CONFIRMATORY MODELS OF SENSORY/MOTOR

AND COGNITIVE CONSTRUCTS

A DISSERTATION

SUBMITTED TO THE GRADUATE SCHOOL

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR THE DEGREE

DOCTOR OF EDUCATION

BY

SCOTT L. DECKER

DISSERTATION ADVISOR: DR. RAYMOND S. DEAN

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BALL STATE UNIVERSITY

MUNCIE, INDIANA

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ABSTRACT

This study examined the relationship between neuropsychological constructs of sensory-motor functioning and cognitive ability constructs in the Cattell-Horn-Carroll (CHC) (Carroll, 1993) theory. Two studies were conducted. For the first study, the Dean-Woodcock Sensory Motor Battery (SMB) (Dean & Woodcock, 1999) was administered to 800 individuals. A factor analysis and a confirmatory factor analysis were used to investigate and develop a factor structure of the SMB. Results from this study suggest sensory and motor tests significantly share common variance and a hierarchical, multifactorial model that included a higher-order factor of both sensory and motor tests best fit the data. The second study examined the SMB model, developed in the first study, in relation to the CHC (Cattell-Horn-Carroll) model of cognitive abilities, as measured by the Woodcock-Johnson Revised Tests of Cognitive Abilities (WJ-R) (McGrew, Werder, & Woodcock, 1991). For this study, the SMB and the WJ-R was administered to 411 individuals. A confirmatory model was tested that included the higher-order factor of the SMB as a broad ability within the CHC model. Results from this analysis suggest the higher order factor of the SMB does have a significant relationship with overall measures of cognitive ability of a similar level to other broad abilities in the CHC model, and significantly improves the fit of CHC model. These results support Roberts, Pallier, and Goff's (1999) argument for the inclusion of an additional broad ability in the CHC taxonomy that represents sensory and motor functioning. Additionally, this study provides empirical support for the utility of including neuropsychological tests of sensory and motor functioning in a comprehensive assessment of cognitive abilities (Dean & Woodcock, 1999). The implications for neuropsychological and psychometric assessment are discussed.

DEDICATION

This dissertation is dedicated to my mother for her unwavering support and to my many educators.

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CHAPTER I

Introduction

Description of Problem

Measures of sensory and motor functioning are an important part of a neuropsychological assessment and are included in most major neuropsychological batteries (Halstead, 1957; Reitan & Wolfson, 1993; Spillane & Spillane, 1982; Korkman, Kirk, & Kemp, 1998; Mapou, 1995). However, due to an emphasis in actuarial methods, little is known about the underlying constructs of sensory-motor tests (Dean & Woodcock, 1999). Historically, neuropsychology has primarily examined the utility of these and other neuropsychological measure by how well the measure predicts brain damage and predicting brain damage was the goal of a neuropsychological assessment (Halstead, 1957; Cytowic, 1996; Dean & Woodcock, 1999). As a result of advances in brain-imaging technology, contemporary neuropsychological assessment has shifted from predicting brain damage to assessment of functional capacities (D'Amato, Dean, & Rhodes, 1998; Dean & Woodcock, 1999), which entails a transition from an actuarial approach to a functional, theory driven approach to assessment (Dean & Woodcock, 1999; Dean, Woodcock, Decker, in preparation). This transition has been described as a radical change in neuropsychology (Cytowic, 1996) that shifts the focus from criterion validity to construct validity (AERA, APA, & NCME, 1999). Additionally, contemporary neuropsychological assessment places a greater emphasis in theory based standardized psychometric tests to aid in making diagnostic decisions (Cytowic, 1996; Kolb & Whishaw, 1995), and, consequently, theory based approaches have become dominant in both test development and interpretation (Meier, 1992).

Despite the growing need for neuropsychologists to better understand the constructs measured by neuropsychological tests and how constructs measured by neuropsychological tests relate to other psychometric constructs frequently included in a neuropsychological evaluation (e.g. intelligence, achievement, & personality), the constructs measured by many neuropsychological tests remain obscure (Dean & Woodcock, 1999). This is primarily due to a historical focus on an actuarial approach in validating neuropsychological tests. As such, there is a need to clarify the constructs measured by neuropsychological tests and their relationship with other constructs measured in a neuropsychological assessment. Additionally, new methods (e.g. structural equation modeling & confirmatory factor analysis) for statistically examining the underlying constructs measured by psychometric tests have radically changed within the last two decades (Flanagan, Genshaft, & Harrison, 1997). Little has been done in using new research methodologies to study the underlying constructs of sensory-motor and neuropsychological tests

This particular study will focus on neuropsychological tests of sensory and motor functioning. Tests of sensory and motor functioning have long been an important component of neuropsychological assessment (Reitan & Wolfson, 1993), but like most other neuropsychological tests, there is little research examining the construct validity, factor structure of sensory and motor functions and their relationship to other psychometric constructs (Hill, Lewis, Dean, &

Woodcock, 2000). This study will investigate the underlying constructs of sensory and motor tests with confirmatory factor analysis, a more contemporary technique in statistics.

Additionally, this study will explore the relationship of sensory-motor constructs in conjunction with a prominent theory of cognitive abilities: Cattell-Horn-Carroll (CHC) theory of cognitive abilities. The CHC theory of human cognitive abilities is one of the most well validated theories of cognitive ability and has become important for the development and interpretation of cognitive measures and it's factor structure is well-understood (McGrew & Flanagan, 1998) and is often viewed as a pinnacle in psychometric history (McGrew, Keith, Flanagan, & Vanderwood, 1997). Indeed, Snow (1986) has stated the CHC theory "defines the taxonomy of cognitive differential psychology for many years to come" (cf Carroll, 1993, p. back cover). Additionally, the CHC model has been sufficiently cross-validated and found to be generalizable to populations that differ on age, ethnicity, and gender (McGrew, & Flanagan, 1998).

The reliable replication of CHC factors across multiple studies has led some to speculate on the possible neurological basis of the factors (i.e. Horn & Noll, 1997). As such, CHC theory may hold important theoretical and practical implications for neuropsychological assessment but only a few studies have begun examining neuropsychological tests within a CHC framework (Stankov, Palier, & Dolph, 1997; Roberts, Pallier, & Goff, 1999).

The CHC model is a hierarchical model covering the major domains of abilities (see figure 1). The CHC model includes eight broad abilities (fluid intelligence, crystallized intelligence, general memory, broad visual, broad auditory, broad retrieval, speediness, and decision speed). In addition, the CHC model includes a “g” or higher order factor that reflects intercorrelations among the broad abilities. The “g” factor is often referred to as a Stratum III factor; whereas, the broad abilities are often referred to as Stratum II factors. Stratum I, lower level factors, often represent individual components of Stratum II factors but such components often have idiosyncratic characteristics that are unique to specific measures. Additional details of the CHC model are provided in a later section of this paper.

Only a few studies have begun to explore neuropsychological constructs in conjunction with the CHC model. Dean and Woodcock (1999) have proposed a model that integrates CHC and neuropsychological constructs and information processing constructs as it relates to parts of the nervous system and sensory-motor functioning. Although this model incorporates CHC factors and neuropsychological tests of sensory and motor functioning, these constructs have not been formally investigated. Ackerman, Kyllonen, & Roberts (1999) have argued for an additional broad ability of sensory-motor functioning to be added to the existing broad abilities of the CHC model and have suggested sensory functioning shares commonality with Gv (visual processing) and Gf (fluid reasoning) constructs. Other studies have examined tactile-kinesthetic measures along with CHC constructs and concluded a tactile kinesthetic factor does exist, and it shares variance with Gv and Gf (Roberts, Stankov, Pallier, & Dolph, 1997). However, these and other authors have concluded the exact empirical status of

TK is presently uncertain and may not be distinguishable from other CHC constructs (Carroll, 1995; Roberts, Stankov, Pallier, & Dolph, 1997; Ackerman, Kyllonen, & Roberts, 1999).

