Carroll Human Cognitive Abilities Project

Institute for Applied Psychometrics

Evans Consulting

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Internal and External Factorial Extensions to the Cattell-Horn-Carroll (CHC) Theory of Cognitive Abilities: A Review of Factor Analytic Research Since Carroll's Seminal 1993 Treatise

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The *Carroll Human Cognitive Abilities* project (HCA) was initiated by the Institute for Applied Psychometrics (IAP) in the fall of 2002. The goal of the HCA Project is to build upon the past 60+ years of factor analytic research on the structure of human cognitive abilities (research which was recently summarized and integrated in John B. Carroll's (1993) seminal Human Cognitive Abilities: A Survey of Factor Analytic Studies) and to extend this line of research into the future. The primary goals of the project are to:

- Electronically archive and document the 460+ datasets used in Carroll's seminal review so they can be made available for secondary analysis by students and researchers in the area of human cognitive abilities
- Supplement Carroll's 460+ (largely pre-1985) datasets with additional datasets published since the mid-1980's in order to extend and expand the pool of datasets available for analysis regarding the structure of human cognitive abilities.
- Establish a CHC HCA "Work Group" that will develop long-term plans for: (a) retrospective re-analysis of the 460+ datasets analyzed by Carroll with contemporary statistical methods (e.g., confirmatory factor analysis) and (b) prospective analysis of contemporary (post-1985+) datasets
- Produce manuscripts intended to refine and extend the understanding of the nature of the broad and narrow abilities subsumed by the CHC theory of human cognitive abilities.

Additional information about the HCA project can be found at:
http://www.iapsych.com/chchca.htm

Cattell-Horn-Carroll (CHC) Theory

The Cattell-Horn-Carroll (CHC) theory of cognitive abilities is widely recognized as the most empirically validated theoretical structural model of human cognitive abilities. CHC theory has evolved from over 100 years of psychometric-based research. Previously recognized as *Gf-Gc* theory, the Cattell-Horn *Gf-Gc* (Horn, 1991; Horn & Noll, 1997) and Carroll three-stratum models of cognitive abilities (Carroll, 1993, 1997) have recently been integrated under a common theoretical umbrella (viz., Cattell-Horn-Carroll theory) (McGrew, in press).

CHC theory is a hierarchical framework of human cognitive abilities that consists of three strata: general intelligence or *g* (stratum III), broad cognitive abilities (stratum II), and narrow cognitive abilities (stratum I). The broad cognitive abilities include Fluid Reasoning (*Gf*), Comprehension-Knowledge (*Gc*), Short-term Memory (*Gsm*), Visual Processing (*Gv*), Auditory Processing (*Ga*), Long-term Retrieval (*Glr*), Processing Speed (*Gs*), and Decision/Reaction Time or Speed (*Gt*), Reading and Writing (*Grw*), and Quantitative Knowledge (*Gq*) (Carroll, 1993, 1997; 2003; Horn & Noll, 1997; McGrew, 1997; McGrew, in press;). The broad cognitive abilities subsume approximately 70 narrow cognitive abilities. It is important to note that the primary architects of CHC theory (Horn and Carroll) do not agree on the validity of *g*. Carroll's model includes a higher-order general intelligence factor while Horn argues against the validity of *g*.

Carroll's 1993 Principia Cognitive Abilities

Carroll's (1993) book, *Human cognitive abilities: A survey of factor-analytic studies*, may represent in the field of applied psychometrics, a work similar in stature to other noted "principia" publications in other fields (e.g., Newton's three volume, *The Mathematical Principles of Natural Philosophy,* or *Principia* as it became known; Whitehead & Russell's, *Principia Mathematica*; see section D in table 1).

Briefly, Carroll summarized a review and reanalysis of more than 460 different data sets that included nearly all the more important and classic factor analytic studies of human cognitive abilities. Carroll proposed a three-tier model of human cognitive abilities that differentiated abilities as a function of breadth. At the broadest level (stratum III) is a *general* intelligence factor (*g*). Next in breadth are eight *broad* abilities that represent "basic constitutional and long-standing characteristics of individuals that can govern or influence a great variety of behaviors in a given domain" (Carroll, 1993, p. 634). Stratum level II includes the abilities of Fluid Intelligence (*Gf*), Crystallized Intelligence (*Gc*), General

Memory and Learning (*Gy*), Broad Visual Perception (*Gv*), Broad Auditory Perception (*Ga*), Broad Retrieval Ability (*Glr*), Broad Cognitive Speediness (*Gs*), and Reaction Time/Decision Speed *(Gt*). Finally, stratum level I includes over 69 *narrow* abilities that are subsumed by the stratum II abilities, which in turn are subsumed by the single stratum III *g* factor.

Intelligence scholars have recognized the importance of Carroll's factor analytic research synthesis. Richard Snow stated that "John Carroll has done a magnificent thing. He has reviewed and reanalyzed the world's literature on individual differences in cognitive abilities…no one else could have done it… it defines the taxonomy of cognitive differential psychology for many years to come." Burns (1994) stated that Carroll's book "is simply the finest work of research and scholarship I have read and is destined to be *the classic study and reference work* on human abilities for decades to come" (p. 35). Horn (1998) described Carroll's (1993) work as a "tour de force summary and integration" that is the "definitive foundation for current theory" (p. 58) and compared Carroll's summary to "Mendelyev's first presentation of a periodic table of elements in chemistry" (p. 58). Jensen (2004) stated that "on my first reading this tome, in 1993, I was reminded of the conductor Hans von Bülow's exclamation on first reading the full orchestral score of Wagner's *Die Meistersinger*, ''It's impossible, but there it is!'' Finally, according to Jensen (2004):

> Carroll's magnum opus thus distills and synthesizes the results of a century of factor analyses of mental tests. It is virtually the grand finale of the era of psychometric *description and taxonomy* of human cognitive abilities. It is unlikely that his monumental feat will ever be attempted again by anyone, or that it could be much improved on. It will long be the key reference point and a solid foundation for the *explanatory* era of differential psychology that we now see burgeoning in genetics and the brain sciences (p. 5).

According to Lubinski (2000), "Carroll's (1993) three-stratum theory is, in many respects, not new. Embryonic outlines are seen in earlier psychometric work (Burt, Cattell, Guttman, Humphreys, and Vernon, among others). But the empirical bases for Carroll's (1993) conclusions are unparalleled; readers should consult this source for a systematic detailing of more molecular abilities" (p. 412). In a sense, Carroll provided the field of intelligence a much needed *Rosetta stone* that can serve as a key in deciphering and organizing the mass of human cognitive abilities structural literature that has accumulated since the days of Spearman.

CHC Abilities Defined

As part of the Carroll *Human Cognitive Abilities* (HCA) project (www.iapsych.com/chchca.htm), the Institute for Applied Psychometrics (IAP), in conjunction with Evans Consulting, initiated the *Cattell-Horn-Carroll (CHC) Definition Project* (www.iapsych.com/chcdef.htm). The primary goal of the CHC Definition Project is to continue the legacy of intelligence scholars who have contributed to the development of the CHC (*Gf-Gc*) taxonomy of human cognitive abilities, via the provision of a clearinghouse mechanism by which to reach consensus definitions of the major narrow (stratum I) and broad (stratum II) abilities that have been identified. Originally based on Carroll's (1993) treatise on the factor structure of human cognitive abilities, and organized as per the CHC taxonomy (McGrew, 1997; McGrew, in press), a set of working definitions for the broad and narrow CHC abilities has been developed. These working definitions are summarized in Table 1.

Table 1. Broad (stratum II) and Narrow (stratum I) Cattell-Horn-Carroll (CHC) Ability Definitions

Fluid Intelligence/Reasoning (*Gf*): The use of deliberate and controlled mental operations to solve novel "on the spot" problems (i.e., tasks that cannot be performed automatically). Mental operations often include drawing inferences, concept formation, classification, generating and testing hypothesis, identifying relations, comprehending implications, problem solving, extrapolating, and transforming information. Inductive (inference of a generalized conclusion from particular instances) and deductive reasoning (the deriving of a conclusion by reasoning; specifically: inference in which the conclusion about particulars follows necessarily from general or universal premises) are generally considered the hallmark indicators of *Gf*. *Gf* has been linked to *cognitive complexity* which can be defined as a greater use of a wide and diverse array of elementary cognitive processes during performance.

