought to be. As such, confirmatory factor analysis allows the researcher to actually test a model rather than merely speculate as to what a given factor pattern might represent.

Our research is directed at performing a critical reanalysis of Vernon's data and reinterpreting his results. Confirmatory factor analysis of the original reaction time measures is the most appropriate route to follow. However, Vernon's data is not adequate to take this approach. Therefore, in order to demonstrate the superior modeling capabilities of confirmatory factor analysis, a replication of a parallel study by Lansman, Donaldson, Hunt, & Yantis, (1982) will be performed.

Lansman, et al.'s data includes several measures of speed-of-processing, one of which, the Posner letter-matching task (Posner, Boies, Eichelman, & Taylor, 1969; Posner & Mitchell, 1967), is a subset of Vernon's experimental tasks. Donaldson's (1983) critical analysis of the Lansman, et al. data supports the application of confirmatory factor analysis over difference scores for testing models of speed of cognitive processing. However, his model specifications include a psychometric test variable which we feel might obscure the relationships between the speed-of-processing variables. Consequently, we have formulated four models of speed of information-processing which do not include a psychometric criterion variable. The results of analyzing these models using confirmatory factor analysis illustrates how explicitly stated models can be confirmed or rejected.

The broad theme addressed by this thesis is the need to be explicit about the cognitive models that the data is intended to support. Certain methodologies themselves implicitly assume specific models that may be inappropriate. Difference scores are a case in point - they implicitly assume a narrowly defined additive model of the kind mentioned above.

Because of the rather complex nature of this thesis, the next two sections contain brief discussions of the competing theoretical perspectives involved in intelligence research. Following these, discussions regarding perceptual speed and the letter comparison task and factor analysis models of these relationships are presented. An understanding and appreciation of the history, methodology, and fundamental tenets of these aspects of the thesis will aid in understanding the manner in which each contributes to the rationale and method used in this study.

PSYCHOMETRIC VIEWS OF SPEED-OF-PROCESSING AND VERBAL ABILITY

Early approaches to a conception of intelligence represented in the work of researchers like Galton, Wundt, and J.M. Cattell revolved around the measurement of various physical characteristics of a person, in particular their reaction times to various stimuli. Over the years, this approach has conceptualized intelligence in several ways: as a single general global ability (Spearman, 1904a; 1904b), an unordered series of primary abilities (Thurstone, 1938; 1948), a hierarchical arrangement of abilities (Burt, 1949; Cattell, 1963, 1971; Holzinger, 1938; Vernon, 1965, 1971), and as geometric arrangements of specific abilities (Guttman, 1965; Guilford, 1967; 1982; Guilford & Hoepfner, 1971).

The various theories are essentially different mathematical expressions of the same correlational patterns. Although the datasets that researchers typically obtain appear to be remarkably similar, there is a wide variety of factor configurations. Sternberg (1985a) suggests that the various factor structures are simply equivalent ways of representing latent abilities. The pattern of covariation among abilities has been fairly well-established. Researchers disagree, however, regarding the best way to structurally represent these patterns.

Of particular relevance to this paper is an aspect of the work of R.B. Cattell (1963; 1971), best known for advocating a view of intelligence that emphasizes fluid and crystallized abilities. Cattell was the first to note the correlation between another of his second-order abilities, clerical and perceptual speed (CPS), and verbal ability. This relationship has been used extensively in much of the work on the relation between basic cognitive processes and psychometric ability measures and is the relationship examined in the study we will review (Vernon, 1983) and in the study we intend to partially replicate (Lansman, et al., 1982).

INFORMATION-PROCESSING VIEWS OF SPEED-OF-PROCESSING AND VERBAL ABILITY

Compared to the psychometric tradition, information-processing psychology has only recently turned its attention to the study of individual differences. It brings with it an emphasis on applying experimental methodology to a detailed analysis of the underlying fundamental processes that contribute to task performance. This is in contrast to the psychometric tradition's basically descriptive correlational approach that examines individual differences in task performance and consequent data-driven theorizing. The cognitive approach looks to the identification and measurement of unobservable, elementary processes that underlie observable behaviors.

Like the psychometric tradition, the information-processing approach exhibits a variety of research emphases (Sternberg, 1985b). The method used in this study is the "cognitive correlates" approach (Pellegrino & Glaser, 1979), where a speed-of-processing measure is correlated with a psychometric measure of an ability that presumably incorporates that particular information-processing operation. In this case, the presumed unobservable latent process is lexical access (Hunt, 1978, 1980; Schwartz, 1981), which is defined as the time it takes to retrieve a semantic symbol from long-term memory (LTM).

Sternberg (1985a) notes three common assumptions and emphases of information-processing models: (1) The unit of analysis is typically the result of processing that occurs in the performance of a rudimentary task and tends to be part of a large set of similarly elementary cognitive abilities that combine to produce some measurable behavior. "We take it as fundamental to all information-processing models that they incorporate a certain number of elementary mental processes or operations, a concatenation of which can produce complex behavior" (Posner & McLeod, 1982, p.478-479). (2) The dominant construct domain for investigating cognitive models has been that of processing speed. This contrasts with the emphasis in psychometric theorizing and testing upon processing accuracy. (3) The tasks that are experimentally imposed upon subjects are not the kind one normally encounters in real life and tend to gravitate towards a rather small set of extremely basic tasks that could be said to be laboratory-bound (Sternberg, 1985a). As such, the preponderance of empirical support for the conclusions that information-processing theorists draw is narrowly defined and binds the researcher to make only very limited generalizations about results.

This last point raises the issue of whether individual differences on molecular tasks are relevant to broader ability domains. The consistent correlations found between psychometric abilities and rather simple information-processing tasks are a contributing factor to the cognitive theorists' drive to examine these processes. A valuable form of support for any avenue of investigation is the validation of a theory against external criteria (Sternberg, 1985a). The ability to predict psychometric abilities from more fundamental processes lends support to a researcher's hypothesis that he/she has "isolated critical aspects of intelligence - ones that are important in central measures or in many measures of intelligence" (Sternberg, 1985a, p.16). One such aspect of intelligence that has gained much support and found wide acceptance is perceptual speed (Irvine & Reuning, 1981).

PERCEPTUAL SPEED AND THE LETTER-MATCHING TASK

Among the eight primary mental factors proposed by Thurstone is Perceptual Speed, described as, "...the ability to recognize likenesses and differences between objects and symbols quickly and accurately" (Kail & Pellegrino, 1985, p.25). A substantial amount of evidence and support for this factor exists (Ekstrom, French, Harman, & Dermen, 1976; Irvine, 1979; Irvine & Reuning, 1981).

Posner's letter-matching task (Posner, Boies, Eichelman, & Taylor, 1969; Posner & Mitchell, 1967) is often used as a measure of this factor. In this test, subjects are required to judge if two letters presented simultaneously or sequentially are the same or different. The letters can be physically identical (e.g. AA or aa) or they can be identical in name only (e.g. Aa or aA). The subject is instructed to respond "same" if the letters are either a physical match or a name match and "different" if the letters do not match at all (e.g. AB or bA).

The letter-matching task is essentially an application of Donders' b-reaction (also called choice reaction) (Donders, 1868, in Koster, 1969). The important feature of Donders' b-reaction is that, in addition to the stimulus input time, decision time, and motor response time that make up simple reaction time (a-reaction), choice reaction time requires time to discriminate between two or more stimuli and time to select a motor response from among two or more choices. Both the physical match condition and the name match condition require a b-reaction. The subject must in either case make a discrimination between two letters (physically same, name same, or different) and make a decision as to which of two motor responses (match or no match) is appropriate. Typically, it takes longer to respond to name identity than to physical identity (Lansman, et al., 1982). Explanations for this finding vary.

Both Hunt (1978) and Schwartz (1981) have suggested that the difference in time between making a physical match versus a name match reflects the time it takes for access to lexical information in long-term memory. Physical matching only requires an immediate determination of similarity; name matching requires that the subject go beyond this and search long-term memory for well-rehearsed codes. Evidence associating lexical access time on the letter-matching task with verbal ability takes the form of fairly consistent correlations (approx. -.30) between this measure, which it should be emphasized is a difference score, and tests of verbal ability (Hunt, 1978; Hunt, et al., 1973; Hunt, et al., 1975; Jackson & McClelland, 1979; Keating & Bobbitt, 1978; Lansman, et al., 1982).