Purpose of Research Project

The goal of this study was to investigate the relationship of sensory and motor constructs and to investigate their relationship with CHC constructs. As a necessary step, the underlying factor structure of the SMB was examined to better understand the sensory and motor constructs measured by this test. Once a suitable model of sensory and motor constructs was derived, the model was then evaluated in a joint-confirmatory factor analysis with the CHC model. Specifically, the degree to which sensory and motor constructs were similar to other broad abilities in the CHC model was evaluated.

Importance of study

The importance of this study is threefold: 1) the investigation of sensory and motor constructs with the CHC theory of human cognitive abilities, 2) the clarifying of sensory and motor constructs, and 3) the general exploration of neuropsychological constructs with psychometric constructs.

There are several important reasons for specifically examining sensory-motor constructs with the CHC model. Assessment of cognitive abilities with a standardized psychometric intelligence test is an important aspect of a neuropsychological evaluation (Moehle, Rasmussen, Fitzhugh-Bell, 1990). The CHC theory is a robust model of human cognitive abilities and provides a good description of cognitive functioning assessed in standardized intelligence tests

(McGrew, Werder, Woodcock, 1991; Ysseldyke, 1990). Because of these characteristics, the CHC model provides a good model for understanding human cognitive abilities and a framework for understanding other psychometric constructs. Additionally, the CHC has been likened to a taxonomy of human abilities, much like that of the periodic table of elements in chemistry and the Diagnostic and Statistical Manual of Mental Disorders in psychiatry (Flanagan & Ortiz, 2001). As such it provides a common terminology across different psychological measures, which can better align research examining cognitive abilities and the practice of psychologists assessing and treating individuals with cognitive problems. Another reason for specifically examining sensory-motor constructs jointly with the CHC model is clinicians rely on the CHC model to determine the scope of abilities assessed in a psychological evaluation. If sensory and motor constructs are equivalent to other broad cognitive abilities and should be included in the CHC model, as suggested by Ackerman, Kyllonen, & Roberts, (1999), clinicians may unwittingly be leaving out an important domain of abilities in assessment. Conversely, if sensory and motor constructs are narrow abilities and should not be included in the CHC model, as suggested by Carroll (1993), assessing sensory and motor constructs may provide marginal returns given the limited amount of time available to clinicians for a comprehensive psychological assessment. As such, understanding where sensory and motor constructs fit into the CHC model, if at all, could have broad implications for researchers and clinicians.

There are multiple reasons for obtaining a better understanding of the specific neuropsychological measures of sensory and motor functioning. First, clarifying sensory and motor constructs holds important implications for psychological and neuropsychological assessment. Sensory and motor functioning are imported aspects of a comprehensive neuropsychological evaluation (Halstead, 1957; Cytowic, 1996; Dean & Woodcock, 1999). Measures of sensory and motor functioning are important for discriminating normal from brain damaged individuals (Reitan & Wolfson, 2001) and are indicative of overall neurological functioning (Hill, Lewis, Dean, & Woodcock, 2000). Additionally, sensory and motor functioning for pre-school aged children have been found to be predictive of academic problems and probability of receiving special education placement several years later (Huttenlocher, Levine, Huttenlocher, & Svenson, 1983). Thus, a better understanding of the underlying constructs of sensory and motor functioning may improve their clinical utility and provide greater specificity for diagnostic outcomes. Second, sensory and motor tests have primarily been validated by the criterion of predicting brain damage (Reitan & Wolfson, 2002), but, like many other neuropsychological measures, their underlying constructs have not been rigorously and empirically analyzed. Understanding the underlying constructs of sensory and motor functioning is in alignment with the growing need for neuropsychologists to understand the functional aspects of a test rather than it's predictive validity of brain damage. Finally, neuropsychological assessment frequently includes sensory-motor assessment and a measure of cognitive ability. However, it is difficult to understand the relationship among different measures included in a comprehensive assessment without knowing the underlying constructs related to the measures. Understanding the underlying constructs between sensory-motor constructs and cognitive ability constructs will provide clarity on two constructs often involved in a comprehensive neuropsychological assessment. Additionally, this will help in reducing possible redundancy in assessment, increase specificity of testing, increase sensitivity of detecting behavioral deficits, assess a broader range of abilities, and aid in differential diagnosis.

In general, the investigation of neuropsychological constructs with the CHC model has important consequences for both practical and theoretical considerations. Understanding the factor structure of neuropsychological tests serves to identify similarities among test constructs, reduce redundancy in assessment, and help indicate the need for additional testing, which in turn improve decision making in identification and placement decisions (Chittooran, D'Amato, Lassiter, & Dean, 1993). Additionally, this research is in line with contemporary trends in neuropsychological assessment to better understand the underlying constructs of neuropsychological measures and an emphasis on theoretical models of behavioral functioning.

To clarify the underlying constructs of sensory and motor functioning and explore how these constructs are related to the CHC model, the present study examined these issues with two studies. In Study 1, exploratory and confirmatory factor analyses were used to explore the underlying constructs measured by a neuropsychological measure of sensory-motor functioning. In Study 2, the factor structure, or model, derived in Study 1 was used in a joint analysis with measures based on the CHC theory of human cognitive abilities.

Research Hypotheses

The major research questions addressed by this study were:

Study 1:

(1) What are the underlying constructs assessed by the Dean-Woodcock Sensory and Motor Batter (SMB)?

Study 2:

(2) Are the underlying constructs of sensory and motor functioning equivalent to the broad abilities of the CHC model as measured by the Woodcock-Johnson Revised Tests of Cognitive Ability?

Since little research has been conducted in examining neuropsychological constructs within CHC theory, particularly sensory-motor constructs, past research provides little aid in guiding research hypotheses. Past research on the SMB suggest a three-factor model is better than a two-factor model (Hill & Dean 2000). Additionally, the theory underlying the SMB suggests at least 3 factors. Therefore, particular emphasis was placed on models with three or more factors. For Study 1, it was hypothesized the factors of the Sensory-Motor Battery would at a minimum consist of sensory, motor, and subcortical motor factors, as suggested by past research (Hill, Dean, & Wodcock, 2000; Dean & Woodcock, 2000). Several competing models of the SMB (developed from factor analysis, theory, and past research) were tested using confirmatory factor analysis. It was anticipated the model that best fits the data and maintained theoretical coherence would be identified through this procedure. The selected model from Study 1 was used in a joint confirmatory factor analysis with CHC constructs in Study 2. Model selection was based on fit indices (chi-square, Akaike, Normed Fit Index, Root Mean Square Residual). Although multiple fit indices were reported, model fit was primarily determined by the NFI and the RMS and differences between models was primarily determined by chi-square and Akaike Information Criterion. Model comparisons were conducted with chi-squares adjusted for degrees of freedom and Akaike Information Criteria (AIC). Path coefficients were also be examined to determine the degree to which certain tests belong or do not belong to a theoretical construct. Improved fit to different models will be explored by with available statistics and guidance from theory.

For Study 2, sensory and motor construct(s) were tested in a joint-confirmatory factor analysis with the CHC model. Specifically, standardized path coefficients between "g" of the CHC model and sensory/motor construct(s) were estimated. The results of this analysis will provide evidence to argue for or against the inclusion of sensory and motor constructs in the CHC model.

Ultimately, this study will attempt to provide a defensible theoretical model of the SMB based on empirical evidence, elucidate the constructs measured by the SMB, and provide information on the relationship between SMB constructs and CHC constructs (see Appendix 1 for definition of important terms, and general discussion for assumptions and limitations).

CHAPTER II

Review of Literature

Overview

Sensory and motor assessments are an important aspect of a comprehensive neuropsychological assessment. Like many other neuropsychological measures, sensory and motor tests were incorporated into a neuropsychological assessment based on their utility in predicting damage in particular areas of the brain. As neuropsychological assessment becomes more theory driven and less dependent on predicting brain damage, there is a growing need to understand the underlying constructs of sensory and motor measures, as well as many other neuropsychological tests. Although empirical research in brain-behavioral relationships will always be important for neuropsychology, psychometric analysis of neuropsychological measures will become more important as theory based approaches become more popular. Psychometric analysis, in general, has developed radically different techniques within the last two decades, but these techniques are rarely used in the analysis of neuropsychological measures. The Cattell-Horn-Carroll (CHC) model of human cognitive abilities was developed using these contemporary psychometric techniques. This chapter will give a brief historical overview of neuropsychology and sensory-motor research and provide a rationale for analyzing sensory and motor functions with the CHC model of cognitive abilities.