<u>General Sequential (deductive) Reasoning (RG):</u> Ability to start with stated assertions (rules, premises, or conditions) and to engage in one or more steps leading to a solution to a problem. The processes are deductive as evidenced in the ability to reason and draw conclusions from given general conditions or premises to the specific. Often known as hypothetico-deductive reasoning.

<u>Induction (I):</u> Ability to discover the underlying characteristic (e.g., rule, concept, principle, process, trend, class membership) that underlies a specific problem or a set of observations, or to apply a previously learned rule to the problem. Reasoning from specific cases or observations to general rules or broad generalizations. Often requires the ability to combine separate pieces of information in the formation of inferences, rules, hypotheses, or conclusions.

<u>Quantitative Reasoning (RQ):</u> Ability to inductively (I) and/or deductively (RG) reason with concepts involving mathematical relations and properties.

<u>Piagetian Reasoning (RP):</u> Ability to demonstrate the acquisition and application (in the form of logical thinking) of cognitive concepts as defined by Piaget's developmental cognitive theory. These concepts include seriation (organizing material into an orderly series that facilitates understanding of relationships between events), conservation (awareness that physical quantities do not change in amount when altered in appearance), classification (abilty to organize materials that possess similar characteristics into categories), etc.

<u>Speed of Reasoning (RE):</u> Speed or fluency in performing reasoning tasks (e.g., quickness in generating as many possible rules, solutions, etc., to a problem) in a limited time. Also listed under *Gs*.

Crystallized Intelligence/Knowledge (*Gc*): "Can be thought of as the intelligence of the culture that is incorporated by individuals through a process of acculturation" (Horn, 1994, p.443). *Gc* is typically described as a person's wealth (breadth and depth) of acquired knowledge of the language, information and concepts of specific a culture, and/or the application of this knowledge. *Gc* is primarily a store of verbal or language-based declarative (knowing "what") and procedural (knowing "how") knowledge acquired through the "investment" of other abilities during formal and informal educational and general life experiences.

<u>Language Development (LD):</u> General development or understanding and application of words, sentences, and paragraphs (not requiring reading) in spoken native language skills to express or communicate a thought or feeling.

<u>Lexical Knowledge (VL):</u> Extent of vocabulary (nouns, verbs, or adjectives) that can be understood in terms of correct word (semantic) meanings. Although evidence indicates that vocabulary knowledge is a separable component from LD, it is often difficult to disentangle these two highly corrected abilities in research studies.

<u>Listening Ability (LS):</u> Ability to listen and understand the meaning of oral communications (spoken words, phrases, sentences, and paragraphs). The ability to receive an understand spoken information.

<u>General (verbal) Information (K0):</u> Range of general stored knowledge (primarily verbal).

<u>Information about Culture (K2):</u> Range of stored general cultural knowledge (e.g., music, art).

<u>Communication Ability (CM):</u> Ability to speak in "real life" situations (e.g., lecture, group participation) in a manner that transmits ideas, thoughts, or feelings to one or more individuals.

<u>Oral Production and Fluency (OP):</u> More specific or narrow oral communication skills than reflected by CM.

<u>Grammatical Sensitivity (MY):</u> Knowledge or awareness of the distinctive features and structural principles of a native language that allows for the construction of words (morphology) and sentences (syntax). Not the skill in applying this knowledge.

<u>Foreign Language Proficiency (KL):</u> Similar to Language Development but for a foreign language.

<u>Foreign Language Aptitude (LA):</u> Rate and ease of learning a new language.

General (domain-specific) Knowledge (*Gkn*): An individual's breadth and depth of acquired knowledge in specialized (demarcated) domains that typically do no represent the general universal experiences of individuals in a culture (*Gc*). *Gkn* reflects deep specialized knowledge domains developed through intensive systematic practice and training (over an extended period of time) and the maintenance of the knowledge base through regular practice and motivated effort. The primary distinction between *Gc* and *Gkn* is the extent to which acquired knowledge is a function of the degree of cultural universality. *Gc* primarily reflects general knowledge accumulated via the experience of cultural universals.

Knowledge of English a Second Language (KE): Degree of knowledge of English as a second language.

Knowledge of Signing (KF): Knowledge of finger-spelling and signing (e.g., ASL) used in communication with the deaf or hard of hearing.

Skill in Lip-reading (LP): Competence in ability to understand communication from others by watching the movement of their mouths and expressions (lip-reading). Also known as speech-reading.

Geography Achievement (A5): Range of geography knowledge (e.g., capitals of countries).

General Science Information (K1): Range of stored scientific knowledge (e.g., biology, physics, engineering, mechanics, electronics).

Mechanical Knowledge (MK): Knowledge about the function, terminology and operation of ordinary tools, machines, and equipment. Since these factors were identified in research prior to the information/technology explosion, it is unknown if this ability generalizes to the use of modern technology (e.g., faxes, computers, internet).

Knowledge of Behavioral Content (BC): Knowledge or sensitivity to nonverbal human communication/interaction systems (beyond understanding sounds and words; e.g., facial expressions and gestures) that communicate feelings, emotions, and intentions, most likely in a culturally patterned style.

Visual-Spatial Abilities (*Gv*): "The ability to generate, retain, retrieve, and transform well-structured visual images" (Lohman, 1994, p.1000). The *Gv* domain represents a collection of different abilities each that emphasize a different process involved in the generation, storage, retrieval and transformation (e.g., mentally reverse or rotate shapes in space) of visual images. *Gv* abilities are measured by tasks (figural or geometric stimuli) that require the perception and transformation of visual shapes, forms, or images and/or tasks that require maintaining spatial orientation with regard to objects that may change or move through space.

Visualization (Vz): The ability to apprehend a spatial form, object, or scene and match it with another spatial object, form, or scene with the requirement to rotate it (one or more times) in two or three dimensions. Requires the ability to mentally imagine, manipulate or transform objects or visual patterns (without regard to speed of responding) and to "see" (predict) how they would appear under altered conditions (e.g., parts are moved or rearranged). Differs from Spatial Relations primarily by a de-emphasis on fluency.

Spatial Relations (SR): Ability to rapidly perceive and manipulate (mental rotation, transformations, reflection, etc.) visual patterns or to maintain orientation with respect to objects in space. SR may require the identification of an object when viewed from different angles or positions.

Closure Speed (CS): Ability to quickly identify a familiar meaningful visual object from incomplete (vague, partially obscured, disconnected) visual stimuli, without knowing in advance what the object is. The target object is assumed to be represented in the person's long-term memory store. The ability to "fill in" unseen or missing parts in a disparate perceptual field and form a single percept.

Flexibility of Closure (CF): Ability to identify a visual figure or pattern embedded in a complex distracting or disguised visual pattern or array, when knowing in advance what the pattern is. Recognition of, yet the ability to ignore, distracting background stimuli is part of the ability.

Visual Memory (MV): Ability to form and store a mental representation or image of a visual shape or configuration (typically during a brief study period), over at least a few seconds, and then recognize or recall it later (during the test phase).

Spatial Scanning (SS): Ability to quickly and accurately survey (visually explore) a wide or complicated spatial field or pattern and identify a particular configuration (path) through the visual field. Usually requires visually following the indicated route or path through the visual field.

Serial Perceptual Integration (PI): Ability to identify (and typically name) a pictorial or visual pattern when parts of the pattern are presented rapidly in serial order (e.g., portions of a line drawing of a dog are passed in sequence through a small "window").

Length Estimation (LE): Ability to accurately estimate or compare visual lengths or distances without the aid of measurement instruments.

Perceptual Illusions (IL): The ability to resist being affected by the illusory perceptual aspects of geometric figures (i.e., not forming a mistaken perception in response to some characteristic of the stimuli). May best be thought of as a person's "response tendency" to resist perceptual illusions.

Perceptual Alternations (PN): Consistency in the rate of alternating between different visual perceptions.

Imagery (IM): Ability to mentally depict (encode) and/or manipulate an object, idea, event or impression (that is not present) in the form of an abstract spatial form. Separate IM level and rate (fluency) factors have been suggested (see chapter text).

Auditory Processing (*Ga*): Abilities that "depend on sound as input and on the functioning of our hearing apparatus" (Stankov, 1994, p. 157). A key characteristic of *Ga* abilities is the extent an individual can cognitively "control" (i.e., handle the competition between "signal" and "noise") the perception of auditory information (Gustafsson and Undheim, 1996), The *Ga* domain circumscribes a wide range of abilities involved in discriminating patterns in sounds and musical structure (often under background noise and/or distorting conditions) and the ability to analyze, manipulate, comprehend and synthesize sound elements, groups of sounds, or sound patterns. Although *Ga* abilities play an important role in the development language abilities (*Gc*), *Ga* abilities do not require the comprehension of language (*Gc*).