Though the question of what is the most likely explanation for this finding is of theoretical significance, it was not the goal of this study to support any one particular hypothesis regarding this issue. Hogaboam & Pellegrino (1978) and Posner (1978), for example, offer alternative explanations for these correlations. In any event, the correlations are fairly consistent and failure to replicate them might also bear on this issue.

In order to explicitly state the goals of this thesis, it is first necessary to examine some specific factor analysis models. This discussion provides a foundation upon which the purpose of the thesis rests.

FACTOR ANALYSIS MODELS FOR THE RELATIONSHIP BETWEEN SPEED-OF-PROCESSING AND VERBAL ABILITY

The variables that are of primary interest in attempting to understand intelligence are unobservable. It is assumed that these underlying source variables or factors contribute in some predictable way towards the effects we can observe and measure in other variables. Factor analysis is a term used to describe a variety of statistical techniques that attempt to explain the covariation among a set of observed variables in terms of a smaller, more fundamental set of latent variables. By imposing a (usually) linear structure on this set of observed variables, a smaller set of dimensions emerges that can account for the observed covariation.

Factor analysis can be used in two general ways. Most commonly, the problem is one of determining the number of factors needed to explain the correlational data and assigning weights to the variables (Carroll, 1982). The method is applied to data in order to ascertain the number of factors and the structure that best fits the data. In this sense, factor analysis is used in an exploratory fashion to examine the underlying dimensions of the data and to generate hypotheses.

Alternatively, factor analysis can be used to test specific hypotheses. A researcher, based on prior understanding of the variables, may have a hypothesis about the number and structure of the factors. Factor analysis can be used to test this hypothesis. In actuality, the researcher can specify, in advance, not only the number of factors anticipated, but a host of other parameters. Used in this manner, factor analysis confirms or refutes the prior expectations of the researcher (Kim & Mueller, 1978; Mulaik, 1972).

Mulaik (1972) reminds us that the major disadvantage of exploratory factor analysis is that it does not always produce readily interpretable results. This is because the researcher "lacks even tentative prior knowledge about the processes which produce covariation among the variables studied" (p.363). The inadequacy of exploratory factor analysis to test hypotheses results from its inability to allow the researcher to specify the relationships among the variables (Long, 1983). Specifically, exploratory factor analysis makes the following assumptions:

1.) All common factors are free to be correlated or uncorrelated;
2.) All observed variables are directly affected by all common factors;
3.) Unique factors are uncorrelated with each other;
4.) Each observed variable is affected by a unique factor;
5.) All common factors are uncorrelated with all unique factors.

These constraints and assumptions tend to make the approach inflexible to specification of desired conditions and estimates of certain parameters. This severely limits the method's ability to test specific models.

In contrast to the limitations imposed by exploratory factor analysis, confirmatory factor analysis (Joreskog, 1967; 1969; Joreskog & Lawley, 1968) presents a relatively wide degree of latitude in fashioning a model with which to compare data. It allows for specifying substantively motivated constraints which can determine:

1.) Which pairs of common factors are correlated;
2.) Which observed variables are affected by which common factors;
3.) Which observed variables are affected by a unique factor;
4.) Which pairs of unique factors are correlated. (Long, 1983, p. 12).

In confirmatory factor analysis, constraints and assumptions are specified ahead of time. After the model is estimated, it is statistically tested for goodness-of-fit to the actual data.

Donaldson (1983) illustrated the use of confirmatory factor analysis with data from a study by Lansman, et al. (1982). This research examined the relationship between Posner's letter-matching task and psychometric measures of ability. Donaldson's approach to analyzing this data differed fundamentally from Vernon's (1983) in its inclusion of error terms in the additive model. Explicitly, Donaldson's model specifies:

$$PI = (1)F_1 + e_1$$

$$NI = (b)F_1 + (1)F_2 + e_2$$

where: PI = physical identity response time;

NI = name identity response time;

F_1 = physical identity true score;

F_2 = lexical access true score;

b = coefficient adjusting for differential value of F_1 in the PI condition vs. the NI condition;

e_1 = physical identity error score;

e_2 = name identity error score.

Furthermore it is assumed that:

$$E(e_1) = E(e_2) = E(F_1e_1) = E(F_2e_1)$$
$$= E(F_1e_2) = E(F_2e_2) = E(e_1e_2) = 0.$$

This last statement is essentially an assumption that errors are 0 on the average and that their correlations with the underlying factors and with each other are 0. It is also assumed that $r_{F1,F2} = 0$.

Coefficient b reflects the idea that the time required to determine whether or not there is a physical match may not be the same in the NI versus the PI conditions even though they are essentially determined by the same underlying factor (i.e. the conditions are different but the factor is the same).

A comparison of the above model with the classic factor analysis model below reveals many similarities:

$$X_{iv} = w_1F_1 + \ldots + w_nF_n + w_uU$$

where: X_{iv} = individual i's score on variable v;

w_1 to w_n = the weight for variable v on factors F_1 to F_n;

F_1 to F_n = individual i's score on common factors F_1 to F_n;

w_u = the weight on variable v's unique factor;

U = individual i's score on the unique factor.

An individual's score (X) on a test (variable v) can be decomposed into n number of common factors (F), each with a weight (loading) assigned to it, and a term (U) that contains all test-specific variance (including any error). Simply stated, the score on a test equals the weighted sum of the factors plus error. Donaldson's model is a special case of this general factor analysis model because it puts restrictions on the parameters. Specifically, the loadings for F_1 and F_2 in the two conditions are:

$$PI = (1)F_1 + (0)F_2 + e_1$$

$$NI = (b)F_1 + (1)F_2 + e_2$$

Compare Donaldson's model to the simple difference score model implicit in Vernon:

$$PI = (1)F_1$$

$$NI = (1)F_1 + (1)F_2$$

The difference score model assumes: (1) no error and (2) b = 1 (no differences in the loadings on F_1 in the PI condition and the NI condition). A fundamental issue involved in a reanalysis of Vernon's data is the legitimacy of not taking into account error when formulating a model of cognitive processes. Donaldson's model allows for error and testing whether or not the loadings on F1 should be equal.

CRITICAL ISSUES AND PURPOSE OF THE INVESTIGATION

Vernon creates composite variables by subtracting one reaction time measure (or two similar measures) from each of two other reaction time measures, both of which are based on nearly identical stimuli and tasks. This introduces an element of spurious correlation that may contribute substantially toward the total correlation between the two new derived variables. This is due to the fact that if the sets of original variables on which two derived variables are based overlap, there is a strong possibility of spurious correlation due to the presence of the shared variables. For example, the same errors of measurement are present in both quantities.

Exploratory factor analysis of the original response time variables was employed to reanalyze Vernon's data. Following the lead of Donaldson in modeling similar data, more satisfactory versions of the additive models implicit in Vernon's analysis were formulated. The alternative models are improvements in that they allow for random error components of the response times. Some of the implications for the proposed factor structure are very general, e.g. implications regarding the number of factors needed to adequately represent the data, and can be checked in a rough way using exploratory factor analysis.

An alternative method, confirmatory factor analysis, is proposed as a better way to analyze this kind of data. The proposed response time models impose constraints on factor loadings, such as requiring loadings of some variables (i.e. response components) to be zero on some tasks. Confirmatory factor analysis techniques are needed to estimate model parameters under these constraints and to provide formal statistical tests of the hypotheses embodied in the constraints. The difference score model can be thought of as a "severely restrictive factor analysis model" (Donaldson, 1983, p.146). As such, it suffers from an "inability to incorporate substantively meaningful constraints, and (the) necessary imposition of substantively meaningless constraints" (Long, 1983, p.12). In contrast, confirmatory factor analysis allows for the imposition of constraints that conform to some previously hypothesized model that specifies the relations to be expected (Donaldson, 1983).

Our goal is to show that factor analyzing the original reaction time measures enables us to account for the correlations between the derived measures with a quite different interpretation than Vernon's. The use of difference scores is unnecessary and only serves to provide support for an interpretation that may be erroneous.