Brain-behavior relationships

Neuropsychologists seek to understand human behavior as it is related to neural anatomy (Lezak, 1995, Dean 1985) and is a result of converging research in neuroanatomy, physiology, biochemistry, and psychology (Cytowic, 1996; Meier, 1992). The term neuropsychology was first coined in D. O. Hebb's (1949) book *The Organization of Behavior*. Prior to this, beginning in the Stone Age period (about a half-million years ago), primitive people recognized the importance of the head region in behavior but relied on superstitious, metaphysical, and religious explanations of behavior (Kolb & Wishaw, 1985). Additional evidence of early man's recognition of the head region as being important in behavior comes from primitive surgical techniques of the head area known as trephening (Hergenhahn, 1992) and later evidenced in the area of phrenology, both of which lacking in veracity (Thorne & Henley, 1997). Regardless, these early developments were important milestones in the progression to contemporary neuropsychology (Damasio, 1995).

Ramon y Cajal (1852-1911) discoveries in neural anatomy provided one of the first true links of brain and behavior relationships. Cajal's findings first demonstrated the neuron was a discrete entity and neurons could work together to produce behavior, a common assumption in contemporary neuropsychology (Gazzaniga, Norton, & Mangun, 1998). Broca and Wernicke provided important evidence suggesting language faculties were localized in particular regions of the brain, and French physiologist, Pierre Flourens, (1794-1867) original work in ablation studies on animals demonstrated reliable brain-behavior between movement and the cerebellum in canines (Capretta, 1967; Hergenhahn, 1992).

Lashley (1890-1958), a modern day advocate of Flourens basic findings, postulated the amount of cortical tissue destroyed is more important for impairing complex behavior than the location of damage (Thorne & Henley, 1997). These researchers provided important evidence that some functions are not localized in the brain but rather distributed throughout brain regions.

Sensory and motor functions, unlike many other behavioral functions, are clearly localized within the brain. Penfield (1965) provided empirical support for the localization of sensory and motor functions that led to a mapping of the primary sensory and motor strips of the cerebral cortex. In general, sensory information is received at the cortical level by the somatosensory strip located posterior to the central gyrus (Bigler & Clement, 1997). Both the sensory and motor strips of the brain contain representations that form an outline, sometimes referred to as a homunculus, of the human body (Kolb & Whishaw, 1985; Bigler & Clement, 1997). Tactile sensory systems (also known as somatosensory) transfer information from sensory receptors to the cortex. Additionally, the sensory systems synapse in the spinal cord to allow for immediate motor reaction (e g. pain response or a reflex). Visual sensory systems synapse in the mid-brain, as does auditory sensory systems, and projects in the occipital lobe of the cortex; whereas auditory systems project to the temporal regions of the cortex (Kolb & Whishaw, 1985).

Neuropsychologists have long known different psychological functions differentially deteriorate as a result of ageing (Banich, 1997; Lezak, 1995). Similar findings have been observed for sensory functions (Anstey, K. J., Stankov, L. & Lord, S. R. 1993). In general, the decline of sensory functions parallels that of fluid intelligence (Anstey, K. J, 1999). However, additional research is needed before a causal relationship can be inferred (Lindenberger, Scherer, & Baltes, 2001).

Psychometrics of brain-behavior relations

These principles became the foundation of what is known as clinical neuropsychology. Clinical neuropsychology is the study of brain-behavior relationships (Kolb & Whishaw; Dean, 1986) with an added emphasis on rehabilitation (Rattan & Dean, 1985). A neuropsychologists primary role is to evaluate the degree to which nervous system damage may have compromised a person's cognitive, behavioral, or emotional functioning (Banich, 1997). Research in clinical neuropsychology has worked to develop practical applications from the empirical research of brain-behavior relationships. Neuropsychology has been included as a subdivision of the American Psychological Association (Division 40), which is evidence of the field's maturation.

Traditional neuropsychological assessment focused on providing a diagnostic probability of brain damage as an alternative to using expensive pneumoencephalograh and/or early brain scanning techniques (Long, 1996), which placed little emphasis on construct validity (Halstead, 1947). With contemporary brain-imaging technology, predicting nervous system damage with psychometric tests is no longer important and insufficient for validating tests. Because imaging technology surpasses psychometric tests in examining the physical nervous system, the use of neuropsychological tests has thus shifted from predictive accuracy to assessment of behavioral deficits (Dean, Woodcock, & Decker, in preparation). As such, the results of neuropsychological tests are no longer simply based on empirically derived cutoff scores, but rather by an understanding of the test's theoretical underpinnings.

Neuropsychologists are now being asked to determine a patient's functional skills for the purpose of developing treatment options and rehabilitation potential (Henrichs, 1990). However, due the dominance of the actuarial approach, the underlying constructs of many neuropsychological tests are not fully understood (Dean & Woodcock, 1999; Dean, Woodcock, & Decker, in press). Although many different tests and measures have been used in neuropsychology, only tests capable of predicting brain damage have been incorporated into a core battery of tests that are routinely used in neuropsychology (Halstead, 1957, Reitan & Wolfson, 1993). The difficulty for contemporary neuropsychologist is they are now being asked to measure functional capacities with traditional neuropsychological measures that were designed for predicting brain damage and have obscure underlying constructs.

The trend toward theory based approaches in neuropsychology places a greater emphasis on the psychometric properties of neuropsychological tests. As such, clarification of the underlying constructs of neuropsychological measures may be expedited by new techniques in psychometrics.

In light of these developments, contemporary neuropsychologists have been forced to shift the focus of neuropsychological testing. Measuring functional deficits in behavior has become more important in neuropsychological assessment than predicting brain damage (Henrichs, 1990; Cytowic, 1996; Dean & Woodcock, 2000). Neuropsychological assessment and brain imaging technology have developed a symbiotic relationship with mutual reliance. Although brain imaging can examine neurological damage with a high degree of certainty, it gives little insight in what behavioral functions are actually impaired. Neuropsychological assessment primarily plays the role of examining behavioral deficits. For neuropsychologists, objective measurement of behavioral deficits solely relies on standardized testing.

Currently, the Halstead-Reitan Neuropsychological Battery is the most frequently used neuropsychological assessment tool in clinical practice (Dean, 1985). Once used with actuarial formula, neuropsychologists are attempting to better understand its underlying structure to fulfill their new role in neuropsychology. Ward Halstead, developer of the Halstead-Reitan, took an empirical approach for selecting tests to be included in the battery. As such, he would often visit the homes of brain damaged patients to observe the patients in their typical environment (Choca, J. P., Laatsch. L., Wetzel, L., & Agresti, A., 1997). The most salient characteristic that he noticed in patients with some sort of brain damage was their inability to solve complex problems that often required abstract thought. He translated this observation into practice in the Halstead-Reitan Neuropsychological Battery's (HRNB) via the Category Test, which is the most sensitive indicator of brain damage in the HRNB (Choca, Laatsch, Wetzel, & Agresti, 1997).

Halstead (1947) was a leading proponent of quantitative, or actuarial, methods of diagnosis and helped establish systematic methods for examining brain injury with psychometric instruments and relied on empirically derived cutoff scores that maximally predicted brain damage. Halsteads atheoretical method that maximized the accurate prediction of brain damage became the basis for validating neuropsychological tests (Cytowic, 1996). Consequently, theoretical notions of brain functioning mattered less than the development of assessment instruments that could reliably predict brain damage (Reitan, 1955; Dean and Woodcock, 2000). As such, there is little reference to the functional aspects or the underlying constructs of the tests used by Halstead. Of closest relevance was Halstead's distinction between psychometric and biological intelligence. Psychometric intelligence, according to Halstead, refers to cultural learning and knowledge. It was this type of intelligence that was primarily measured by psychometric tests of his time. Biological intelligence refers more to reasoning and thinking. It was this type of intelligence, according to Halstead, that was most influenced by brain damage. Although his primary purpose of making the distinction between psychometric and biological intelligence was for methodological reasons, this distinction helps provide a theoretical basis and rationale of neuropsychological batteries currently in use (Pallier, Roberts, & Stankov; Reitan & Wolfson, 1985).