Phonetic Coding (PC): Ability to code, process, and be sensitive to nuances in phonemic information (speech sounds) in short-term memory. Includes the ability to identify, isolate, blend, or transform sounds of speech. Frequently referred to as phonological or phonemic awareness.

Speech Sound Discrimination (US): Ability to detect and discriminate differences in phonemes or speech sounds under conditions of little or no distraction or distortion.

Resistance to Auditory Stimulus Distortion (UR): Ability to overcome the effects of distortion or distraction when listening to and understanding speech and language. It is often difficult to separate UR from US in research studies.

Memory for Sound Patterns (UM): Ability to retain (on a short-term basis) auditory events such as tones, tonal patterns, and voices.

General Sound Discrimination (U3): Ability to discriminate tones, tone patterns, or musical materials with regard to their fundamental attributes (pitch, intensity, duration, and rhythm).

Temporal Tracking (UK): Ability to mentally track auditory temporal (sequential) events so as to be able to count, anticipate or rearrange them (e.g., reorder a set of musical tones). According to Stankov (2000), UK may represent the first recognition of the ability (Stankov & Horn, 1980) that is now interpreted as working memory (MW).

Musical Discrimination and Judgment (U1 U9): Ability to discriminate and judge tonal patterns in music with respect to melodic, harmonic, and expressive aspects (e.g., phrasing, tempo, harmonic complexity, intensity variations).

Maintaining and Judging Rhythm (U8): Ability to recognize and maintain a musical beat.

Sound-Intensity/Duration Discrimination (U6): Ability to discriminate sound intensities and to be sensitive to the temporal/rhythmic aspects of tonal patterns.

Sound-Frequency Discrimination (U5): Ability to discriminate frequency attributes (pitch and timbre) of tones.

Hearing and Speech Threshold factors (UA UT UU): Ability to hear pitch and varying sound frequencies.

Absolute Pitch (UP): Ability to perfectly identify the pitch of tones.

Sound Localization (UL): Ability to localize heard sounds in space.

Short-term Memory (*Gsm*): The ability to apprehend and maintain awareness of elements of information in the immediate situation (events that occurred in the last minute or so). A limited-capacity system that loses information quickly through the decay of memory traces, unless an individual activates other cognitive resources to maintain the information in immediate awareness.

Memory Span (MS): Ability to attend to, register, and immediately recall (after only one presentation) temporally ordered elements and then reproduce the series of elements in correct order.

Working Memory (MW): Ability to temporarily store and perform a set of cognitive operations on information that requires divided attention and the management of the limited capacity resources of short-term memory. Is largely recognized to be the mind's "scratchpad" and consists of up to four subcomponents. The *phonological or articulatory loop* processes auditory-linguistic information while the *visuo-spatial sketch/scratchpad* is the temporary buffer for visually processed information. The *central executive* mechanism coordinates and manages the activities and processes in working memory. The most recent component added to the model is the *episodic buffer*. Recent research (see chapter text) suggests that MW is *not* of the same nature as the other 60+ narrow factor-based trait-like individual difference constructs included in this table. MW is a theoretically developed construct (proposed to explain memory findings from experimental research) and not a label for an individual-differences type factor. MW is retained in the current CHC taxonomy table as a reminder of the importance of this construct in understanding new learning and performance of complex cognitive tasks (see chapter text).

Long-term Storage and Retrieval (*Glr*): The ability to store and consolidate new information in long-term memory and later fluently retrieve the stored information (e.g., concepts, ideas, items, names) through association. Memory consolidation and retrieval can be measured in terms of information stored for minutes, hours, weeks, or longer. Horn (Horn & Masunaga, 2000) differentiates two major types of *Glr*--fluency of retrieval of information over minutes or a few hours (intermediate memory) and fluency of association in retrieval from storage over days, months or years. Ekstrom et al. (1979) distinguished two additional characteristic processes of *Glr*: "(1) reproductive processes, which are concerned with retrieving stored facts, and (2) reconstructive processes, which involve the generation of material based on stored rules" (p. 24). *Glr* abilities have been prominent in creativity research where they have been referred to as idea production, ideational fluency, or associative fluency.

Associative Memory (MA): Ability to recall one part of a previously learned but unrelated pair of items (that may or may not be meaningfully linked) when the other part is presented (e.g., paired-associative learning).

Meaningful Memory (MM): Ability to note, retain, and recall information (set of items or ideas) where there is a meaningful relation between the bits of information, the information comprises a meaningful story or connected discourse, or the information relates to existing contents of memory.

Free Recall Memory (M6): Ability to recall (without associations) as many unrelated items as possible, in any order, after a large collection of items is presented (each item presented singly). Requires the ability to encode a "superspan collection of material" (Carroll, 1993, p. 277) that cannot be kept active in short-term or working memory.

Ideational Fluency (FI): Ability to rapidly produce a series of ideas, words, or phrases related to a specific condition or object. Quantity, not quality or response originality is emphasized. The ability to think of a large number of different responses when a given task requires the generation of numerous responses. Ability to call up ideas.

Associational Fluency (FA): A highly specific ability to rapidly produce a series of words or phrases associated in meaning (semantically associated; or some other common semantic property) when given a word or concept with a restricted area of meaning. In contrast to Ideational Fluency, quality rather quantity of production is emphasized.

Expressional Fluency (FE): Ability to rapidly think of and organize words or phrases into meaningful complex ideas under general or more specific cued conditions. Requires the production of connected discourse in contrast to the production of isolated words (e.g., FA FW). Differs from FI in the requirement to rephrase given ideas rather than generating new ideas. The ability to produce different ways of saying much the same thing.

Naming Facility (NA): Ability to rapidly produce accepted names for concepts or things when presented with the thing itself or a picture of it (or cued in some other appropriate way). The naming responses must be in an individuals long-term memory store (i.e., objects or things to be named have names that are very familiar to the individual). In contemporary reading research is ability is called ***rapid automatic naming*** (RAN).

Word Fluency (FW): Ability to rapidly produce isolated words that have specific phonemic, structural, or orthographic characteristics (independent of word meanings). Has been mentioned as possibly being related to the "tip-of-the-tongue" phenomenon (Carroll, 1993). One of the first fluency abilities identified (Eckstrom et al., 1979)

Figural Fluency (FF): Ability to rapidly draw or sketch as many things (or elaborations) as possible when presented with a non-meaningful visual stimulus (e.g., set of unique visual elements). Quantity is emphasized over quality or uniqueness.

Figural Flexibility (FX): Ability to rapidly change set and try-out a variety of approaches to solutions for figural problems that have several stated criteria. Fluency in successfully dealing with figural tasks that require a variety of approaches to a given problem.

Sensitivity to Problems (SP): Ability to rapidly think of a number of alternative solutions to practical problems (e.g., different uses of a given tool). More broadly may be considered the "ability to imagine problems associated with function or change of function of objects and to suggest ways to deal with these problems" Royce (1973). Requires the recognition of the existence of a problem.

Originality/Creativity (FO): Ability to rapidly produce unusual, original, clever, divergent, or uncommon responses (expressions, interpretations) to a given topic, situation, or task. The ability to invent unique solutions to problems or to develop innovative methods for situations where a standard operating procedure does not apply. Following a new and unique path to a solution. FO differs from FI in that FO focuses on the quality of creative responses while FI focuses on an individual's ability to think of a large number of different responses.

Learning Abilities (L1): General learning ability rate. Poorly defined by existing research.

Cognitive Processing Speed (*Gs*): The ability to automatically and fluently perform relatively easy or over-learned cognitive tasks, especially when high mental efficiency (i.e., attention and focused concentration) is required. The speed of executing relatively over-learned or automatized elementary cognitive processes.

Perceptual Speed (P): Ability to rapidly and accurately search, compare (for visual similarities or differences) and identify visual elements presented side-by-side or separated in a visual field. Recent research (Ackerman et al., 2002; Ackerman & Cianciolo, 2000; see chapter text) suggests P may be an *intermediate* stratum ability (between narrow and broad) defined by four narrow sub-abilities: (1) *Pattern Recognition (Ppr)*--the ability to quickly recognize simple visual patterns; (2) *Scanning (Ps)*—ability to scan, compare, and look up visual stimuli; (3) *Memory (Pm)*--ability to perform visual perceptual speed tasks that place significant demands on immediate short-term memory, and (d) *Complex (Pc)*—ability to perform visual pattern recognition tasks that impose additional cognitive demands such as spatial visualization, estimating and interpolating, and heightened memory span loads.