This thesis attempts to replicate results obtained by Lansman, et al., (1982), who employed a paradigm similar to Vernon's (1983), in order to demonstrate the use of confirmatory factor analysis for testing hypotheses. The second goal of this study is to replicate certain aspects of Donaldson's findings. This replication will illustrate the advantages of confirmatory factor analysis over exploratory factor analysis since it will allow for goodness-of-fit tests of alternative models. This feature of the confirmatory factor analytic method provides another powerful reason for its use as an alternative to difference scores. Donaldson (1983) notes the following regarding goodness-of-fit tests:

> It is possible to use this statistic to test the reasonableness of the cognitive theory on which the formal model is based against plausible alternatives. The flexibility of the structural modeling approach encourages consideration of such alternative models. (p.148)

The substantive issue involved in a replication of Lansman, et al. (1982), using Donaldson's (1983) method of analysis, is clarification of the appropriateness of the assumptions made when formulating a serial model of the type proposed by Hunt (Hunt, et al., 1973; Hunt, et al., 1975; Hunt, 1978). If the processing stages are not completely serial (McClelland, 1979) or if the PI processes common to both PI and NI conditions take different amounts of time in the different conditions, then the values of b in the two conditions may not be equal (Donaldson, 1983). Confirmatory factor analysis can be used to test models where b is allowed to vary. This is, of course, in addition to the method's ability to include error terms in the models.

The common theme in this review of Vernon (1983) and partial replication of Lansman, et al. (1982) and Donaldson (1983) is the issue of using factor analysis as a way of going beyond the use of difference scores in examining models of cognitive reaction time. This issue can be summarized by the following points:

(1) If the assumption is made that reaction time tasks are additive in nature, then they are essentially factor analysis models.

(2) Unless dubious assumptions are made regarding the error terms (i.e. the measures are error-free), difference scores have undesirable statistical properties; e.g., spurious correlations between such measures easily occur.

(3) It is better to make inferences about underlying processes using factor analysis of the original

unmodified variables. Some inferences regarding the number of factors and their character can be done using exploratory factor analysis. More explicit tests of the additive model require confirmatory factor analysis techniques, as suggested by Donaldson (1983).

The theoretical issue of interest that unites these studies as a follow-up of Vernon and Lansman, et al. is the nature of the factor structure and whether a single common factor can account for the data. Carroll (1980) suggests that there is only one underlying perceptual speed factor. Neither Vernon's study nor Lansman, et al.'s research is convincing in suggesting that more than one factor is needed to account for the variation (Vernon proposes 3 factors, Lansman, et al. propose 2 factors). If there is more than one factor, another issue is whether they relate the way Vernon or Lansman, et al. suggest.

CHAPTER II

STUDY 1:
REANALYSIS OF VERNON'S DATA

VERNON'S METHOD OF ANALYSIS

Vernon's (1983) research relates a number of measures of speed of information-processing to intelligence test scores. Particularly germane to this thesis is Vernon's method of defining certain variables as the difference between reaction times on specific speed-of-processing tests. The following is a description of each of these tests. In all of them the measure of interest is the reaction time in performing the test.

DIGIT: The subject is presented with a string of digits, waits a brief interval, and then is presented with a probe digit. The subject responds as to whether the probe is contained within the previous string. This test is the Sternberg task (1966) in its pure form.

SD2: A pair of words is presented to the subject who must then judge whether they are the same or different. This test is the Posner task in one of its forms.

SA2: Same as SD2 only using synonymous/antonymous word pairs. Again, a variation of the Posner task.

The next four speed-of-processing tests are best defined by first illustrating the general structure of a task devised by Vernon that incorporates aspects of both the Sternberg and Posner tasks. The general structure of this combined task is presented in Table I.

TABLE I

GENERAL STRUCTURE OF VERNON'S COMBINED TASK

Step #		
1	string of digits is presented	
2	interstimulus interval	
3	a word pair is presented	Reaction time for Word-Posner task
4	subject responds to word pair	
5	interstimulus interval	
6	probe digit presented	Reaction time for Digit - Modified Sternberg task
7	subject responds to probe	
8	end of test	

It is important to note that there are two tasks contained within this overall test: the Posner task and a modified Sternberg task. The Sternberg task is modified in the sense that, before the subject can respond to the probe digit, the Posner task intervenes. The next four tests are characterized as being exclusively either the Posner task portion of the overall test or the modified Sternberg task component.

DT2 Digit: This is the reaction time for just the modified Sternberg task portion of the overall test. In this test, same/different word pairs are used in the Posner task component of the test.

DT3 Digit: Same as DT2 Digit only using synonymous/antonymous word pairs in the Posner task component.

DT2 Word: This is the reaction time for the Posner task portion of the overall test using same/different word pairs.

DT3 Word: Same as DT2 Word only using synonymous/antonymous word pairs.

Vernon suggests that one way to isolate a measure of long-term memory (LTM) retrieval is to subtract the reaction time necessary to ascertain if two words are literally (physically) same or different (test SD2) from the reaction time required to ascertain if two words are synonymous or antonymous (SA2) - both are variations of Posner's letter-matching task. Presumably, the first task only requires an ability to perceive differences in stimuli whereas the second task incorporates this recognition ability plus an ability to access information that can only be held in LTM. By subtracting the SD2 reaction time from the SA2 reaction time, we are left with LTM retrieval time minus the perceptual component. Vernon is not clear about what this derived measure represents. It is assumed that it represents a "pure" measure of lexical access. We call this variable LTM #1 (SA2 - SD2 = LTM #1) and refer to it, and other such variables, as a composite or derived variable.

Vernon then performs the same procedure on the Posner task components of the overall test described above. By subtracting the same/different letter-matching reaction time from the synonymous/antonymous letter-matching reaction time, he thus defines another measure of long-term memory response time. We call this variable LTM #2 (DT3 Word - DT2 Word = LTM #2). It is assumed that this reaction time variable provides an alternative measure of LTM retrieval. Vernon feels that this alternative measure differs from the first in that the first test only requires immediate processing of the presented word pair whereas the second test requires short-term memory (STM) storage of the string of digits for the Sternberg task in addition to the processing of a word pair. Thus, Vernon postulates that there may be a difference in cognitive processing efficiency between them.

It is important to note the similarity of the task content of the tests used to form the first composite variable, LTM #1, with the tests used to form the second derived variable, LTM #2. In both instances, the Posner task is the prominent feature and leads to a substantial correlation between the variables. This issue is discussed in the results section.

Vernon proceeds to create two more composite variables via the method described above but which supposedly require different cognitive skills and represent another dimension of cognitive processing, short-term memory (STM) scanning: STM #1 (DT2 Digit-DIGIT) and STM #2 (DT3 Digit-DIGIT). In this case, reaction time for the pure Sternberg task is subtracted from the reaction time for each of two similar modified Sternberg tasks. The resulting difference apparently represents a measure of the efficiency of short-term memory storage and processing. He then correlates these composite variables. These correlations are presented in Table II.

TABLE II

CORRELATIONS BETWEEN DERIVED SPEED-OF-PROCESSING VARIABLES (Vernon, 1983)

Variable	STM1	STM2	LTM1	LTM2
STM1	1			
STM2	.765	1		
LTM1	.277	.251	1	
LTM2	-.054	.189	.525	1

Vernon's definitions of the variables are as follows:
STM #1: short-term memory composite #1 (DT2 Digit-DIGIT)
STM #2: short-term memory composite #2 (DT3 Digit-DIGIT)
LTM #1: long-term memory composite #1 (SA2-SD2)
LTM #2: long-term memory composite #2 (DT3 Word-DT2 Word)

As can be seen in the correlation matrix, the highest correlations are between composite variables LTM #1 and LTM #2 ($r = .525$) and STM #1 and STM #2 ($r = .765$). These correlations are a subset of a larger matrix which includes several other measures that do not bear on this thesis. His principal factor analysis of the larger matrix, using Varimax rotation, reveals three factors which collectively account for 72.8% of the total common variance (see Table III). The variables that load highly on factor 3 are not derived from difference scores, yet form a factor by themselves. Since we are primarily interested in the issues raised by the use of difference scores, the data were not analyzed. Worth closer examination are the first two factors, each of which is largely defined by one or the other of the similarly derived pairs of composite variables. Composite variables STM #1 & STM #2 load primarily on factor 1, and composite variables LTM #1 & LTM #2 load most heavily on factor 2.

TABLE III

FACTOR LOADINGS OF DERIVED SPEED-OF-PROCESSING VARIABLES (Vernon, 1983)

Derived Variable	First Unrotated Factor Loadings	Varimax Rotated Factor Loadings		
		Factor 1	Factor 2	Factor 3
STM1	.722	.842	.027	.055
STM2	.939	.909	.239	-.151
LTM1	.401	.224	.517	.098
LTM2	.321	-.062	.987	.177

Variables are as defined in Table II

Vernon's interpretation of the factor loadings is that those derived variables that load highly on factor 1 share a common short-term memory process and those that load highly on factor 2 share a common long-term memory process. Our interpretation is that the composite variables that load highly on factor 1 share a common task content and are derived from the modified Sternberg task. The composite variables that load highly on factor 2 share another kind of common task content and are derived from the Posner task. In essence, Vernon interprets the STM and LTM variables in terms of different cognitive processes whereas our interpretation suggests that the variables that load highly on each of the factors share a common task content.