The interpretation of the Halstead tests relies on a single composite score (Fischer, D'Amato, Gray, & Dean, 1987). This composite is not based on the factor dimensions of the test and lacks any psychometric evidence (Fischer &

Dean, 1990). Additionally, the impairment index interpretation is modified by the intelligence level of the patient (Bigler & Clement, 1997). Reitan (1985) suggests a .4 or greater impairment index should be interpreted as an indicator of brain damage if the individual has an intelligence level of 100. If the intelligence level is less than 100, an impairment index cutoff of .5 should be indicative of brain damage.

Although it had little influence in test interpretation, Halstead (1957) did factor analyze the tests of the Halstead-Reitan and concluded four major factors were extracted: 1) comprehensive field (similar to long-term memory), 2) abstract thinking, 3) "power" factor (similar to concentration), and 4) directionality (sensory-motor). In retrospect, many the tests of the Halstead-Reitan are described as "performance" measures and predominantly measure non-verbal factor dimensions (Boll, 1981). These original factor dimensions were, for the most part, ignored as the dominant approach to neuropsychological diagnosis was based on cut-scores.

Because neuropsychologists have added a cognitive battery to supplement the tests of the Halstead-Reitan, which has almost exclusively been the Wechsler scales, many studies include cognitive variables in the factor analysis (Moehle, Rasmussen, & Fitzhugh-Bell 1990). The inclusion of a cognitive battery became commonplace and changed the dimensions measured in a comprehensive neuropsychological exam. The added dimension, primarily from the Wechsler intelligence test, were primarily verbal and performance dimensions. When factor analyzed together, tests from the Halstead-Reitan test primarily load on the performance factor but there is major variation in this and other factors (Moehle, Rasmussen, Fitzhugh-Bell, 1990). No studies to the authors knowledge have replicated these studies with confirmatory factor analysis.

Psychometric developments

Although there has not been much advance in understanding sensory and motor or intelligence from a psychometric perspective, substantial improvements have been made in the methodology used to understand constructs and measurement of abilities.

Like many neuropsychological measures, the first cognitive assessment instruments, by today's standards, lacked validity, reliability, and were not based on any theory of cognitive functioning. With better statistical tools (e.g. correlation, regression, factor analysis), more sophisticated tests that are more reliable and valid have been developed.

Factor analysis made many major contributions to understanding the construct of intelligence (Carroll, 1993). Factor analysis is based on exploratory analyses performed on a matrix of intercorrelations from various measures (Kyllonen, 1996). Factor analysis was the logical progression to the correlation in that factor analysis is capable of finding regularities in the correlation matrix and reducing the matrix to a more simplified set of variables. These reduced variables can be analyzed for causal relationships and higher- level associations.

Factor analysis is a statistical procedure that uses matrix algebra that summarize the interrelationships among the variables in a concise but accurate manage as an aid in conceptualization (Gorsuch, 1983). Factor analysis aids in conceptualization by clarifying constructs. Constructs are theoretical, unobservable, constructions that help organize the environment, and construct validation is the process in which the validity of inferences about the unobserved constructs are clarified on the basis of observed variables (Pedhazur & Schmelkin, 1991).

Factor analytic techniques play a crucial role in construct validation (Pedhazur & Schmelkin, 1991) and have radically transformed the field of psychometrics as it provided a new method to test old philosophical assumptions. Promulgating intelligence as a unitary construct, Spearman (1904) provided evidence to suggest one single construct could account for the majority of variance on measures of intelligence. He termed this construct as "g". Thurstone (1938) described intelligence as having multiple components, termed primary mental abilities, that incorporated such areas as reasoning, verbal ability, perceptual speed, etc. Using the centroid method of factor analysis, Thurstone found support for each of these factors but also found that all of the primary mental ability factors were correlated, which led him to later consider the viability of a higher order g factor.

Gf-Gc Theory

Cattell (1941) first promulgated Gf-Gc theory somewhat as a reaction to the inadequate contemporary theories of intelligence in his time. Gf-Gc is the acronym for "fluid and crystallized intellectual abilities." Cattell postulated that two major classes of influences affected the normal development of cognitive abilities. The first class, fluid intelligence, was related to biological influences such as genetic, physiological, and neurological factors. The second class, crystallized intelligence, was related to educational-cultural opportunities and influences.

Cattell used the term "fluid intelligence" to describe a host of biological factors that influenced cognitive ability. It was primarily defined by non-verbal ability with an emphasis on novel reasoning tasks. Problems requiring fluid intelligence were characterized by a minimal reliance on stored information that could be implemented routinely. It was termed "fluid" because it was conceived as flowing into different mental activities. The extent to which it "flowed" into cultural learning influenced the extent of a person's crystallized intelligence (Cattell, 1987). Cattell introduced the term "crystallized intelligence" to describe influences from education and culture. The strain on intelligence needed to develop crystallized skills could be minimized if the skill was encountered or repeated for a long period of time. Also, these skills would be more difficult to acquire after the individual reaches biological maturity of his/her mental capacity.

Through subsequent research, predominately through the use of factor analysis, the basic two-factor theory was extended to encompass 10 broad dimensions of intellectual functioning. Carroll's (1993) seminal work provided additional specification and verification to the already extended Gf-Gc theory of Horn and Cattell. Carroll's theory was derived from the statistical and logical analysis of hundreds of data sets that include various collections of published and unpublished tests. Based on his factor analysis, Carroll suggested an empirically derived three-stratum theory of intelligence that approximately corresponded to Horn and Cattell's extended Gf-Gc model. Carroll's theory consist of 10 broad abilities that have a commonality through "g". Figure 1 presents an overview of Carroll's model. The major distinction between the Horn/Cattell and Carroll's model is the third-stratum ability, or "g" factor. Carroll included a higher order "g" factor in his model; whereas, Horn adamantly denied the existence of a "g" or a Stratum III variable (Horn, 1991; Horn & Noll, 1997). Despite this difference, most researchers agree the models are more similar than different. As such the model is often referred to as the Horn-Cattell-Carroll (CHC) model. Carroll's model can be described as a hierarchy of abstractions with the first stratum traits being the most specific, the second-stratum traits (a.k.a. broad abilities) being more general, and the third-stratum trait being the most general. The third-stratum variable, also known as "g," represents general intelligence and is indicative of the commonality between all psychometric tests. The second-stratum factors are more numerous and are usually represented by eight broad categories of individual abilities. These broad abilities are: Fluid Reasoning, Comprehension/Knowledge, Correct Decision Speed, Visual Processing, Auditory Processing, Processing Speed, Long-Term Retrieval, and Quantitative Ability. More specific abilities that are a modified expression of one of these broad categories are narrow abilities, or Stratum I variables. This "mapping" of the cognitive territory has been influential in the development of contemporary cognitive assessment instruments by providing a basis to judge an instruments breadth by the degree to which all abilities in this model are assessed.

One feature of CHC theory is that it is not based on any particular battery of tests. As such, it is easily generalized to different assessment instruments. Additionally, it provides a blueprint for what an appropriately designed and analyzed factor analysis study (Woodcock, 1990). Another important feature of Gf-Gc theory is its distinction between broad and narrow abilities. (The broad abilities of Gf-Gc theory correspond to stratum 2 in Carroll's three-stratum theory; the narrow abilities correspond to stratum 1.) Each of the broad abilities can be measured by a variety of tasks, each of which measures a narrow aspect of the broad ability. For example, verbal-conceptual knowledge (Gc) is the factor measured by tests such as vocabulary, general information, geology, or even "street-wiseness". Scores from various tests of the same broad ability will show varied patterns of strengths and weaknesses within different individuals.