Rate-of-Test-Taking (R9): Ability to rapidly perform tests which are relatively easy or over-learned (require very simple decisions). This ability is not associated with any particular type of test content or stimuli. May be similar to a higher-order "psychometric time" factor (Roberts & Stankov, 1998; Stankov, 2000). Recent research has suggested that R9 may better be classified as an *intermediate* (between narrow and broad strata) ability that subsumes most all psychometric speeded measures (see chapter text).

Number Facility (N): Ability to rapidly perform basic arithmetic (i.e., add, subtract, multiply, divide) and accurately manipulate numbers quickly. N does not involve understanding or organizing mathematical problems and is not a major component of mathematical/quantitative reasoning or higher mathematical skills.

Speed of Reasoning (RE): Speed or fluency in performing reasoning tasks (e.g., quickness in generating as many possible rules, solutions, etc., to a problem) in a limited time. Also listed under *Gf*.

Reading Speed (fluency) (RS): Ability to silently read and comprehend connected text (e.g., a series of short sentences; a passage) rapidly and automatically (with little conscious attention to the mechanics of reading). Also listed under *Grw*.

Writing Speed (fluency) (WS): Ability to copy correctly words or sentences repeatedly, or writing words, sentences, or paragraphs, as quickly as possible. Also listed under *Grw* and *Gps*.

Decision/Reaction Time or Speed (*Gt*): The ability to react and/or make decisions quickly in response to simple stimuli, typically measured by chronometric measures of reaction and inspection time. In psychometric methods, quickness in providing answers (correct or incorrect) to tasks of trivial difficult (CDS; correct decision speed)—may relate to cognitive tempo.

Simple Reaction Time (R1): Reaction time (in milliseconds) to the onset of a single stimulus (visual or auditory) that is presented at a particular point of time. R1 frequently is divided into the phases of decision time (DT; the time to decide to make a response and the finger leaves a home button) and movement time (MT; the time to move finger from the home button to another button where the response is physically made and recorded).

Choice Reaction Time (R2): Reaction time (in milliseconds) to the onset of one of two or more alternative stimuli, depending on which alternative is signaled. Similar to R1, can be decomposed into DT and MT. A frequently used experimental method for measuring R2 is the Hick paradigm.

Semantic Processing Speed (R4): Reaction time (in milliseconds) when a decision requires some encoding and mental manipulation of the stimulus content.

Mental Comparison Speed (R7): Reaction time (in milliseconds) where stimuli must be compared for a particular characteristic or attribute.

Inspection Time (IT): The ability to quickly (in milliseconds) detect change or discriminate between alternatives in a very briefly displayed stimulus (e.g., two different sized vertical lines joined horizontally across the top).

Psychomotor Speed (*Gps*): The ability to rapidly and fluently perform body motor movements (movement of fingers, hands, legs, etc.) independent of cognitive control.

Speed of Limb Movement (R3): The ability to make rapid specific or discrete motor movements of the arms or legs (measured after the movement is initiated). Accuracy is not important.

Writing Speed (fluency) (WS): Ability to copy correctly words or sentences repeatedly, or writing words, sentences, or paragraphs, as quickly as possible. Also listed under *Grw* and *Gps*.

Speed of Articulation (PT): Ability to rapidly perform successive articulations with the speech musculature.

Writing Speed (fluency) (WS): Ability to to copy words or sentences repeatedly, or writing words, sentences, or paragraphs, as quickly as possible. Also listed under *Grw* and *Gs*.

Movement Time (MT): Recent research (see summaries by Deary, 2003; Nettelbeck, 2003; see chapter text) suggests MT may be an intermediate stratum ability (between narrow and broad strata) that represents the second phase of reaction time as measured by various elementary cognitive tasks (ECTs). The time taken to physically move a body part (e.g., a finger) to make the required response is movement time (MT). MT may also measure the speed of finger, limb, or multi-limb movements or vocal articulation (diadochokinesis; Greek for "successive movements") (Carroll, 1993; Stankov, 2000) and is also listed under *Gt*.

Quantitative Knowledge (*Gq*): A person's wealth (breadth and depth) of acquired store of declarative and procedural quantitative knowledge. *Gq* is largely acquired through the "investment" of other abilities primarily during formal educational experiences. It is important to recognize that RQ, which is the ability to reason inductively and deductively when solving quantitative problems, is not included under *Gq*, but rather, is included in the *Gf* domain. *Gq* represents an individual's store of acquired mathematical knowledge, not reasoning with this knowledge.

<u>Mathematical Knowledge (KM):</u> Range of general knowledge about mathematics. Not the performance of mathematical operations or the solving of math problems.

<u>Mathematical Achievement (A3):</u> Measured (tested) mathematics achievement.

Reading/Writing (*Grw*): A person's wealth (breadth and depth) of acquired store of declarative and procedural reading and writing skills and knowledge. *Grw* includes both basic skills (e.g., reading and spelling of single words) and the ability to read and write complex connected discourse (e.g., reading comprehension and the ability to write a story).

<u>Reading Decoding (RD):</u> Ability to recognize and decode words or pseudowords in reading using a number of sub-abilities (e.g., grapheme encoding, perceiving multi-letter units, and phonemic contrasts, etc.)

<u>Reading Comprehension (RC):</u> Ability to attain meaning (comprehend and understand) connected discourse during reading.

<u>Verbal (printed) Language Comprehension (V):</u> General development, or the understanding of words, sentences, and paragraphs in native language, as measured by reading vocabulary and reading comprehension tests. Does not involve writing, listening to, or understanding spoken information.

<u>Cloze Ability (CZ):</u> Ability to read and supply missing words (that have been systematically deleted) from prose passages. Correct answers can only be supplied if the person understands (comprehends) the meaning of the passage.

<u>Spelling Ability (SG):</u> Ability to form words with the correct letters in accepted order (spelling).

<u>Writing Ability (WA):</u> Ability to communicate information and ideas in written form so that others can understand (with clarity of thought, organization, and good sentence structure). Is a broad ability that involves a number of other writing subskills (knowledge of grammar, the meaning of words, and how to organize sentences or paragraphs).

<u>English Usage Knowledge (EU):</u> Knowledge of the "mechanics" (capitalization, punctuation, usage, and spelling) of written and spoken English language discourse.

<u>Reading Speed (fluency) (RS):</u> Ability to silently read and comprehend connected text (e.g., a series of short sentences; a passage) rapidly and automatically (with little conscious attention to the mechanics of reading). Also listed under *Gs*.

<u>Writing Speed (fluency) (WS):</u> Ability to copy words or sentences repeatedly, or writing words, sentences, or paragraphs, as quickly as possible. Also listed under *Gs* and *Gps*.

Psychomotor Abilities (*Gp*): The ability to perform body motor movements (movement of fingers, hands, legs, etc) with precision, coordination, or strength.

<u>Static Strength (P3):</u> The ability to exert muscular force to move (push, lift, pull) a relatively heavy or immobile object.

<u>Multi-limb Coordination (P6):</u> The ability to make quick specific or discrete motor movements of the arms or legs (measured after the movement is initiated). Accuracy is not relevant.

<u>Finger Dexterity (P2):</u> The ability to make precisely coordinated movements of the fingers (with or without the manipulation of objects).

<u>Manual Dexterity (P1):</u> Ability to make precisely coordinated movements of a hand, or a hand and the attached arm.

<u>Arm-hand Steadiness (P7):</u> The ability to precisely and skillfully coordinate arm-hand positioning in space.

<u>Control Precision (P8):</u> The ability to exert precise control over muscle movements, typically in response to environmental feedback (e.g., changes in speed or position of object being manipulated).

<u>Aiming (AI):</u> The ability to precisely and fluently execute a sequence of eye-hand coordination movements for positioning purposes.

<u>Gross Body Equilibrium (P4):</u> The ability to maintain the body in an upright position in space or regain balance after balance has been disturbed.

Olfactory Abilities (*Go*): Abilities that depend on sensory receptors of the main olfactory system (nasal chambers). The cognitive and perceptual aspects of this domain have not yet been widely investigated (see chapter text)

Olfactory Memory (OM): Memory for odors (smells).
Olfactory Sensitivity (OS): Sensitivity to different odors (smells).