It may be that Vernon's interpretation and our interpretation are not mutually exclusive. It could be argued that the modified Sternberg task does measure some kind of short-term memory process and that the Posner task measures a type of long-term memory process. But Vernon's method of arriving at his conclusions, via manipulations of the original data, is circuitous and obscures the relationships between the measured variables and latent abilities. It cannot be determined whether the factors are a function of cognitive processes or data manipulation. For example, the large correlation observed between LTM #1 and LTM #2 would occur whether or not the SA2 and SD2 measures on which they are based differ in terms of a long-term memory component.

Vernon's principal factor analysis of the correlations between the original, nonmanipulated variables, suggests a one-factor model. Table IV contains the correlations among the speed-of-processing tests and Table V presents the means, standard deviations, and loadings on the first principal factor of these tests. He finds that only one factor with an eigenvalue greater than one can be extracted from the analysis and that it accounts for a very large part of the variance (65.5%). But from the correlations between his various composite variables, he derives a principal factor analysis factor pattern that suggests three factors (as illustrated in Table III). He concludes that this result can be attributed to the isolation, via the use of difference scores, of distinct cognitive processes.

TABLE IV

CORRELATIONS OF MEAN REACTION TIMES ON SPEED-OF-PROCESSING TESTS (Vernon, 1983)

Test	SD2	DIGIT	DT2 Word	DT2 Digit	DT3 Word	DT3 Digit	SA2
SD2	1						
DIGIT	.689	1					
DT2 Word	.841	.683	1				
DT2 Digit	.682	.827	.793	1			
DT3 Word	.693	.681	.782	.756	1		
DT3 Digit	.629	.742	.722	.888	.823	1	
SA2	.665	.555	.748	.675	.864	.657	1

TABLE V

MEANS, STANDARD DEVIATIONS, AND LOADINGS ON FIRST PRINCIPAL FACTOR OF MEAN REACTION TIMES ON SPEED-OF-PROCESSING TESTS (Vernon, 1983)

Test	$\bar{X}$ (msec.)	SD	Loadings on First Principal Factor
SD2	746.17	146.88	.804
DIGIT	553.01	156.03	.808
DT2 Word	741.12	127.91	.881
DT2 Digit	597.27	147.72	.919
DT3 Word	886.01	154.61	.890
DT3 Digit	561.71	133.23	.893
SA2	1006.01	185.13	.792

REANALYSIS OF VERNON'S DATA

It was argued in the introduction that a more appropriate method of examining the relations among the speed-of-processing variables was via confirmatory factor analysis of Vernon's implied difference score model. The confirmatory factor analysis model representing difference scores is presented in Table VI.

TABLE VI

CONFIRMATORY FACTOR ANALYSIS MODEL FOR REPRESENTING DIFFERENCE SCORES

Variable	Factor Loadings F_B	F_S	F_L
DIGIT	b_1	0	0
DT2 Digit	b_1	b_4	0
DT3 Digit	b_1	b_5	0
SD2	b_2	b_6	0
SA2	b_2	b_6	b_8
DT2 Word	b_3	b_7	0
DT3 Word	b_3	b_7	b_9

F_B = F_{Basic} = simple RT factor
F_S = short-term memory access component
F_L = long-term memory access component

Coefficients (b) with the same subscript are constrained to be equal. The first factor, F_B, represents a simple reaction time factor, analogous to the intercept in the Sternberg task. All of the reaction time tasks are assumed to load on this factor, although not equally. The second factor, F_S, is a more complex short-term memory processing factor. Only DIGIT, which requires a singular simple reaction time process, does not load on this factor. F_L is a long-term memory access factor. It represents the lexical access component of letter-matching ability. SA2 and DT3 Word load on this factor; the weights of this factor for all other variables are fixed at zero.

The matrix can be interpreted in the following way. The loadings of DIGIT, DT2 Digit, and DT3 Digit imply that DT2 Digit-DIGIT and DT3 Digit-DIGIT yield pure measures of F_S, short-term memory processing. The loadings of SA2 and SD2 and the loadings of DT3 Word and DT2 Word suggest that SA2-SD2 and DT3 Word-DT2 Word are pure measures of F_L, the long-term memory access component.

The attempt to subject this model to confirmatory factor analysis met with no success. It was determined that this model was too constrained, consequently the program could not find a starting solution. As a result, the next best step was to perform an exploratory factor analysis of the original variables. The object behind this was to search for any factors that might be contained within these variables.

Since Vernon's derived measures are linear combinations of the original variables, factor analysis of them should not yield anything which could not be obtained by further factor analysis of the original reaction time variables. Although the eigenvalue greater-than-one rule in principal components analysis suggests that we retain only one factor, the results of Vernon's analysis of the derived variables suggested examination of a three-factor solution. It was interesting to see how well Vernon's correlations among the derived variables could be replicated using only the original variables without resorting to the use of difference scores.

Whereas Vernon derived composite variables using difference scores, determined the correlations among these newly created variables, and then performed a factor analysis on these derived variable correlations, we performed a principal factor analysis of the correlations among the original reaction time measures. Vernon employed orthogonal principal factor analysis with Varimax rotation on the derived variables and obtained a three-factor solution which he interpreted as support for a model with additive memory-processing stages. A simpler alternative interpretation was suggested by our factor analysis, specifying three factors, of the original variables. SAS version 5.0 (SAS Institute, 1985) was used to perform all reanalyses of Vernon's data.

Table VII presents the factor pattern resulting from a principal factor analysis, using Varimax rotation, of the correlations among the original reaction time data. 100% of the variance is accounted for with three factors. Factor 1 accounts for 40.7% of the common variance, factor 2 accounts for 31.6%, and factor 3 accounts for 27.7%. Vernon's one-factor solution only accounted for 65.5% of the variance. Note that the three variables that load the highest on factor 1 are DT3 Digit, DT2 Digit, and DIGIT. All three of these variables are largely defined by the Sternberg task. For factor 2, DT3 Word and SA2 load the most highly. These variables reflect the processing required to perform the Posner task using synonymous/antonymous word pairs. The two variables that load the highest on factor 3 are SD2 and DT2 Word. Again, the Posner task, in this case using same/different word pairs, is the salient feature of these variables.

TABLE VII

PRINCIPAL FACTOR ANALYSIS OF VERNON'S ORIGINAL REACTION TIME DATA: ROTATED FACTOR PATTERN

Variable	Factor 1	Factor 2	Factor 3
SD2	0.330	0.362	0.792
DIGIT	0.613	0.282	0.485
DT2 Word	0.416	0.496	0.646
DT2 Digit	0.772	0.363	0.419
DT3 Word	0.448	0.799	0.324
DT3 Digit	0.824	0.453	0.233
SA2	0.293	0.765	0.371
Common Variance Accounted for:	0.407	0.316	0.277

Using the algebra of expectations and the factor loadings from our three-factor solution, the expected correlations for the original variables were obtained. These are presented below the diagonal in Table VIII. The residuals obtained by subtracting the expected correlations from the observed correlations are presented above the diagonal. As evidenced by the very small residuals, the predicted correlations approximated Vernon's original empirical correlations quite well, as was to be expected.

TABLE VIII

EXPECTED CORRELATIONS & RESIDUALS OF MEAN REACTION TIMES FOR ORIGINAL REACTION TIME VARIABLES (expected r's below diagonal; residuals above diagonal)

Test	SD2	DIGIT	DT2 Word	DT2 Digit	DT3 Word	DT3 Digit	SA2
SD2	1	.001	.013	-.036	-.001	.009	-.002
DIGIT	.688	1	-.025	.048	.024	-.004	-.020
DT2 Word	.828	.708	1	.021	-.011	.004	.007
DT2 Digit	.718	.779	.772	1	-.016	-.010	.016
DT3 Word	.694	.657	.793	.772	1	.016	.001
DT3 Digit	.620	.746	.718	.898	.807	1	-.017
SA2	.667	.575	.741	.659	.863	.674	1

In order to demonstrate that it was possible to arrive at the correlational patterns and values that Vernon obtained among the derived variables, the <u>predicted</u> correlations and empirical standard deviations for the original reaction time variables were used to calculate the expected covariances and variances of the derived variables. Once these were obtained, the expected correlations of the derived variables were calculated. These correlations are presented in Table IX.