Applying new psychometric models to neuropsychological measures

The long history of intellectual assessment has culminated in a description of human cognitive abilities that is represented in the CHC model(McGrew, Keith, Flanagan, & Vanderwood, 1997). Intelligence, once conceptualized as a nebulous whole, is now considered to have distinct components with multiple parts. This development has been facilitated by modern statistical techniques, particularly confirmatory factor analysis. Neuropsychology has also been interested in understanding the nature of cognitive abilities and has also come to recognize cognitive abilities are multiple in nature and not unitary (Lezak, 1995). More so, neuropsychology has sought to link the discovered cognitive abilities to the physical substrate of the nervous system.

As future research further elaborates the nature of cognitive abilities, the etiology, or etiologies, of these abilities will become more of an interest. Indeed, Jensen (1993) proposed the next major development in psychometric will come from understanding the biological basis of human cognitive abilities. Jensen has speculated on the biological basis of "g" and has explained this construct to individual differences in the speed of information processing capacities of the nervous system. Additionally, Ittenbach, Esters, & Wainer (1997) stated "...it is almost certain that cognitive theories coupled with neuropsychological perspectives will change the face of intellectual assessment as it is presently known" (p. 28).

Horn and Noll (1997) have examined the neurocognitive evidence of psychometric constructs and have speculated "different sets of genes determine structures and functions of the brain and that these different structures and functions support cognitive capabilities." (p. 81). For example, the norepinephrine system of the brain regulates arousal and it is believed that tests with Gf characteristics are most influenced by norepinephrine systems. Horn and Noll also state the serotonin system as being important in cognitive ablities but fail to ascribe it to any broad ability. Anatomical evidence, as described by Horn and Noll (1997), has also been found, which suggest the left and right hemisphere are involved in different cognitive functions. This position is supported by Goldberg (2000), a student of Luria, who ascribes cognitive processing of novel information to the right hemisphere and cognitive processing of familiar information to the left hemisphere.

Although many respected authors in both neuropsychology and in intelligence theory have surmised the ultimate explanation of cognitive ability will come from understanding the brain, research in this area has not produced enough empirical evidence to make any definitive statements about the relationship between cognitive performance and physiological mechanisms. In recognition of this fact, Jensen (1993) stated, "The main problem…is our almost total ignorance of the extent of individual differences in the structural features of the brain and the degree to which they are related to g." (p. 124). This statement can be generalized to all constructs postulated by psychometric theory. This area of research will surely play a significant role in the future of neuropsychology and cognitive assessment.

Neuropsychologists have also recognized a particular pattern of strengths and weaknesses after brain injury (Cytowik, 1996). This pattern is often referred to as "spared" and "impaired" pattern and highly suggest a link between the nervous system and cognitive abiliities. After sustaining a head injury, individuals often show greater deficits in fluid abilities but do not show any deficits in crystallized abilities. The exact cause of this pattern of impairment is not known but probably is related to repetition. Abilities, like crystallized abilities, that are learned through repetition may develop multiple pathways within the brain and stronger connections. Such abilities are less likely to decrement from neurological insult. Fluid reasoning problems, being novel by nature, never become solidified because of the continual newness of the problem. Because the problems are novel, no extra neural pathways have been developed and thus destruction of only one or a few pathways involved with fluid abilities can cause grave consequences. Although such an explanation is plausible, further research would be needed to firmly link these psychometric constructs to the actual functioning of the nervous system.

One difficulty in relating psychometric measures with neuropsychological measures is reification. As written by Gould (1981), reification is the assignment of physical meaning to the first principle component of a factor analysis. This, as Gould states, is not a physical reality but a mathematical abstraction. Important, Gould (1981) does not believe reification is never justified but "such a claim should never arise from the mathematics alone, only from additional knowledge of the physical nature of the measures themselves" (p. 250).

Providing additional valid evidence for a clear relationship between the physical aspects of abilities, such as a deficit in ability as a consequence of brain damage, has long been part of neuropsychology (e.g. Hebb, 1949; Halstead 1947). In fact, the ultimate explanation for skills and abilities must, in some way, refer to aspects of the nervous system. As stated by Howe (1996) "...unless we believe in some kind of dualism we have to accept that there is some kind of physical embodiment corresponding with any psychological capacity, so even if an ability is not a thing it is not true to say that there is not any material event or mechanism that corresponds with the notion of an ability" (p. 42). Although the ultimate explanation of cognitive behavior may reside in properties of the nervous system, it is important to be aware of Gould's reification error. As such, just because a relationship is found, or not found, between a neuropsychological test that has a clear relationship with a part of the nervous system and a measure of cognitive ability, does not necessarily imply the two measures relate to the same area of the nervous system. Always, additional information must be found to elucidate the causal mechanisms related to a specific measure and the brain or nervous system functioning.

CHC theory and neuropsychology

Cognitive assessment is considered vital to any neuropsychological assessment. Although most neuropsychologists believe describing cognitive ability, or intelligence, as a unified construct is essentially meaningless and lacks any clinical utility in neuropsychology (Lezak, 1995), neuropsychological research incorporating multidimensions of intelligence is quite sparse (Dean & Woodcock, 1999). As such, CHC theory may provide an important framework for neuropsychological measurement despite a lack of research of CHC and neuropsychological measures. For instance, several of the abilities in the CHC model, and the WJ Tests of Cognitive Ability, specifically incorporate visual ability and visual processing. The occipital lobe of the brain has long been known to play a role in the processing of visual information (Hubel, 1973; Luria, 1973). Luria has described this processing as occurring in several stages: primary, secondary, and tertiary. The complexity of visual processing increases through the stages with the most complex processing occurring in the tertiary areas. Hubel's work similarly describes visual processing as being hierarchical in nature and, like Luria, ascribes the occipital lobes as having a special role in the processing visual information. From this, it may be hypothetically deduced that damage to the occipital lobes in the brain may influence scores on Gv, or tests of visual processing. Similarly, the temporal lobes have been found to play a special role in the processing of auditory information. It may be the case that damage to the temporal lobes will influence performance on Ga or tests of auditory comprehension.

McGrew (1998), using factor analysis, content analysis, and heuristic judgment has attempted to describe CHC abilities in terms of different neuropsychological models. One model analyzed was a left/right brain model. This model is a description of CHC abilities in terms of a right hemisphere and left hemisphere brain localization. After factor analyzing the tests in the WJTCA, both a verbal and non-verbal factor was identified that was ascribed to indicate left hemisphere and right hemispheric functions respectfully. In addition, some WJTCA tests were categorized as having an integrated classification if both right and left hemispheres were thought to play a role in the particular test.

Although neuropsychologists developed very similar theories of intelligence, these theories were never incorporated into assessment. Halstead's (1947) distinction between psychometric and biological intelligence comes close to Cattell's fluid and crystallized theory of intelligence. Halstead described psychometric intelligence as incorporating aspects of learned or cultural knowledge and biological intelligence incorporated aspects of novel problem solving (Choca, Laatsch, Wetzel, & Agresti, 1997). Halstead's psychometric intelligence, defined by aspects of learned or cultural knowledge, was similar to Cattell's crystallized intelligence. In both theories, the biological/fluid construct was described as being less influenced by cultural factors and memorized learning and is more sensitive to brain damage, which included aspects of novel problem solving as measured by the Category Test.

Donald Hebb, another prominent neuropsychologist, was one of the first neuropsychologists to claim standard intelligence tests are not highly sensitive to brain lesions (Hebb, 1942). Hebb proposed a theory of intelligence that distinguished between type A and type B intelligence. According to Hebb, intelligence A was a biologically based form of intelligence that represents the capacity to reason; whereas, intelligence B was more reflective of cultural learning. Halstead's biological intelligence and psychometric intelligence and Hebb's type A and type B intelligence are nearly indistinguishable from Cattell's fluid and crystallized intelligence. The similarities in these theories suggest research at the time was converging on similar conceptions of intelligence.