Tactile Abilities (*Gh*): Abilities that depend on sensory receptors of the tactile (touch) system for input and on the functioning of the tactile apparatus. The cognitive and perceptual aspects of this domain have not yet been widely investigated (see chapter text)

Tactile Sensitivity (TS): The ability to detect and make fine discriminations of pressure on the surface of the skin.

Kinesthetic Abilities (*Gk*): Abilities that depend on sensory receptors that detect bodily position, weight, or movement of the muscles, tendons, and joints. The cognitive and perceptual aspects of this domain have not yet been widely investigated.

Kinesthetic Sensitivity (KS): The ability to detect, or be aware, of movements of the body or body parts, including the movement of upper body limbs (arms) and the ability to recognize a path the body previously explored without the aid visual input (blindfolded)

Note. Many of the ability definitions in this table, or portions thereof, were originally published in McGrew (1997), which in turn, were developed from a detailed reading of *Human Cognitive Abilities: A Survey of Factor Analytic Studies*, by J. B. Carroll. 1993, New York: Cambridge University Press, Copyright 1993 by Cambridge University Press. The two-letter narrow (stratum I) ability factor codes (e.g., RG), as well as most of the broad ability factor codes (e.g, *Gf*) are from Carroll (1993). McGrew's (1997) definitions have been revised and extended here based on a review of a number of additional sources. Primary sources included Carroll (1993), Corsini (1999), Ekstrom et al. (1979), Fleishman & Quaintance (1984), and Sternberg (1994). An ongoing effort to refine the CHC definitions of abilities can be found in the form of the *Cattell-Horn-Carroll (CHC) Definition Project* (http://www.iapsych.com/chcdef.htm).

CHC Internal and External Factorial Extensions : A Review of the Literature

CHC theory currently consists of nine broad abilities (*Gf, Gc, Gv, Ga, Gsm, Glr, Gs, Gq, Grw*). Recently, McGrew (in press) reviewed a number of factor analytic studies that provided support for the validity of the broad strokes of the CHC structural model. McGrew (in press) concluded that a variety of large and small sample factor analytic studies published during the past decade, when examined with a CHC lens, support the broad strokes (i.e., broad stratum II abilities) of contemporary CHC theory. The broad abilities of *Gf, Gc, Gv, Ga, Gsm, Glr, Gs, Gq*, an *Grw* have been validated in and across studies that have included a sufficient breadth of CHC indicators to draw valid conclusions.

A review of the factor analytic research during the past decade (1993-2003) also suggests a number of possible extensions to the CHC taxonomy. Following Stankov's (2000) research distinction, structural extensions reported here are classified as either *internal* (i.e., elaboration on the nature of existing well-established broad CHC factors) or *external* (i.e., research that suggests new broad ability domains or domains that have been only been partially investigated).

The purpose of this report is to provide a qualitative narrative review of the structural human intelligence literature since the publication of Carroll's 1993 treatise. This narrative serves as a precursor to more systematic and empirical extensions of Carroll's work via secondary exploratory and confirmatory factor analysis of Carroll's original data sets and new datasets published since the late 1980s. As such, the current report fits within the overriding goals of the HCA (http://www.iapsych.com/chchca.htm) which include:

- Electronically archive and document the 460+ datasets used in Carroll's seminal review so they can be made available for secondary analysis by students and researchers in the area of human cognitive abilities
- Supplement Carroll's 460+ (largely pre-1985) datasets with additional datasets published since the mid-1980's in order to extend and expand the pool of datasets available for analysis regarding the structure of human cognitive abilities.
- Establish a CHC HCA "Work Group" that will develop long-term plans for: (a) retrospective re-analysis of the 460+ datasets analyzed by Carroll with contemporary statistical methods (e.g., confirmatory factor analysis) and (b) prospective analysis of contemporary (post-1985+) datasets
- Produce manuscripts intended to refine and extend the understanding of the nature of the broad and narrow abilities subsumed by the CHC theory of human cognitive abilities.

Internal CHC Structural Extensions

During the past decade, significant factor analytic research has been limited primarily to five well-established CHC domains—*Gv, Ga, Gsm, Gc, and Gs.*

Gv structural extension research

Gv abilities have been cursed by with a schizophrenic relationship with intelligence researchers. Despite inclusion in most all models of human cognitive abilities, and being one of the more studied domains of human cognitive functioning (Carroll, 1993), "spatial abilities have long been relegated to a secondary status in accounts of human intelligence" (Lohman, 1996, p.97). According to Lohman (1996), *Gv's* second class status is due, in part, to the fact that: (1) beyond a minimum level of proficiency, *Gv* abilities do not consistently predict success in school or work,[1] (2) the relations between *Gv* and outcome criteria are dwarfed when other more powerful predictors (e.g., *Gc, Gf*) are included in prediction studies, (3) the typical criterion variables used in prediction studies tend to be biased in favor of verbal and language-based measures, (4) existing *Gv* measures used in studies may be poor measures of visual-spatial functioning, and (5) the typical practice of first entering a *g* proxy in prediction studies may mask potential important *Gv*-outcome relations. The love-hate status *Gv* has experienced in the intelligence research is also due to the fact that *Gv* has concurrently been associated with both highly acclaimed and prestigious achievements in demanding professions such as engineering, architecture, physics, chemistry and mathematics, as well as more pedestrian trades such as carpentry, auto mechanics, and technical/industrial occupations (Lohman, 1996; Shea et al., 2001).

Recently, *Gv* has enjoyed a renaissance in status due to the linkage of high *Gv* abilities with: (1) higher-order thinking in science, math and the achievement, (2) incremental prediction of performance (above and beyond verbal and quantitative abilities) in gifted and talented populations (Shea, Lubinski & Benbow, 2001), and (3) the observation of creative "insights by means of thought experiments on visualized systems of waves and physical bodies in states of relative motion" (Lohman, 1996, p. 99). For example, high spatial ability, particularly the ability to visual complex dynamic systems, has been reported to play a prominent role in the accomplishments of such imminent scientists and inventors as Albert Einstein, Michael Faraday, Herman Von Helmholtz, Benjamin Frankin, Francis Galton and Leonardo da Vinci (Lohman, 1996; West, 1997). As an example, "on several occasions Albert Einstein reported that verbal processes seemed not to play a role in his creative thought. Rather, he claimed that he achieved insights by means of thought experiments on visualized systems of waves and physical bodies in states of relative motion" (Lohman, 1994, p. 1000).

With the exception of studies investigating the role of *Gv* in information processing/working

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[1] However, according to Lohman (1994), tests of spatial abilities are: (1) among some of the best predictors training of machine and bench workers, and air crews, (2) have been moderately associated with grades in engineering and trade schools, and (3) are listed among 84 job categories from the United States Employment Service (1957).

memory models (Lohman, 1996), only a handful of investigations have studied the structural characteristics of the *Gv* domain during the past decade. Juhel (1991), using Carroll-based exploratory factor methods and procedures in a sample of college students, confirmed the existence of the well documented Visualization (Vz), Spatial Relations (SR), and Visual Memory (MV) abilities (see Carroll, 1993; Lohman, 1979; 1996). More importantly, contrasts of subgroups categorized as high or low on Vz and MV reinforced the notion that *Gv* tasks vary as a function of cognitive complexity. Vz abilities were reported to require the most complex cognitive processing (i.e., require greater complex mental manipulations and transformations; load highest on *Gv*). MV was found, in a relative sense, to be a lower level (less complex) ability in the domain of visual-spatial abilities. This finding is consistent with Lohman's (1979) statement, regarding the narrow *Gv* abilities of MV, P, and CS, that these "factors consistently fall near the periphery of scaling representations, or at the bottom of a hierarchical model" (p. 126-127). Although MV may be viewed as an ability of lower stature within the *Gv* domain (e.g., relatively lower *g*-loadings than Vz and SR), Juhel's (1991) research suggested that the more complex *Gv* abilities are partially dependent on, and supported by, MV.

Miyake, Friedman, Rettinger, Shah, Hegarty's (2001) structural equation-based investigation of the relations between measures of information processing and psychometric measures of *Gv* (Vz, SR, P) reinforces the findings of Juhel (1991). These investigators hypothesized (and confirmed) that Vz, SR, and P abilities differed as a function of the relative demands each placed on the working memory system, particularly the visuo-spatial sketchpad and executive function components. Similar to prior research (Carroll, 1993; Lohman, 1979), Miyake et al. (2001) found it difficult to structurally differentiate the Vz and SR factors. However, the Vz and SR factors, as well as the P factor, were clearly differentiated as a function of degree of information processing demands. Miyake et al. (2001) concluded that Vz, SR and P differed in the degree of executive involvement, with Vz requiring the most and P the least. It is possible that the higher complexity attributed to Vz and SR tasks is due to a greater use of verbal analytic processing during these task. Furthermore, the "three spatial abilities require a substantial degree of visuo-spatial storage, but the maintenance of visuo-spatial representations involved in the performance on these spatial ability tests (particularly the Spatial Visualization and Spatial Relations tests) may be strongly tied to executive functioning or controlled attention. Finally, these relations between the WM-related constructs and the spatial ability factors are substantial. In fact, they are so substantial that, together, the Executive Functioning and Visuo-spatial STM-WM variables were able to essentially fully explain the pattern of the intercorrelations between the three spatial ability factors" (Miyake et al. 2001. p 637).