TABLE IX

EXPECTED CORRELATIONS BETWEEN DERIVED SPEED-OF-PROCESSING VARIABLES

Variable	STM1	STM2	LTM1	LTM2
STM1	1			
STM2	.803	1		
LTM1	.113	.248	1	
LTM2	.139	.269	.527	1

Variables are as defined in Table II

Note the close similarity in the values between Vernon's derived variable correlations and the expected correlations based on predicted covariances and variances obtained from the original reaction time measures. In order to see if our correlations were comparable to Vernon's, that is, whether the two samples could be considered random samples from a common population, Fisher r-to-z tests were performed. They revealed no significant differences between any pairs of correlations (see Table X).

TABLE X

FISHER r-to-z CRITICAL VALUES

	STM1	STM2	LTM1
STM1			
STM2	-0.732		
LTM1	1.123	0.000	
LTM2	-0.599	-0.592	0.000

An examination of Vernon's factor pattern of derived variables in Table III reveals a distinct pattern of low and high loadings. The two derived variables that Vernon proposes require STM storage processing load on factor 1 and the two derived variables that require LTM retrieval load on factor 2. As noted earlier, the variables that load on factor 3 were not involved in difference scores, hence were not pertinent to our reanalysis.

Recall that DT2 Digit is the reaction time for the Digit portion of the entire experimental task using same/different word pairs in the earlier stages of the procedure. DT3 Digit differs from DT2 Digit only in that it incorporates synonymous/antonymous word pairs in place of same/different word pairs in the distracting portion of the task. DIGIT is a simplified version of the experimental procedure in that there are no intervening distractors or tasks. It is important to recognize that reaction times to all three of these tests reflect performance on what is essentially the Sternberg task which is nested within the larger experimental procedure.

DT2 Word and DT3 Word are the reaction times for the Word portion of the experimental task using same/different and synonymous/antonymous word pairs respectively. SD2 and SA2 are simplified versions of DT2 Word and DT3 Word respectively in that they are not contained within the more complex experimental procedure. The primary processing required of all four of these tests is that necessary to solve the Posner task.

STM #1 is the result of subtracting the reaction time for DIGIT from the reaction time for DT2 Digit. Similarly, STM #2 is the difference score resulting from subtracting DIGIT from DT3 Digit. LTM #1 results from the subtraction of SD2 from SA2. LTM #2 is the result of subtracting DT2 Word from DT3 Word.

Since we have forced the factor solution to be orthogonal and it is evident that the variables are highly correlated, it was thought that an oblique analysis might be more appropriate. A three-factor oblique factor analysis using Harris-Kaiser rotation was performed. The results of this analysis are presented in Table XI.

TABLE XI

OBLIQUE FACTOR ANALYSIS OF VERNON'S ORIGINAL REACTION TIME DATA: ROTATED FACTOR PATTERN

Variable	Factor 1	Factor 2	Factor 3
SD2	0.725	0.711	0.929
DIGIT	0.652	0.805	0.762
DT2 Word	0.818	0.784	0.902
DT2 Digit	0.757	0.947	0.808
DT3 Word	0.968	0.815	0.781
DT3 Digit	0.784	0.959	0.716
SA2	0.897	0.687	0.741
Common Variance Accounted for:	0.738	0.804	0.749

Note that the oblique solution is not as interpretable as the three-factor orthogonal analysis of the data. Consequently, it was decided that the orthogonal solution would be utilized for discussion. Inter-factor correlations are presented in Table XII.

TABLE XII

OBLIQUE FACTOR ANALYSIS INTER-FACTOR CORRELATIONS

	Factor 1	Factor 2	Factor 3
Factor 1	1		
Factor 2	0.794	1	
Factor 3	0.811	0.807	1

DISCUSSION

In a comparison of Vernon's factor pattern of the derived variables (Table III) with the factor pattern resulting from our analysis of the original variables (Table VII) it is important to observe that in Vernon's analysis the two variables that load highly on factor 1 are derived from the same variables that load highly on factor 1 in our analysis. That is, STM #1 is derived from DT2 Digit and DIGIT and STM #2 is derived from DT3 Digit and DIGIT. But rather than interpreting this factor as some sort of general STM storage processing factor, an alternative explanation would be that this factor reflects processing that is involved in performing the Sternberg task. In the case of the second factor, the two variables in Vernon's analysis that load highly (LTM #1 & LTM #2) are derived from variables that also load highly on the second factor in the factor analysis of the original reaction time data. Vernon's LTM #1 is derived from SA2 and SD2 and LTM #2 is derived from DT3 Word and DT2 Word. We interpret this factor as resulting from processing involved in solving the Posner task using synonymous/antonymous word pairs. A similar argument leads us to interpret high loadings on the third factor in terms of the processing skills needed to perform the Posner task using same/different word pairs.

Vernon employed difference scores to manipulate his original variables. This resulted in the creation of new composite variables which are essentially linear transformations of the original variables. Vernon's factor analysis of the correlations among the derived variables resulted in a three-factor solution which he interprets as support for his model of additive memory-processing stages.

Relying solely on the original reaction time variable correlations and using the algebra of expectations to calculate expected values for both the original variable correlations and the derived variable correlations, we were able to demonstrate that the correlations and factors Vernon obtained could just as easily have been obtained from the original data without resorting to using difference scores to transform the data.

We hypothesized that a three-factor model could account for Vernon's data. As such, we wanted to know if the correlations for both the original and derived variables could be predicted by this model. We therefore used this model to estimate expected values for the correlations in both the original and derived data, using the factor loadings from a principal factor analysis of the original correlations as our starting point.

A comparison of Vernon's matrices with our matrices for both the original variable correlations and the derived variable correlations shows remarkable similarity in values and patterns of correlations. Based on this, we would argue that one does not need to use difference scores, or the constructs which they represent to account for a three-factor solution. Difference scores simply perform linear transformations of the original data.

We maintain that each factor can be explained by noting that a particular experimental task loads heavily on each. DT3 Digit, DT2 Digit, and DIGIT load primarily on factor 1. These three variables essentially make up that portion of the experimental procedure that can be characterized as the Sternberg task. DT3 Word, SA2, and DT2 Word load primarily on factor 2. These three variables are associated with the Posner task portion of the experiment that utilizes synonyms and antonyms. SD2 and DT2 Word load primarily on factor 3. This factor can be characterized as reflecting those skills involved in solving the Posner task again, however this time the content is composed of same/different words.

We are faced with two interpretations: one that maintains that the factors represent various memory-processing stages and the other which postulates that the factors reflect the nature of the experimental task. How do we resolve this issue? One way to tell which interpretation is superior would have been to include a fourth task that was completely different from the other three yet contained a short-term or long-term memory component. If Vernon's cognitive abilities interpretation were appropriate, this fourth task would load on one or more of the other three factors. This is due to the fact that this task would require some of the processing shared by the other three. If this fourth task loaded solely on a fourth factor, it would lend support to our task content interpretation. This would indicate that the nature of the task was the sole determiner of factor pattern. There was no fourth task included in Vernon's experimental design and it may well be that it is not possible to create one. A task that could discriminate between content and process that neatly may be beyond our means. This deficit demonstrates once more the need to be explicit about the model being proposed and selecting the most appropriate method to test it.

Another reason for preferring the factor analysis model based on the original variables over the more constrained difference score model for this data is because of the methodological issues discussed in the introduction. Difference scores tend to introduce, among other undesirable properties, spurious correlations which can affect the interpretation of the results of a study. The factor analysis model based on the original variables is not susceptible to these problems. The fact that the patterns of correlations for the derived variables can be closely approximated, without using difference scores, lends further support for a model that does not introduce potential statistical hazards.

In conclusion, difference score models for reaction time data are subject to methodological and interpretive problems which can be avoided by using the more general factor analysis model. This model allows for error terms in the underlying additive model and suggests alternative interpretations of the factor structure that are more straightforward and parsimonious.

CHAPTER III

STUDY 2:
REPLICATION OF LANSMAN, DONALDSON, HUNT, & YANTIS (1982)

The first part of this thesis demonstrated that there is more than one reasonable interpretation of the results obtained by Vernon's examination of cognitive reaction time processes. However, a major problem with Vernon's research is that his study is not designed in such a way as to allow for the direct testing of his interpretation of the results against our interpretation. The purpose behind performing a replication of Lansman, et al.'s reaction time study is to show that if a modeling study is designed correctly, it is possible to use confirmatory factor analysis to compare alternative models for best fit to the data.