To the extent Gf-Gc constructs are similar to Halstead's biological and psychometric intelligence, and Hebb's type A and type B intelligence, it is possible to make some inferential hypothesis about Gf-Gc by what is known about biological/psychometric and type A/ type B intelligence. Essentially, both biological and type A constructs are more susceptible to decline upon neurological insult (Hebb, 1942: Halstead, 1947). This may imply that Gf tests would be better indicators of brain damage than Gc tests, and Gc tests may be better indicators of pre-morbid functioning. Research comparing CHC constructs of fluid intelligence and Halstead's biological intelligence, as measured by the Category Test, has shown these constructs to be highly related and best explained by a single underlying factor (Decker, Hill, & Dean, in preparation). Additionally, neuropsychologists, in interpreting patterns of strengths and weaknesses on Wechsler intelligence scales, often describe performance measures as more "fluid" and verbal measures as more crystallized (Bigler & Clement, 1997). Despite these similarities, little research has been done to formally investigate and synthesizes these theoretical perspectives as Gf-Gc theory predominately stayed in psychometrics and neuropsychologists, being less interested in theory, maintained an actuarial perspective.

Making connections between the more modern Gf-Gc theory and neuropsychology is more difficult because it has grown to incorporate additional abilities. Although Cattell's initial dichotomous Gf-Gc theory postulated two factors, this two-factor model of human cognitive abilities has not been the view of either Horn or Cattell for nearly 30 years, despite the persistence of the Gf-Gc label (McGrew & Flanagan, 1998). Cattell and Horn expanded the initial Gf-Gc theory to incorporate four additional abilities; short-term memory, long-term memory, visual perception, and speed of information processing (McGrew & Flanagan, 1998).

CHC and sensory/motor measures

Carroll's (1993) factor analytic work that eventually led to the development of the CHC theory of cognitive abilities included only a limited number of sensory and motor tests. Carroll included sensory and motor factors in a miscellaneous domain of abilities. Using numerous datasets, the sensory factors that reliably emerged were Visual Sensitivity, Color Vision, Olfactory Sensitivity, and Tactile-

Kinesthetic Sensitivity. Tests of motor functioning were also included in Carroll's analysis. In one dataset that was cross-referenced by Carroll, the motor factors derived were Static Strength, Gross Body Equilibrium, Reaction Time, Speed of Limb Movement, Wrist-finger Speed, Multilimb Coordination, Finger Dexterity, Manual Dexterity, Arm-hand Steadiness, and Control Precision.

In its current form, the CHC theory does not include sensory and/or motor factors as second stratum abilities. With regards to motor factors, Carroll concludes that psychomotor factors are clearly distinct from cognitive ability factors. There is some exception to this rule for tests that involve reaction time measures. A number of distinct factors have also been found for various sensory abilities. It is possible that these factors are generally not included in clinical interpretation of various tests because distinct measures of sensory and motor abilities are not given along with cognitive abilities tests. However, based on Carroll's work, such tests would provide non-redundant information as these tests load on separate factors. From a logical view, deficits in sensory or motor abilities may cause secondary impairments in higher cognitive abilities. Given these factors are orthogonal, tests of sensory-motor functioning would provide could provide valuable information in clinical practice.

Although lacking in immediate psychometric implications, Luria (1973) has discussed theoretical relations between sensory, motor, and cognitive processes. According to Luria, sensory and motor areas can be found in the highest levels of the cortex. Cortical areas specific for sensory information are located in a post-central region (parietal lobe) of the cortex; while, motor areas are located in precentral regions (frontal lobe). These different regions have different cellular structures. Lesions in the sensory regions of the cortex may result in an inability to synthesize individual stimuli into whole structures. Lesions in the motor regions of the cortex may result in a lack of differential control over muscles. Luria also explicitly stated a significant relation between sensory and motor functions. In describing sensory lesions, Luria (1973) states:

> It would be a mistake to suppose that disturbances arising in lesions of the secondary zones of the postcentral cortex are limited to afferent or Gnostic disorders. An essential feature of these cortical zones is that a *pathological lesions* in them is *invariably reflected in the course of movement* [italics in original]. (p. 173).

Additionally, Luria describes lesions in the motor areas of the cortex in relation to other aspects of behavior, such as language. Motor deficits, according to Luria, often manifest in language expression difficulties. Additionally, motor functioning is localized in the frontal lobes of the brain, which have extensive inputs and outputs to subcortical areas. Similarly, Luria's theory places complex problem solving and planning as a function of the frontal lobes. Since language, planning, and problem solving are important components of cognitive ability measures, it is plausible a relationship exists between cognitive abilities and motor functioning, as described by Luria's theory. Although Luria's theory specifies theoretical relationships between sensory, motor, and cognitive functions, it does not make an explicit statement about the psychometric implications. From Luria's theory, it is clear that sensory and motor functioning should be highly correlated. Additionally, it is plausible to assume from Luria's theory that sensory, motor, and cognitive measures would be highly correlated. However, Luria is less clear about the relationship between sensory/motor and cognitive functioning. More empirical research is needed to examine these aspects of Luria's theory.

Results from sensory and motor research of the Halstead-Reitan can be tentatively generalized to the current study. In examining specific tests of sensory and motor functioning of the Halstead-Reitan within studies examining all tests of the Halstead and Weschsler, it has been found that tests such as the Tactual Performance Test often loads with Wechsler performance tests. Leonberger, Nicks, Goldfader, and Munz (1991) argue this represents an underlying dimension of spatial reasoning. Conflicting evidence against this interpretation has been presented (Yeudall, Fromm, Reddon, & Stefanyk, 1996). Many of the contradictions and ambiguities in understanding the relationship of sensory-motor functions and cognitive abilities through past research is possibly due to the overreliance on Wechsler scales to measure intelligence, which do not evaluate a broad spectrum of cognitive abilities (Pallier, Roberts, & Stankov, 2000) and most intelligence tests poorly measure their purported underlying constructs (McGrew & Flanagan, 1998).

Few studies have specifically examined the role of neuropsychological tests (specifically sensory-motor tests) in conjunction with the CHC theory. Pallier, Roberts, & Stankov (2000) examined neuropsychological tests of sensory-motor abilities (neuropsychological constructs) with cognitive measures in CHC theory. Specifically, the authors note similarities between Halstead's (1947) neuropsychological theory and Horn and Cattell's Gf-Gc theory of human cognitive abilities. In this study, tactile kinesthetic measures, or what Halstead referred to as biological intelligence, were analyzed in comparison with measures of Gf, Gc, Gsm, Gs, and Gv. The authors conclude that Halstead's construct of biological intelligence is indeed an additional factor that may be added to the other Gf-Gc theory factors. Interestingly, the biological intelligence, or tactile kinesthetic, factor was a heterogeneous factor that mixed with Fluid Reasoning tests. Although accolades should be given for the studies leading attempt to synthesize psychometric theory with neuropsychological theory, it's lack of methodological rigor and statistical reasoning yield questionable conclusions. The study only focused on a very narrow aspect of neuropsychological theory (Halstead's biological intelligence) instead of a more comprehensive synthesis of neuropsychological and psychometric theories. Additionally, the sample used in this study was from a relatively homogenous section of the population. The majority of subjects were highly educated and neurologically intact. As such, the results from this analysis cannot be generalized to a neurological population, where it would have the most implications. Some of the measures used to represent the Gf-Gc domains were unconventional tests with little background research and questionable psychometric properties. Although the study employed group testing, most of the tests were specifically designed for one-to-one administration. The factor extraction and rotation procedure was not justified nor were the studies adherence to 6 factors despite having extracted 8. Although this study points in the direction of where future research is headed, it's many flaws and unsubstantiated conclusions beckons further research.

Dean and Woodcock (1999) have presented a model that incorporates neuropsychological and psychometric constructs. The Dean-Woodcock Neuropsychology Model assesses 9 of these 10 broad abilities directly from the Woodcock-Johnson III (McGrew & Woodcock, 2001). The Dean-Woodcock Neuropsychological Assessment System was designed to map all CHC abilities as well as the narrow abilities involved with Sensory-Motor functioning.

The Dean-Woodcock Neuropsychology Model, Figure 2, was derived from combining CHC theory with information processing and neuropsychological theory. The model, in Figure 2, indicates what part of the nervous system is engaged for a cognitive process (peripheral, central, or both). It represents the input of physical stimuli from external or internal sources, indicates whether the output is cognitive and motor, and the "depth" in which a stimulus is processed. The vertical dimension of the model represents the level of cognitive processing. Reflexive processes are represented in the lowest portion of the model. Above this level are represented the automatic processes. The upper region of the model includes the thinking and reasoning processes. The model recognizes that cognitive and motor performance is not determined by cognitive abilities alone but also by the influence of non-cognitive factors, called facilitators-inhibitors.