"Imagery refers to the mental depiction or recreation of people, objects, and events that are not actually present" (Finke & Freyd, 1994, p. 561). Visual imagery has been linked to a variety of abilities such as: (1) *Gf*--thinking hypothetically; constructing mental models of complex conceptual systems; "seeing" relationships and solutions to problems, (2) efficient retrieval of *Gc* information, (3) *Gv*--mental rotation of objects or patterns, and (4) mental extrapolations involved in complex motor activities (e.g., driving a car; athletic performance) (Finke & Freyd, 1994). According to Carroll (1993), imagery was not clearly defined by the factor studies available at the time of his review. Following Carroll's (1993) recommendation for further IM research, Burton and Fogarty (2003) reported exploratory and confirmatory factor analysis of 26 cognitive ability measures, 5 self-report visual imagery inventories, 7 experimental imagery tasks, and 2 tasks requiring creative imagery. Consistent with the extant *Gv* structural literature (Carroll, 1993; Lohman, 1979), support was found for the narrow abilities of Vz, SR, MV, and CS. In addition, three first-order IM factors (quality, self-report, and speed) were suggested. The IM (quality) and IM (speed) factors shared moderate amounts of variance with the Vz, SR, MV, and CS factors, while the IM (self-report) factor did not.[2] Burton and Fogarty's (2003) findings are consistent with research that suggests that IM may be a multidimensional construct characterized along the dimensions of generation, vividness, clarity, controllability, transformation and/or maintenance (Kosslyn, 1981; Poltrock & Agnoli, 1986). Burton and Fogerty's study reinforces the specification of the visual IM (i.e., the IM quality factor) ability alongside the other major *Gv* narrow abilities. Left unanswered by this study is whether the IM (quality) and IM (speed) abilities represent the *level* and *rate* aspects of the imagery domain.

Ga structural extension research

In the long history of research on individual differences in human cognitive abilities, *Ga* has played the role of "stepchild" to its elder visual-spatial processing (*Gv*) sibling. According to Carroll (1993), auditory abilities have "received little attention in the factor-analytic literature" (p. 364). Fortunately, interest and research in the *Ga* domain has increased due to: (1) technological advances that have made research in the *Ga* domain easier (Stankov, 1994), (2) an increased interest in the psychophysics of auditory perception (Hirsh & Watson, 1996), (3) an explosion of research focused on the relations between the *Ga* abilities of phonological processing or phonemic awareness (Phonetic Coding-PC as per Carroll, 1993) and early reading development and reading disabilities (see Bus & van IJzendoorn,1999; Ehri, Nunes, Willows, Schuster, Yoghoub-Zadeh & Shanahan, 2001; McBride-Chang, Chang, & Wagner, 1997; McBride-Chang, 1995, 1996; Metsala, Stanovich, & Brown, 1998; Stahl & Murray, 1994; Stone & Brady,1995; Torgesen, Wagner, Rashotte, Rose, Lindamood, Conway & Garvan, 1999; Wagner, Torgesen, Laughon, Simmons & Rashotte, 1993; Wagner, Torgesen &

[2] It is very likely that the IM (self-report) factor represents a "method" factor as it was the only factor defined in this investigation by the subjects self-reports.

Rashotte, 1994), (4) the increased interest in Central Auditory Processing Disorder (CAPD); (Ricco & Hynd, 1996) in the professions of speech-language pathology and audiology, and (5) the inclusion of the *Ga* abilities of pitch, rhythm and sound discrimination in Howard Gardner's (1983) musical and linguistic intelligences.

In 1998, Flanagan and McGrew (McGrew & Flanagan, 1998) were persuaded by a small number of exploratory and confirmatory research studies with young children (Wagner, Torgesen, Laughon, Simmons & Rashotte, 1993; Yopp, 1988) that Phonetic Coding (PC) should be split into two narrow PC abilities—PC:Analysis (PC:A) and PC:Synthesis (PC:S). Research during the past decade, which includes an "about face" by Wagner et al. (1993), now largely supports a unidimensional PC ability.

In a longitudinal study of 244 young children (grades K-2), Wagner, Torgesen and Rashotte (1994) specified their previously hypothesized PC:A and PC:S factors in a confirmatory modeling research study. However, the high latent factor correlations between the two PC abilities proved problematic (high multi-colinearity) when both were included in prediction models. In a subsequent longitudinal investigation of 216 kindergarten thru fourth grade students, Wagner, Torgesen, Rashotte, Hecht, Barker, Burgess, Donahue & Garon (1997) again reported very high PC:A/PC:S latent factor correlations, with the actual correlation approaching a perfect 1.0 at third grade. Wagner et al. (1997) concluded that the two factors were representing the same construct and subsequently respecified their model to include a single PC (phonemic awareness) ability.

The unidimensional interpretation of PC was recently echoed by Van Bon and Van Leeuwe (2003) who may have provided the most comprehensive listing of studies (viz., de Jong & van der Leij, 1999; Høien et al., 1995; Holopainen et al., 2000; Lundberg, Frost & Petersen, 1988; Mommers, 1987; Muter, Hulme, Snowling, & Taylor, 1997; Schatschneider et al., 1999; Stahl & Murray, 1994; Stanovich et al., 1984; Valtin, 1984; Wagner & Torgesen, 1987; Wagner et al., 1997) in support of a unidimensional PC ability. Van Bon and Van Leewe (2003) further report that their independent reanalysis of Yopp's (1988) data supported a single PC ability. The one exception noted in the literature by Van Bon and Van Leeuwe (2003) was the tendency for rhyming abilities to stand separate from PC. Consistent with this conclusion, Hatcher and Hulme's (1999) exploratory factor analysis revealed separate rhyming and phonemic manipulation (PC) factors derived from the five phonological measures used in their study of 124 children experiencing reading difficulties. In their own longitudinal study of 171 Dutch students in the primary grades, Van Bon and Van Leeuwe's (2003) exploratory and confirmatory analysis of measures of phoneme recognition, blending, counting, deletion, segmentation, and pseudoword repetition and rhyme judgment reinforced the presence of a unidimensional PC ability.

In a welcome contribution to the internal (structural) and external *Ga* validity literature, Anvari, Trainor, Woodside and Levy (2002) explored the relations between phonological awareness (PC), music perception, and early reading in a sample of 100 four- and five-year old children. Consistent with the above reviewed literature, factor analyses of the four Anvari et al. (2002) PC measures (rhyme generation, oddity, blending, and the Rosner task) revealed a single factor at both age levels. Exploratory analysis of the music tasks (same/different melody, same/different chord, chord analysis, same/different rhythm, and rhythm production tasks) revealed a single music factor for four-year olds and two factors (pitch perception; rhythm perception) for five-year olds. The musical factors appear to measures aspects of the Musical Discrimination and Judgment (U1, U9) and Sound-Frequency Discrimination (U5) reported by Carroll (1993). Moderate factor correlations (.33 to .59) supported the independence of the music perception and PC ability factors. Further support for separate music perception and PC abilities was the intriguing finding that "music perception skill predicts reading even after the variance shared with phonemic awareness is removed. This suggests that phonemic awareness and music perception ability tap some of the same basic auditory and/or cognitive skills needed for reading but that they each also tap unique processing skills" (Anvari et al., 2002, p.127).

In the final structurally relevant *Ga* study, Schatschneider, Francis, Foorman, Fletcher and Mehta (1999) investigated the dimensionality (via factor and IRT analyses) of a battery of seven phonological awareness measures in a large kindergarten to second grade sample (n = 945). Results of a confirmatory factor analysis supported the unidimensionality of the PC tasks. A test of the Wagner et al. (1993) PC:A/PC:S two-factor correlated model produced an extremely high correlation (r = .95), again suggesting a single PC construct. The most intriguing finding came from the IRT analysis of a combined pool of all the items. IRT analyses of the PC items revealed a wide range of variation in item difficulty that appeared to be a function of item tasks demands. Schatschneider et al., (1999) suggested that the different types of PC tasks commonly used in most reading research differ not so much in the measurement of different underlying traits or constructs, but instead, represent different tasks that vary developmentally along a common single latent trait ability continuum.