In order to demonstrate how confirmatory factor analysis can be used to explore alternative models of speed-of-processing variables we decided to replicate a study by Lansman, et al. (1982) which Donaldson (1983) has analyzed using confirmatory factor analysis. Lansman et al.'s reaction time data is essentially the same as Vernon's. Donaldson's approach to an analysis of the Posner task portion of this data is the approach that Vernon should have used with his data.

LANSMAN ET AL.'S STUDY & DONALDSON'S ANALYSIS

Lansman, et al.'s subjects were forty-five male and forty-six female undergraduate students at the University of Washington. Their reaction times on the letter comparison task were correlated with measures of ability based on the Cattell-Horn theory of intelligence. The psychometric measures were selected on the basis of their ability to load on any of four factors: crystallized intelligence (g_c), fluid intelligence (g_f), spatial visualization (g_v), and perceptual speed (CPS). Lansman, et al. (1982) found that letter-matching was highly correlated with perceptual speed (r = .69). They also found a moderate correlation (r = -.35) between this information-processing task and g_c as represented by measures of verbal ability that included Vocabulary, Remote Associations, General Information, and Esoteric Analogies. These results are consistent with the values obtained in many other studies (Hunt, 1978; Hunt, et al., 1973; Hunt, et al., 1975; Jackson & McClelland, 1979; Keating & Bobbitt, 1978; Lansman, et al., 1982).

Donaldson (1983) used this data to illustrate how a model could be tested using confirmatory factor analysis. The outcomes of his analyses were based on the above results. We collected data similar to that used by Lansman, et al. and used the general method employed by Donaldson (1983) to analyze this data. However, different detailed specifications of the confirmatory factor analysis model were tested in addition to those Donaldson used.

Donaldson rejected a one-factor model, based partly on empirical results and partly on theoretical grounds, but it was open to question whether Donaldson's results are sufficient for rejection of this model. Donaldson makes what seems to be curious model specifications regarding factor loadings. Donaldson's analysis looks only at an enhanced model which includes a verbal ability measure. He did not examine models that did not include the psychometric criterion variable. In order to reveal the relationships among the reaction time variables more clearly, the present study examines the factor structure that includes the cognitive measures alone, i.e. without the verbal ability measure.

It may be that a single basic speed-of-processing factor accounts for most of the relationship between the variables, with some additional variance perhaps accounted for by specific content factors. If this is the case, then a multi-factor model becomes plausible on theoretical grounds. It is this ambiguity in the data, and the presence of several reasonable competing models to explain this data, that provides the rationale for testing additional one-factor models and models with more than one factor.

METHOD USED IN THE REPLICATION

Subjects

101 subjects were recruited from undergraduate psychology classes at Portland State University.

Materials and Apparatus

Initial materials consisted of a page requesting informed consent for participation in a research study (Appendix).

Presentation of stimuli and recording of responses were under the control of an Apple IIe microcomputer. In all cases, subjects responded using either the key immediately to the left or right of the space bar.

Procedure

A fixation stimulus was continuously visible in the center of the screen. Stimuli were pairs of letters presented simultaneously, one letter above the fixation stimulus and one letter below. Subjects were instructed to respond as quickly as possible, pressing the key on the right if a match was perceived or the key on the left if the letters did not match. If correct, the reaction time was displayed following the response; if not correct, the word "wrong" was displayed. The feedback message was displayed for 500 msec., followed by a 1000 msec. inter-trial interval. Subjects were presented with a block of 18 practice trials. Following this, there were four blocks of 96 trials each.

Letter combinations were distributed as follows within each block: 25% physical match, 25% name match, 50% no match.

The confirmatory factor analysis approach outlined by Donaldson (1983) requires two measures each of the name identity (NI) and physical identity (PI) tasks. Ordinarily, there should be more variables available in the analysis than number of factors expected so, in order to have a few more variables to work with, the experimental procedure was such that the second and third trial blocks were used to obtain NI measures and the first and fourth trial blocks were used for PI measures. In this manner, an attempt was made to counterbalance fatigue and practice effects.

DESCRIPTION OF THE MODELS TESTED

Figure 1 presents the standard algebraic form and matrix algebra form of the models tested. Model #1 is the generally accepted model proposed by Donaldson as the best fitting model to the Lansman et al. data. It specifies a factor for perceptual speed (PS), which influences PI_1, PI_2, NI_1, and NI_2 and a factor for lexical access (LA), which influences only NI_1 and NI_2. It further assumes that the weight of the perceptual speed factor remains the same in both task conditions. The weight is, therefore, a constrained parameter. The model makes the following

Model 1

$$PI = b_1F_1 + e_1$$
$$NI = b_1F_1 + b_2F_2 + e_2$$

	PS	LA
PI_1	b_1	0
PI_2	b_1	0
NI_1	b_1	b_2
NI_2	b_1	b_2

Model 2

$$PI = b_1F_1 + e_1$$
$$NI = b_2F_1 + b_3F_2 + e_2$$

	PS	LA
PI_1	b_1	0
PI_2	b_1	0
NI_1	b_2	b_3
NI_2	b_2	b_3

Model 3

$$PI = b_1F_1 + e_1$$
$$NI = b_2F_1 + e_2$$

	F_1
PI_1	b_1
PI_2	b_1
NI_1	b_2
NI_2	b_2

Model 4

$$PI_1 = b_1F_1 + e_1$$
$$PI_2 = b_2F_1 + e_2$$
$$NI_1 = b_3F_1 + e_3$$
$$NI_2 = b_4F_1 + e_4$$

	F_1
PI_1	b_1
PI_2	b_2
NI_1	b_3
NI2	b_4

Figure 1. Standard algebra and matrix algebra representations of four confirmatory factor analysis models for letter-matching.

assumptions: 1) the factors are uncorrelated among themselves, 2) the factors are uncorrelated with errors, and 3) the error variances are equal within conditions but not necessarily equal between conditions.

Model #2 assumes two factors, one for perceptual speed and one for lexical access. It does not however constrain the perceptual speed factor (PS) to have the same weight in both the PI and NI conditions. In this model the weight is a free parameter. The same assumptions underlying model #1 apply to this model.

Model #3 specifies only one factor (F1). It makes the assumption that the name matching condition simply requires more of the same processing that takes place in the physical matching condition. In this case, the model specifies that the weights be the same within a given condition but can vary between conditions. This model assumes that the errors are uncorrelated among themselves and with the factor and that the error variances are equal within conditions but not necessarily equal between conditions.

Model #4 is a one-factor model which allows all of the weights to be free to take on any value. It is constrained to have the measured variables load on one factor. The model makes the same assumptions as model #3 with the exception that the error variances are free to be unequal both within conditions and between conditions.

RESULTS OF THE REPLICATION

The correlations among the four PI and NI measures are presented in Table XIII. Note that they are highly correlated as would be expected. These acted as the input data for the PC-LISREL 6.12 program (Joreskog & Sorbom, 1986) used to perform the confirmatory factor analysis.

TABLE XIII

CORRELATIONS AMONG THE REACTION TIME VARIABLES

Variable	PI2	PI2	NI1	NI2
PI_1	1			
PI_2	.917	1		
NI_1	.909	.884	1	
NI2	.884	.912	.923	1

The judgement of which model or models fit the data the best is based on an examination of several overall goodness-of-fit measures. Table XIV summarizes these indices for each of the models. The first index examined was a χ^2 goodness-of-fit measure, the smaller the index the better. The χ^2 for models 1 and 2 are identical and models 3 and 4 nearly so. Also, models 1 and 2 have smaller χ^2's than models 3 and 4- the first clue that the former two models are more accurate in representing the data. In confirmatory factor analysis, the null hypothesis for chi-square states that the model

TABLE XIV

GOODNESS-OF-FIT MEASURES

Model	χ^2	df	Probability	rho	GFI	AGFI	RMR
1	11.64	5	.040	.986	.948	.896	.009
2	11.64	4	.020	.980	.948	.870	.009
3	18.69	5	.002	.972	.928	.857	.014
4	18.70	3	.000	.947	.928	.760	.017
NULL	593.28	6	.000	---	.289	-.185	.701
Nested Models							
χ^2_{1-2}	0.0	1	NONSIGNIFICANT				
χ^2_{3-2}	7.05	1	SIGNIFICANT AT .01				
χ^2_{3-4}	-0.01	2	NONSIGNIFICANT				

fits the data, hence we do not want to reject H_0. The chi-square for each of the four models was significant, suggesting that the null hypothesis that each model fits the data should be rejected. Interpreting this index is problematic however, because it is very sensitive to sample size - if N is too large, the statistic becomes too powerful making it easy to reject H_0. If the sample is too small, it will say the model fits when it actually doesn't. The chi-square test does not support any of our four models, but its validity in this case is suspect. All four of the following measures are unaffected by sample size making them superior measures of fit. However, bear in mind that when interpreting these indices there are no hard and fast rules for accepting or rejecting a given model's fit. The minimum criterion level associated with each index is a general rule-of-thumb and the fit of the model based on the index should be interpreted with caution.