The horizontal dimension of the model represents only a single cycle of functioning such that the contents of the sensory register on the right side of the model are simultaneously acting upon the contents of the sensory register represented on the left side. As depicted in the model and consistent with memory research, sensory information will rapidly decay if there is no further input.

The path from conscious awareness through executive control, and to certain other areas in the complete model, is represented by two CHC broad abilities, short-term memory (Gsm) and automatic processing speed (Gs). Declarative and procedural knowledge depict a storage of information (i.e. long term memory). CHC abilities that are part of the store of knowledge are Gc (verbal-conceptual knowledge), Gq (quantitative knowledge), and Grw (reading-writing). This area could also include various sensory and motor knowledge stores could be added to the model.

In the case where an automatic response or recall of information from stored knowledge is not available, additional processing in the form of strategies is required. These strategies include the Gf-Gc abilities of Visual-Spatial Thinking (Gv), Auditory Processing (Ga), Long-Term Storage-Retrieval (Glr) and Novel Reasoning (Gf). Although neuropsychologists are also concerned with motor, tactile, and kinesthetic abilities, it has yet to be empirically determined where these abilities may fit within the model. It is assumed these abilities represent a complex interaction of cortical and subcortical functions as well as pathways in the spinal cord and the peripheral nervous system.

Although the Dean-Woodcock model represents a synthesis of neuropsychological, cognitive science, and psychometric models, it has yet to be empirically tested. For example, a tactile/kinesthetic factor was postulated and given a similar role as Gv, Ga, Glr, and Gf in the cognitive performance model. However, no statistical evidence is given to demonstrate the relationship between these constructs. As such, it is questionable whether the tactile/kinesthetic factor can be considered unitary, and whether it can be given equivalent status in a model to other CHC constructs.

Ackerman, Kyllonen, & Roberts (1999) have provided evidence to argue for the addition of a broad ability of sensory functioning (tactile-kinesthetic) to the existing broad abilities of the CHC model and have suggested sensory and tactile functioning shares commonality with Gv (visual processing) and Gf (fluid reasoning) constructs. Other studies have examined tactile-kinesthetic measures along with CHC constructs and concluded a tactile kinesthetic factor does exist, and it shares variance with Gv and Gf (Roberts, Stankov, Pallier, & Dolph, 1997). However, these and other authors have concluded the exact empirical status of TK is presently uncertain and may not be distinguishable from other CHC constructs (Carroll, 1995; Roberts, Stankov, Pallier, & Dolph, 1997; Ackerman, Kyllonen, & Roberts, 1999).

Purpose of current study

The purpose of the current study was to examine the factorial structure of a standardized neuropsychological test of sensory-motor functioning (SMB Battery) and to relate the constructs measured by this test to the CHC model of human cognitive abilities. Previous research suggests the CHC theory is a robust model of human cognitive abilities and provides a good description of cognitive functioning (McGrew, Werder, Woodcock, 1991; Ysseldyke, 1990). The goal of this study is to determine the degree of similarity between constructs of sensory and motor functioning and the broad abilities of the CHC model. In Study 1, a factor analysis and confirmatory factor analysis was used to explore the underlying constructs measured by the SMB. In Study 2, the factor structure derived in Study 1 will be used in a joint analysis with a measure based on the CHC theory of human cognitive abilities. The two main questions that will be answered by this study are: 1) what constructs are measured by the Sensory-Motor Battery, and 2) how do the constructs of the SMB relate to the constructs of CHC theory.

CHAPTER III

Methodology

The purpose of this study was to examine the neuropsychological constructs of sensory and motor functioning in relation to contemporary psychometric constructs of cognitive ability. This study examined the factor structure underlying the Dean-Woodcock Sensory-Motor Battery and explored how its underlying factors relate to an established theory of human cognitive abilities, the CHC theory. This study will help clarify the interpretive framework of the CHC theory in regards to neuropsychological assessment (e.g. Dean & Woodcock, 2000) of sensory and motor functions and explore how such functions relate to the cognitive abilities in CHC theory model.

Statistical method

The core methodology used in this study was a confirmatory factor analysis. Confirmatory factor analysis (CFA) is subsumed under a branch of statistics knows as structural equation modeling. Structural equation modeling (SEM) refers to a family of statistical procedures that were developed in the 1970's and may be referred to as latent variable modeling, covariance structure analysis, or linear structural relationships (Kline, 1998; Schumacker & Lomax, 1996)

All structural equation models consist of two kinds of variables: observed and latent variables (Kline, 1998). Observed variables reflect the actual measurement of some variable (e.g., IQ, SES, Age). Latent variables typically correspond to hypothetical constructs that are not directly observable. Nunnaly and Bernstein (1994) described latent variables as reflecting a hypothesis that a variety of behaviors will correlate together and be similarly influenced by experimental manipulation.

Structural equation models are also described as having two types of models: a measurement and structural model (Schumacker & Lomax, 1996). The measurement model includes observed variables and latent variables that are formed from the observed variables. The structural model involves the specification of the relationships between latent variables.

The fundamental unit of a structural equation model is the covariance matrix. Even if correlation data or raw data are used as input, SEM software will usually transform the input data to a variance-covariance matrix, with a few exceptions. Some researchers have concluded using correlation matrixes lead to imprecise calculations of parameter estimates (Boomsma, 1983), and as a general rule, the covariance matrix should be used in SEM.

In SEM, a model is specified *a priori,* before data collection, and is done so based on theory. The specified measurement and structural models represent hypothesized relationships among the variables and latent factors. From the model, parameter estimates are derived. These are the model-implied parameters, which consists of a covariance matrix that would be “implied” from the model. Next, an empirically derived covariance matrix is derived. This covariance matrix is then compared to the implied covariance matrix from the model. If the two covariance matrixes share a certain amount of similarity, then the *a priori* structural equation model can be considered a plausible explanation for relations between the measures.

Identification of a model is also an important issue in confirmatory factor analysis. Identification involves determining whether the researcher's implied model is capable of being estimated with SEM. Other factors contribute to the validity of model parameter estimation besides identification; thus, identification is a necessary but not sufficient condition for estimating a model. A model is identified if it is possible to calculate a unique estimate for each of the model's parameters based on the available data. The optimum solution to ensure model identification is to evaluate the model after the model is specified and before data entry. Estimated over-identified models produce unrealible results and are difficult to interpret. Over-identified models are best dealt with by imposing additional constraints on the model. Often, one or more parameters are fixed or constrained to a certain constant, such as 0 or 1 (note: a fixed parameter is a parameter set to a certain numerical constant and a constrained parameter is set to equal another parameter that is estimated).

Fit indices provide a direct indicator of how well the implied covariance matrix matches the observed data (Loehlin, 1992). The concept of "goodness of fit" indices are derived from the model implied and observed comparison. No single statistical test can identify a correct model (Schumaker & Lomax, 1996). As such, a variety of indicators have been used for evaluating the fit of a model. In general, fit indices are used to evaluate the obtained solution and aid in the search for the best model, or optimum model fit. A chi-square statistic is a frequently given indicator of the fit of a model. Chi-square evaluates the extent observed data deviate from expected probabilities. A non-significant chi-square is indicative of a good model fit (Klein 1998). However, chi-square analysis is easily biased by a large sample sizes; therefore, other indicators of fit are needed, especially in large samples. Chi-square can also be used to judge the parsimony of the model when it is evaluated in relation to the degrees of freedom of the model. Fit indices are based on a discrepant function where a minimum value of the discrepancy function is obtained. The discrepancy attempts to minimize the error in the estimation and the fit indices evaluates how well the discrepancy function achieves this goal. Fit indices are analogous to a squared multiple correlation and can be interpreted as representing the proportion of explained variance from the implied model. Another widely used fit index is the Standardized Root Mean Squared Residual (SRMR). This index mainly focuses on the residual variance not explained by the researcher's implied model. When the implied model is perfect, the SRMR will equal 0. Therefore, lower values of SRMR are desirable. In general, an SRMR of .10 or less is judged to be acceptable.