Gsm Structural Extension Research

Are Memory Span (MS) and Working Memory (MW) the same or different? Ever since Kyllonen and Christal (1990) published "Reasoning Ability is (little more than) working-memory capacity?!" intelligence scholars have been enamored with the construct of working memory (MW; see Table 3). A fundamental question is whether MS is different from MW. Three studies during the past four years suggest that MS and MW are distinct constructs.

In a sample of 133 university students, Engle, Tuholski, Laughlin and Conway (1999) used confirmatory factor analytic methods to test if three simple short-term storage tasks and three tasks requiring complex processing and storage were best represented by a single memory factor or an alternative two-factor (i.e., MS and MW) model. The two-factor model provided a better fit to the data and also suggested a MS/MW latent factor correlation of .68. Also using CFA methods in two childhood samples (ages 7-13 years; n = 155, 132), Kail and Hall (2001) found support for separate MS and MW factors, with latent factor correlations of .32 and .36. Finally, in a sample of 120 young adults who were administered four simple MS storage tests and three complex MW tests, Conway, Cowan, Bunting, Therriault and Minkoff's (2002) CFA supported the existence of separate, but highly correlated (.82) MS and MW tests.

The wide range of latent factor MS/MW correlations (.32 to .82) reported across these three studies is difficult to interpret given the differences in the study samples and measures used. To minimize the effect of sampling error and measurement differences, we returned to the WJ III three-stratum CFA model studies reported in the WJ III technical manual (McGrew & Woodcock, 2001) and respecified separate MS and MW correlated factors. MS was operationally defined by the WJ III Memory for Words and Memory for Sentences tests, while MW was defined by the WJ III Auditory Working Memory, Numbers Reversed, Understanding Directions, and Sound Awareness tests.[3] The latent factor correlations, across five large nationally representative samples that differed by age (6-8; 9-13; 14-19; 20-29; 40-90+ years of age) were .67, .79, .82, .84, and .80. These findings mirror the age trend patterns in the other three studies (i.e., children displayed lower MS/MW correlations than adults), but differ in absolute magnitude. It appears that MS and MW are strongly correlated, yet separate constructs that become more highly correlated with increasing age.

Should working memory be considered a CHC trait/factor? According to Baddeley (2001), the construct of working memory (MW) was first proposed in 1960 by Miller, Galanter and Pribram. The first multiple component conceptualization was provided by Baddeley and Hitch (1974) who proposed that MW consisted of three components: the visuo-spatial sketchpad, phonological loop and central executive. MW has been referred to as the "mind's scratchpad" (Jensen, 1998, p. 220) and most models postulate that it consists of a number of subsystems or temporary "buffers." The phonological or articulatory loop processes auditory-linguistic information while the visuo-spatial sketch/scratchpad is the temporary buffer for visually processed information. Most models hypothesize that the central executive mechanism coordinates and manages the activities and processes in working memory. Baddeley (2000, 2001) has recently proposed the addition of a fourth component, namely, the episodic

[3] Memory for Sentences and Understanding Directions were also specified to have loadings on *Gc*. Sound Awareness had a loading on *Ga*.

buffer.[4] The research literature regarding the MW construct is voluminous and attests to the importance of MW as an important psychological construct.

Although Flanagan and McGrew (McGrew & Flanagan, 1998; Flanagan et al. 2000) previously argued for MW's preliminary "membership" status in the CHC taxonomy, this recommendation was based primarily on logical and rational considerations. Our current recommendation is tempered by Carroll's (1993) skepticism toward the working memory construct. Carroll (1993) stated that "although some evidence supports such a speculation, one must be cautious in accepting it because as yet there has not been sufficient work on measuring working memory, and the validity and generality of the concept have not yet been well established in the individual differences research" (p. 647).

Although MW is undeniably a valid and important psychological construct, this does not necessarily mean MW is a factor analytic, latent trait, individual differences type construct similar to the 60+ narrow cognitive abilities that are the cornerstone of the CHC taxonomy (see Table 3). According to Carroll (1993), "evidence for the existence of a latent trait derives from a demonstration that a number of similar task sets are highly correlated, or in factor-analytic terms, have weights on the same *factor*. A factor, if it is well established in a number of empirical investigations, is in essence a latent trait reflecting differences over individuals in ability characteristics or potentials" (p. 22). According to Carroll's definition, the trait-factor evidence for MW is still questionable.

First, the three studies (Conway et al., 2002; Engle et al., 1999; Kail & Hall, 2001) cited in support of separate MS and MW factors either restricted their variable pool to only MS and MW test indicators or used confirmatory methods that specified apriori MS and MW factors. In a variety of unpublished exploratory factor analyses of the variables described for the WJ III CFA studies (McGrew & Woodcock, 2001), as well as an exploratory analyses using Carroll's EFA software, the current authors never found the two primary WJ III MW tests (Numbers Reversed and Auditory Working Memory) to form a factor distinct from the MS tests (Memory for Words and Memory for Sentences). Instead, in all analyses across all ages, a clear MS factor is defined primarily by high loadings by the MS tests. The MW tests were consistently factorial complex. For example, in a Carroll EFA of 50 WJ III tests and subtests, at the first-order level we found an MS factor defined primarily by Memory for Words (.80) and Memory for Sentences (.47; also .35 on *Gc*). Numbers Reversed loaded on two factors (MS = .13; Quantitative Reasoning-RQ = .21). The best WJ III operational measure of MW, Auditory Working Memory, also loaded on RQ (defined primarily by

[4] See Baddeley (2001) for an overview of the history and evolution of the Baddeley working memory model. Space limitations do not allow for a detailed description and definition of the working memory model and its components, nor is such understanding necessary in the current context.

Number Series and Number Matrices tests) as well as MS (.26) and *Ga* (.27).

When a complete set of CHC indicators are present in an EFA study, it appears that MW measures do not represent a distinct trait-like MW factor construct, but instead are factorially complex mixtures of abilities. This should not be unexpected given the multicomponent conceptualization of MW. In the case of the WJ III Auditory Working Memory test, one could speculate that the RQ component reflects the manipulation of stimuli (numbers) in the visuo-spatial sketchpad (or use of part of the executive function component that is typically associated with *Gf* abilities), MS the memory span component, and *Ga* the use of the phonological loop to facilitate performance.

Based on the theoretical, logical, and empirical evidence, we conclude that working memory (MW) is indeed a multicomponent cognitive construct of significant importance, but, it should not be considered to be similar to the other 60+ narrow factor-based trait-like individual difference CHC constructs identified in the psychometric literature. This conclusion is consistent with Kyllonen (1996) who stated that "the working memory capacity construct does not depend on factor analysis for its identification. The working memory system was developed theoretically not as a label for an individual-differences factor, but rather as a construct to explain experimental results in the memory literature" (p.73), This conclusion does not negate the practical and theoretical importance of measures of working memory. Obviously, how amalgam constructs like working memory are integrated in the CHC taxonomy needs further deliberation and discussion. In order to decompose and measure the various processes underlying working memory, additional research focused on the subcomponents of working memory is needed (e.g., see the research of Süß, Oberauer, Wittmann, Wilhelm & Schulze, 2002; Oberauer, Süß, Schulze, Wilhelm & Wittmann, 2000).

Gc/Gkn structural extension research

One of the most frequent methods used to assess *Gc* is to ask individuals to define or solve problems (e.g., antonyms) that require the use and understanding of words that vary in frequency in the general culture. Vocabulary, general information, and concepts associated with specialized occupations/professions and knowledge domains are typically avoided in *Gc* assessment or research. High performance in one or more of the narrow specialized knowledge domains is instead associated with the constructs of *wisdom* or *expertise* (Hunt, 2000). Typically a dark and deep line is drawn in the psychometric sand between the measurement of generalized (general cultural) and specialized domain-specific knowledge.