Rho is considered the most stable and accepted descriptive measure of fit. Its mathematical form is described as follows:

$$\frac{\chi^2{}_0/df_0 - \chi^2{}_A/df_A}{\chi^2{}_0/df_0 - 1}$$

Rho indicates how much better the hypothesized model fits the data than a model that assumes that there are no common factors. A rho $\geq$ .90 is considered an indicator of very good fit. All four models met this criteria but now we could begin to rank them in terms of fit. Model #1 has the highest rho followed by #2, then #3, and finally #4.

Next we examined what is simply called the Goodness-of-Fit Index (GFI). The GFI is based on a ratio of the sum of the squared discrepancies between the observed correlation matrix and the implied matrix to the observed variances, thus allowing for scale. The GFI should be $\geq$ .85 for a model to be acceptable. All models met this criterion.

The Adjusted Goodness-of-Fit Index (AGFI) adjusts the GFI by a ratio of the degrees of freedom of the restricted matrix to the null matrix. This allows for a comparison of

GFI across models. For a model to be meaningful it should have an AGFI that is $\geq$ .80. Only three models met this criterion with the following ranking: #1, #2, #3. Model #4 failed the .80 AGFI criterion.

Lastly, we examined the Root Mean Square Residual or RMR. The RMR is the square root of the mean of the squared discrepancies between the observed correlation matrix and the implied matrix. It is a kind of average of the absolute discrepancies between the observed and implied matrices. The RMR should be less than .010. It can be interpreted in much the same manner as residuals in regression - the smaller, the better. We again noted that models #1 & #2 were tied for having the smallest, i.e. best, value and were followed by, in order, model #3 and then #4 with the latter two not meeting the RMR criterion.

When making a determination regarding which model may represent a dataset the best, all five indices should be examined as a whole, for they complement one another. Doing this with our data we saw that a very definite pattern had emerged. Across all indices the same ranking of fit of the models occurred. In terms of preference, model #1 provides the best fit to the data, followed closely by model #2.

Nested models can be tested to determine if the extra free parameter improves fit significantly. Nesting refers to the instance where one model is part of another, more general model. For example, all the free parameters in model #3 are also contained within, and remain free in, model #2. In our study there were three nested models we could examine. The results of these tests are presented in Table XIV. The free parameters of model #2 are nested within model #1. Model #2 does not differ significantly from model #1. Likewise, model #3 is not significantly better than #4, although neither model #3 nor model #4 fit the data as well as the other two. Lastly, it is evident that the two-factor models, #1 and #2, are very similar and the one-factor models, #3 and #4, are similar. Do these two pairs differ significantly from one another? Using models #3 and #2 as representatives of each of these models we find that there is a significant difference in fit between models #3 and #2, with the two-factor model #2 fitting significantly better than the one-factor model #3.

DISCUSSION

What do these various measures tell us about our original question: which of these models represents the data the best? First of all, it should be noted that the significant chi-square for each model suggests that it is possible there is a similar simple model that accounts for the data that we have overlooked. However, on the basis of the strength of all the remaining indices, the tested models present themselves as reasonable representations of the data and were accepted as such. Both models #1 and #2 fit the data very well and are extremely comparable. They both provide a better fit than models #3 and #4. Models #1 and #2 are both two-factor models. This suggests that a two-factor model portrays letter-matching ability better than a one-factor model. Using model #2 as representative of the two-factor model and model #3 as representative of a one-factor model, we find that, in a paired comparison, model #2 fits the data significantly better than model #3, providing clear evidence for a two-factor model of letter-matching. There appears to be two cognitive functions required to perform this task.

Given that a two-factor model is superior to a one-factor model, the question remains: which of the two-factor models ultimately provides the best fit? The models are very similar and the distinction between them is fine, however there is some basis for choosing one over the other. Model #1 has a slightly better rho and AGFI and, since it has one more degree of freedom, it is slightly more parsimonious than model #2. The fact that adding an extra parameter does not improve fit significantly suggests that beta is virtually equivalent in the two conditions. Therefore, beta can be fixed to be equal across matching conditions for the first factor, as in model #1, reflecting identical perceptual speed regardless of the matching condition - in other words, it doesn't matter whether you are faced with a physical match or a name match, the speed with which perceptual scanning proceeds remains the same. Thus, we have confirmed Donaldson's model specifications and perhaps have provided additional support for Hunt et al.'s (1973; 1975) interpretation of it.

CHAPTER IV

CONCLUSIONS

The use of difference scores implies a model for speed of information-processing that is essentially additive although highly restrictive. As such, data of this nature would be well represented by a factor analysis model and can, in principle, be analyzed by confirmatory factor analysis methods, which have the advantage of providing model statements that are explicit. A compelling reason for using confirmatory factor analysis on the original data is that it avoids the potential for spurious correlations that result in analyzing difference scores because it takes into account random error. The factor analytic model can uncover interpretable factors from the original data without resorting to difference scores.

A reanalysis of Vernon's (1983) original reaction time variables demonstrated the above to be true. The correlations between the derived variables, those created via taking differences between the original variables, were closely approximated from a factor analysis of the original variables.

An attempt to test the assumptions of Vernon's difference score model using confirmatory factor analysis failed. It was determined that the model was too constrained making the model impractical to represent the data. An exploratory factor analysis of the original reaction time variables fit the data very well. Our alternative interpretation of this factor pattern emphasized the nature of the task that the subject was performing. One factor clearly represents Sternberg task processing, one is the result of processing the Posner task using synonymous/antonymous words, and one represents Posner task processing using same/different words. We argue that this is a more precise and parsimonious interpretation of the factors than Vernon's interpretation of the factors representing short-term memory processing and long-term memory retrieval. However, due to inadequacies in Vernon's experimental design, i.e. the lack of a task that could discriminate between cognitive processing and task content, neither interpretation could be conclusively demonstrated superior.

As an alternative way of demonstrating the application of confirmatory factor analysis, a reaction time study by Lansman, Donaldson, Hunt, & Yantis (1982) was replicated, using Donaldson's (1983) approach, in which four different models of speed-of-processing were tested. The utility of the technique was established by demonstrating that certain models were clearly superior to others. More importantly, close examination of two very similar models permitted small but significant distinctions to be drawn between them allowing for the selection of the best model. Two goodness-of-fit measures indicated that model #1, a two-factor model with equivalent perceptual speed components, provided the best fit. These distinctions would not have been apparent in an exploratory factor analysis.

It is clear that there is usually more than one way to model cognitive processing and analyze data. Determination of the best way to do this is not always obvious. But constant questioning of methods and careful scrutiny of results will help the researcher in his or her quest for the most appropriate technique.

REFERENCES

Burt, C. (1949). The structure of the mind: A review of the results of factor analysis. British Journal of Educational Psychology, 19, 100-111, 176-199.

Carroll, J. B. (1980). Individual difference relations in psychometric and experimental cognitive tasks. (NR 150-406 ONR Final Report). Chapel Hill, NC: L.L. Thurstone Psychometric Laboratory, University of North Carolina.

Carroll, J. B. (1982). The measurement of intelligence. In R. J. Sternberg (Ed.), Handbook of human intelligence (pp. 29-120). Cambridge: Cambridge University Press.

Carroll, J. B., & Maxwell, S. E. (1979). Individual differences in cognitive abilities. Annual Review of Psychology, 30, 603-640.

Cattell, R. B. (1963). Theory of fluid and crystallized intelligence: A critical experiment. Journal of Educational Psychology, 54, 1-22.

Cattell, R. B. (1971). Abilities: Their structure, growth and action. Boston: Houghton-Mifflin.

Chiang, A., & Atkinson, R. C. (1976). Individual differences and interrelationships among a select set of cognitive skills. Memory and Cognition, 4, 661-672.

Cohen, J., & Cohen, P. (1975). Applied multiple regression/correlation analysis for the behavioral sciences. Hillsdale, NJ: Lawrence Erlbaum Associates.

Cronbach, L. J., & Furby, L. (1970). How should we measure "change" - or should we? Psychological Bulletin, 74, 1, 68-80.