The criterion used to determine model fit and model rejection should be chosen prior to model estimation and researcher should construct several models prior to estimation. Models may differ by "fixing" or "freeing" certain parameters, such as variance or residuals. The various proposed models are then said to compete with each other with the model with the best fit statistics being selected as the best model to explain the observed data. Structural equation modeling permits hypothesis testing for the whole model and for specific path coefficients. Path coefficients are calculated with a t value. If the t value is significant, it is concluded that a relationship exists between the two variables and the null hypothesis of “no relationship” is rejected. Additionally, model comparison is sometimes the focus of a study.

Overview of study

To evaluate the structure of the Sensory-Motor Battery and its relationship to CHC theory, two studies were conducted. The first study was composed of two sections. The first section of Study 1 consisted of an exploratory factor analysis of the Sensory-Motor Battery. The second section of Study 1 consisted of a confirmatory factor analysis of the Sensory-Motor Battery that was guided by the empirical results of the first section of Study 1 and the theoretical basis of the SMB.

Study 2 consisted of two joint confirmatory factor analysis of the Woodcock-Johnson Cognitive Tests- Revised (WJ-R) and the Sensory-Motor Battery. The WJ-R was used as an indicator of the constructs measured by the Cattell-Horn-Carroll theory of cognitive abilities. The second section consisted of a joint confirmatory factor analysis of the Sensory-Motor Battery and the WJ-R. For this section, the CHC theory was modeled in conjunction with the Sensory-Motor Battery to explore relationships between the CHC theory and Sensory-Motor constructs.

Study 1

Section A

Introduction

Study 1 was divided into two sections (A and B). Section A consisted of a factor analysis on the SMB for all subjects in the standardization sample. The interpretation of factors was guided by neuropsychological theory, and the interpretable factors from the factor analysis were used to clarify and guide confirmatory models developed in subsequent sections (section B and Study 2).

Section A (Study 1)

Method

Participants. Participants were taken from the standardization sample of the Sensory-Motor Battery. In total, 800 participants were used in both analyses. Age statistics can be found in Table 2, racial status of sample can be found in Table 3, handedness of sample can be found in Table 4. The gender characteristics of the sample consisted of 40.6% of males and 59.4% females.

Measures. Sensory Motor Battery: The Sensory-Motor Battery incorporates traditional neuropsychological measures of sensory and motor functioning and provides norm-referenced scores for different age groups. The battery includes eight tests of sensory functioning and eight tests of motor functioning. In addition, a lateral preference test is provided. A list of all variable labels, and modality tested can be found in Table 1. These tests provide an improvement in reliability and validity estimates over traditional tests of sensory-motor functioning (Woodward, 2000, in preparation).

Although the SMB consists of 17 tests, certain tests have multiple subtests (e.g. Palm Writing) and different scores for the left, right, and both sides of the body (e.g. Near Point Visual Acuity). A total of 51 variables were available for analysis. Of these 51 variables, only 48 variables were used in this analysis. The three variables excluded from this analysis were Palm Writing Total Dominant, Palm Writing Total Non-Dominant, and Lateral Preference. The Palm Writing variables were excluded due to communality with other variables that exceeded 1.0 (Palm Writing Number and Palm Writing Letters). The Lateral Preference variable was excluded since it is primarily a descriptive variables rather than a continuous variable, like all other variables. In some preliminary analysis that included these variables, there was difficulty in deriving a solution due to reaching the maximum iteration limit. It was noticed in these preliminary studies the Lateral Preference scale did not load on any factors with other SMB variables.

Procedure. SPSS 9.0 (1999) was used to perform the factor analysis and analyze all demographic information and descriptive statistics. All variables used in the analysis were initially screened for outliers and data entering errors. To control for age related variance, the age variable was regressed on the raw score for each SMB test used in the analysis. The residuals of this regression analysis were saved as variables. In the transformation process, these variables were transformed into z-scores, which made the mean of all tests equal to 0 and the standard deviation equal to 1. The transformation used on these variables was performed for all variables used in Study 1 and Study 2. It has been suggested that this transformational procedure provides more accurate scores than raw scores or standard scores (Keith, 2001; Jensen & Sinha, 1993). Additionally, a linear trend-at-point data interpolation procedure was used to replace missing values. This procedure replaces missing values by regressing the existing series on an index variable scaled 1 to n. Missing values are replaced with its predicted values. This procedure was also used for all variables in Study 1 and Study 2.

Principle axis factoring was used as the factor analytic extraction procedure. Often, principle components is used for exploratory factor analysis. However, this extraction procedure is biased toward finding a general or single factor solution (Gorsuch, 1983). This procedure was not used because the SMB is known based on theory (Dean & Woodcock, 2000) and empirical research (Hill, Dean, & Woodcock, 2001) to have more than a single factor solution. It should be noted, however, that past research on the SMB did use a principle components procedure in finding a three-factor solution. Since this procedure maximizes the probability of deriving a single factor solution, it is likely this study underestimated the number of factor in the SMB. In addition, the present study focused on the unique factors measured by the SMB and not necessarily the most efficient means of collapsing the variance into a single factor, as is the case with principle components procedure. Additionally, principle axis factoring is similar to most other extraction procedure in that it adequately captures shared variance among multiple factors (Gorsuch, 1983). The derived factor solution was rotated to clarify interpretation with varimax rotation. Factor coefficients were sorted by size and only coefficients of .30 or greater were reported.

Results and Discussion

Age corrected scores were saved as standardized residual scores for both factor analyses. Therefore, means for all tests were approximately 0 with a SD of 1. Initial means and standard deviations can be found in Table 5. Results from the rotated factor analysis are presented in Table 6. Tests are listed in order of factor importance. Twelve factors were extracted. Nine of the factors had eigenvalues greater than 1.0. The interpretation of a factor was based on the variables related to the factor and salient loadings of different tests on each factor (Gorsuch, 1983). Although there are various heuristics for factor interpretation (i.e. scree plot or eigenvalue greater than one) the full range of extracted factors were considered since this step in the research was largely exploratory. Although all extracted factors were considered, traditional guidelines were used in that smaller factors, although interpreted, were given less emphasis than larger factors (Gorsuch, 1983). Additionally, factors that adhered to theoretical specifications of the sensory-motor battery but had eigenvalues less than 1.0 were still interpreted and considered a valid factor. An additional exploratory analysis was conducted to aid in the number of factors to retain. Model fit indices for 1 to 12 factors were computed. The results of this analysis can be found in Table 7.

Several important observations about the SMB can be made from this factor analysis. The first observation is that the first factor extracted consists of both sensory and motor variables. This may suggest certain tests of sensory and motor functioning, although conceptualized as distinct constructs, actually have a high degree of shared variance. The first factor extracted may represent a dimension common to both sensory and motor tests or it may represent a higher-order factor that is correlated with both sensory and motor tests. This can be better investigated with the confirmatory models in Section B. Another important finding is that by all reasonable criteria, the SMB seem to consist of a least 3 factors and at most 7 that most parsimoniously accounts for the variance in the test but also consists of up to 12 factors that are readily interpretable. Also, many tests considered to measure a single construct, may in fact measure several constructs. For instance, Simultaneous Localization (SL) test may consist of a simple SL, a complex SL, and a cross-lateral SL. Similarly, there seems to be some evidence to suggest Palm Writing Letters and Palm Writing Numbers measure two different constructs.

The first factor extracted consisted of both sensory and motor tests. This is somewhat surprising and it is difficult to determine why these particular sensory and motor tests are related rather than other sensory and motor tests. Additionally, it is difficult to determine why a sensory test that involves identifying numbers in the palm of the hand (Palm Writing Numbers) should be related to a motor test that involves drawing a cross or a clock (Construction A & B). A possible common element among the tests loading on the first factor appears to be related to sensory and motor acts involving the hand or the arm. Many of these tests also required a naming or identifying facility (e.g. Naming Picture of Objects, Object Identification, Palm Writing Numbers) or memory retrieval (e.g. Cross and Clock Construction and Mime Movements).