Donaldson, G. (1983). Confirmatory factor analysis models of information processing stages: An alternative to difference scores. Psychological Bulletin, 94, 1, 143-151.

Donders, F. C. (1969). On the speed of mental processes. In W. G. Koster (Ed. and Translator), Attention and performance II, Amsterdam: North-Holland. (Reprinted from Acta Psychologica, 1969, 30, 412-431.) (Original work published 1868.)

Egan, D. E. (1978). Characterizing spatial ability: Different mental processes reflected in accuracy and latency scores. Murray Hill, NJ: Bell Laboratories.

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

Guilford, J. P. (1967). The nature of human intelligence. New York: McGraw-Hill.

Guilford, J. P. (1982). Cognitive psychology's ambiguities: Some suggested remedies. Psychological Review, 89, 48-59.

Guilford, J. P., & Hoepfner, R. (1971). The analysis of intelligence. New York: McGraw-Hill.

Guttman, L. (1965). A faceted definition of intelligence. In R.R. Eiferman (Ed.), Scripta Hierosolymitana (Vol. 14). Jerusalem: Magnes Press.

Hogaboam, T. W., & Pellegrino, J. W. (1978). Hunting for individual differences in cognitive processes: Verbal ability and semantic processing of pictures and words. Memory and Cognition, 6, 189-193.

Holzinger, K. J. (1938). Relationships between three multiple orthogonal factors and four bifactors. Journal of Educational Psychology, 29, 513-519.

Horn, J. L. (1963). Equations representing combinations of components in scoring psychological variables. Acta Psychologica, 21, 184-217.

Horn, J. L., & Donaldson, G. (1980). Cognitive development II: Adulthood development of human abilities. In O. G. Brim & J. Kagan (Eds.), Constancy and change in human development. Cambridge, Mass.: Harvard University Press, 445-528.

Hunt, E. (1978). Mechanics of verbal ability. Psychological Review, 85, 109-130.

Hunt, E. (1980). Intelligence as an information-processing concept. British Journal of Psychology, 71, 449-474.

Hunt, E., Frost, N., & Lunneborg, C. (1973). Individual differences in cognition: A new approach to intelligence. In G. Bower (Ed.), Psychology of learning and motivation (Vol. 7). New York: Academic Press.

Hunt, E., Lunneborg, C. & Lewis, J. (1975). What does it mean to be high verbal? Cognitive Psychology, 7, 194-227.

Irvine, S. H. (1979). The place of factor analysis in cross cultural methodology and its contribution to cognitive theory. In L. Eckensberger et al. (eds.), Cross cultural contributions to psychology. Lisse, Switzerland: Swets and Zeitlinger.

Irvine, S. H., & Reuning, H. (1981). "Perceptual speed" and cognitive controls: Tasks in reconstructing group test theory and practice within and across cultures. Journal of Cross-Cultural Psychology, 12, 4, 425-444.

Jackson, M. D., & McClelland, J. L. (1979). Processing determinants of reading speed. Journal of Experimental Psychology: General, 108, 151-181.

Jensen, A. R. (1980). Bias in mental testing. New York: Free Press.

Joreskog, K. G. (1967). Some contributions to maximum likelihood factor analysis. Psychometrika, 32, 443-482.

Joreskog, K. G. (1969). A general approach to confirmatory maximum likelihood factor analysis. Psychometrika, 34, 183-202.

Joreskog, K. G., & Lawley, D. N. (1968). New methods in maximum likelihood factor analysis. British Journal of Mathematical and Statistical Psychology, 21, 85-96.

Joreskog, K.G., & Sorbom, D. (1986). PC-LISREL VI. Users Guide. Chicago: National Educational Resources.

Kail, R., & Pellegrino, J. W. (1985). Human intelligence: Perspectives and prospects. New York: W. H. Freeman.

Keating, D. P., & Bobbitt, B. L. (1978). Individual and developmental differences in cognitive processing components of mental ability. Child Development, 49, 155-167.

Kim, J. O., & Mueller, C. W. (1978). Introduction to factor analysis: What it is and how to do it. Sage University Paper series on Quantitative Applications in the Social Sciences, 07-013, Beverly Hills and London: Sage.

Lansman, M., Donaldson, G., Hunt, E., & Yantis, S. (1982). Ability factors and cognitive processes. Intelligence, 6, 347-386.

Lawley, D. N., & Maxwell, A. E. (1971). Factor analysis as a statistical method. London: Butterworth and Co.

Long, J. S. (1983). Confirmatory factor analysis: A preface to LISREL. Sage University Paper series on Quantitative Applications in the Social Sciences, 07-033, Beverly Hills and London: Sage.

McClelland, J. L. (1979). On the time relations of mental processes: An examination of systems of processes in cascade. Psychological Review, 86, 4, 287-330.

Mulaik, S. A. (1972). The foundations of factor analysis. New York: McGraw-Hill.

Pellegrino, J. W., & Glaser, R. (1979). Editorial: Cognitive correlates and components in the analysis of individual differences. Intelligence, 3, 187-216.

Posner, M. I. (1978). Chronometric explorations of mind. New York: Lawrence Erlbaum Associates.

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

Posner, M. I., & McLeod, P. (1982). Information processing models: In search of elementary operations. Annual Review of Psychology, 33, 477-514.

Posner, M. I., & Mitchell, R. F. (1967). Chronometric analysis of classification. Psychological Review, 74, 5, 392-409.

SAS Institute Inc. SAS User's Guide: Statistics Version 5 (1985). Cary NC: SAS Institute Inc.

Schwartz, S. (1983). Verbal ability, attention, and automaticity. In M. P. Friedman, J. P. Das, & N. O'Connor (Eds.), Intelligence and learning. New York: Plenum.

Schwartz, S., Griffin, T. M., & Brown, J. (1983). Power and speed components of individual differences in letter-matching. Intelligence, 7, 369-378.

Smith, G. A., & Stanley, G. (1983). Clocking g: Relating intelligence and measures of timed performance. Intelligence, 7, 353-368.

Spearman, C. (1904a). "General intelligence" objectively determined and measured. American Journal of Psychology, 15, 201-293.

Spearman, C. (1904b). The proof and measurement of association between two things. American Journal of Psychology, 15, 72-101.

Sternberg, R. J. (1985a). Beyond I.Q.: A triarchic theory of intelligence. Cambridge: Cambridge University Press.

Sternberg, R. J. (Ed.). (1985b). Human abilities: An information-processing approach. New York: W. H. Freeman.

Sternberg, S. (1966). High speed scanning in human memory. Science, 153, 652-654.

Thurstone, L. L. (1938). Primary mental abilities. Chicago: University of Chicago Press.

Thurstone, L. L. (1948). Psychological implications of factor analysis. American Psychologist, 3, 402-408.

Vernon, P. A. (1983). Speed of information processing and general intelligence. Intelligence, 7, 53-70.

Vernon, P. A., Nador, S., & Kantor, L. (1985). Group differences in intelligence and speed of information-processing. Intelligence, 9, 137-148.

Vernon, P. E. (1965). Ability factors and environmental influences. American Psychologist, 20, 723-733.

Vernon, P. E. (1971). The structure of human abilities. London: Methuen.

APPENDIX

INFORMED CONSENT

I, ____ hereby agree to serve as a subject in the research project on Letter-Matching Reaction Time and Verbal Ability conducted by Gary Uhland.

I understand that the study involves pressing keys on a computer in response to stimuli presented on the screen.

I understand that possible risks to me associated with this study are loss of time or interest during participation and that the investigator may have access to my SAT scores.

Please sign only one

I, ____ hereby give permission to the investigator to obtain from the Registrar my SAT scores for use in this study.

To my best recollection, my SAT scores are:

Verbal ________

Quantitative ________

I, ____ hereby DO NOT give permission to the investigator to obtain from the Registrar my SAT scores for use in this study.

It has been explained to me that the purpose of the study is to learn about the relationship between cognitive reaction time and verbal ability.

I may not receive any direct benefit from participation in this study, but my participation may help to increase knowledge which may benefit others in the future.

Gary Uhland has offered to answer any questions I may have about the study and what is expected of me in the study. I have been assured that all information I give will be kept confidential and that the identity of all subjects will remain anonymous.

I understand that I am free to withdraw from participation in this study at any time without jeopardizing my course grade or my relationship with Portland State University.

I have read and understand the foregoing information.

Date ________________ Signature __________________________

If you experience problems that are the result of your participation in this study, please contact Robert Tinnin, Office of Graduate Studies and Research, 105 Neuberger Hall, Portland State University, 229-3423.