Research regarding the nature and structure of the *Gc* domain has languished as researchers have focused on "romancing the domains" with more desirable appeal, such as *Gf* and *Gv*. According to Hunt (2000):

> Gc is the wallflower of the intellectual trio. Researchers want to go dancing (or to be less lyrical) to understand Gf and Gv. After all, is it not more important to study things that are fluid and dynamic than to study something that is crystallized and just sits there in memory? Besides, if Gf and g are identical, studying Gf kills two birds with one stone. Studies of Gv can be justified by dramatic examples of its importance in glamorous situations (e.g., aviation) or because of its fairly close ties to biology, and especially male-female differences. Like the wallflower it is, Gc languishes in the corner. How can you start a controversy about who acquires and uses culturally defined problem-solving methods? Who, but a few educators, are interested in such nearsighted, bookish behavior? (p. 124)

Anticipating Hunt's (2000) admonition to researchers "to ask Gc to put away the horn-rimmed glasses, put on a party dress, and take turn on the dance floor" (p.124), Rolfhus and Ackerman (1999) investigated the relations between traditional measures of *Gc*, a large collection *(n* = 20) of specialized knowledge tests,[5] and traditional cognitive measures of spatial and numerical abilities. In a university sample, these researchers first factored the 20 knowledge tests with the software and procedures employed by Carroll (1993). Four stratum I knowledge ability factors were found (Humanities, Science, Civics and Mechanical) which were, in turn, subsumed by a broad second-order General Knowledge (*Gkn*) factor.[6] The Rolfhus and Ackerman narrow knowledge factors are very similar to the Information about Culture (K2), Science (K1), and Mechanical and Technical Knowledge (MK) narrow abilities reported in Chapter 12 (*Abilities in the Domain of Knowledge and Achievement*) of Carroll (1993).

Of particular interest was the finding that the broad verbal (*Gc*) and knowledge (*Gkn*) factors correlated at a moderate level, a level which indicated that *Gc*, as typically assessed, was related to, but was *independent* of *Gkn*. It is doubtful that a separate broad *Gkn* ability would be present at younger developmental levels given the large source of common educational variance shared by children vis-à-vis the cultural homogenizing mechanism of schooling. However, at least by young adulthood, and

[5] The Rolfhus and Ackerman (1999) knowledge tests were in the domains of American government, history, and literature and art, astronomy, biology, business/management, chemistry, economics, electronics, geography, law, music, physics, psychology, statistics, technology, tools/shop, western civilization, and world literature.

[6] Although prior to the time frame for the current review, Kyllonen and Christal (1990), in four separate samples, previously established the validity of a general knowledge domain with confirmatory factor analysis methods. Both Kyllonen and Christal (1990) and the Ackerman research group have used *Gk* as the abbreviation for broad general knowledge. Given that *Gk* has also been used to designate a broad general kinesthetic ability (discussed later in this chapter), one of the two abbreviations needed further specification. *Gkn* was choosen to replace *Gk* for general knowledge. *Gk* was selected to remain "as is" for general kinesthetic ability.

possibly durintg high school, a *Gc/Gkn* distinction appears viable. The *Gc/Gkn* distinction is consistent with Cattell's (1971/1987) notions regarding *Gc* where he wrote that crystallized intelligence (Rolfus & Ackerman, 1999):

> must become different for different people. If [individuals' learning experiences] are sufficiently varied and lack any common core, the very concept of general intelligence begins to disappear. An effort to measure Gc in practice might amount to producing as many tests as there are occupations. (p. 144)

Collectively, the knowledge abilities catalogued by Carroll (1993), the research of Rolfhus and Ackerman (1999), and Hunt's (2000) wisdom (i.e., domain-specific knowledge in intelligence theory and research), argues for the inclusion of a broad *Gkn* domain that emerges and "breaks off" from *Gc* during adulthood.

General Knowledge (*Gkn*) can be defined as an individual's breadth and depth of acquired knowledge in specialized domains that do not represent the general universal experiences of individuals in a culture. In our highly specialized society, knowledge is not a unitary entity, especially at the higher levels of functioning and mature adulthood (Hunt, 2000). *Gkn* abilities result from domain-specific experiences and training and typically "depend on regular, frequent, and systematic practice and training over at least a decade" (Gilhooly, 1994, p. 638). The primary distinction between *Gc* and *Gkn* is the extent to which acquired knowledge is a function of degree of general cultural universality. *Gc* primarily reflects general knowledge accumulated via the experience of cultural universals. *Gkn* reflects deep specialized domain-specific knowledge developed through intensive practice (over an extended period of time) and the maintenance of the knowledge base through regular practice and motivated effort (Horn, 1998; Horn & Masunaga (2000).

Similar to *Gc*, *Gkn* abilities can be categorized as both declarative (static) and procedural (dynamic) knowledge. Declarative or explicit knowledge refers to knowledge "that something is the case, whereas procedural or implicit knowledge is knowledge of how to do something" (Gagne, 1985, p. 48). Declarative knowledge is consciously known and can typically be communicated by the "knower" (via spoken or written language, or, a specialized code, such as music notation). Although procedural knowledge can be demonstrated in behavior, it is often difficult to explicitly communicate (is not at a conscious level of awareness) (Gilhooly, 1994, p. 637). One manner in which procedural knowledge is conceptualized is in the form of schemas, which can be thought of as well "organized methods of problem solving" (Hunt, 1999, p. 21) that emerge from cumulative experience. A psychologist's knowledge of the definitions of the broad CHC abilities (see Table 1) would reflect declarative knowledge, while the psychologist's ability to instantly recognize and interpret the meaning of a specific pattern of CHC ability scores from an intellectual assessment would require procedural knowledge (i.e., CHC intelligence interpretation schema). The empirically identified narrow *Gkn* abilities are listed in Table 1.[7] The degree of correlation between *Gkn* narrow abilities will likely be a function of the extent to which expertise within one domain overlaps with expertise in another.

The positing of a broad *Gkn* ability separate from *Gc* (during adulthood) may facilitate the bridge between CHC and information processing theories vis-à-vis a common focus on the development of expertise. *Expertise* involves the acquisition, storage, and utilization of both the implicit (tacit) and explicit knowledge in a field "where *domain* refers to a knowledge base and *field* to the social organization of that knowledge base" (Sternberg, 1998). For example, a psychologist with expertise in psychometrics would likely have a well developed explicit knowledge of the facts, formulas, principles, statistics, and major ideas of the domain of psychometrics (e.g., SEM and IRT theory and methods). The person's implicit or tacit knowledge might constitute unspoken information regarding whom to consult for a specific technical question, which federal agency is likely to have the most relevant grant monies, and which professional conferences provide the best networking for acquiring new project contracts.

Horn and Masunaga (2000) have recently studied the construct of expertise from the perspective of CHC theory. For example, Horn and Masunaga (2000) hypothesized that the "reasoning involved in exercise of expertise is largely knowledge based and deductive, in contrast to reasoning that characterizes Gf, which is inductive" (p. 145). Furthermore, reflecting a new CHC-based perspective from which to conceptualize expert "performance," Horn and Masunaga (2000) concluded that:

> The superior performance of experts is characterized by a form of long-term working memory (LTWM). Within a circumscribed domain of knowledge, LTWM provides the expert with much more information in the immediate situation than is available in the system for short-term retention that has been found to decline with age in adulthood. LTWM appears to sublimate a form of deductive reasoning that utilizes a complex store of information to effectively anticipate, predict, evaluate, check, analyze, and monitor in problem-solving within the knowledge domain. These abilities appear to characterize mature expressions of intelligence (p. 152).

Speed, Structural (Gs, Gt, and Gps) extension research

Mental quickness as an indicator of a bright or intelligent person has stood front-and-center in the study of human cognitive abilities for decades (Nettelbeck, 1992, 1994; Nyborg, 2003; Stankov &

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[7] We took the liberty, based on a review of Carroll (1993) and the recent *Gkn* research literature, to add certain narrow abilities previously reported by Carroll (but which have not been included in most contemporary publications), and to move some that have previously been listed under *Gc*.

Roberts, 1997). According to Nettelbeck, two different perspectives have dominated the study of mental processing speed. The "speediness" perspective is that most associated with applied intelligence batteries and is defined by the quickness in performing tasks of trivial difficulty or tasks that have been over-learned. Broad cognitive processing speed (*Gs*) can be defined as the ability to automatically and fluently perform relatively easy or over-learned cognitive tasks, especially when high mental efficiency (i.e., attention and focused concentration) is required (McGrew, 1993). Woodcock (1993) has likened *Gs* to the opening or closing of a valve in a water pipe. When the valve is wide open, the rate of flow increases (high cognitive processing speed). When the valve is only partially open, the rate of flow is lessened (lower *Gs*). The narrow (stratum I) abilities subsumed by *Gs*, which reflect the integration of recent factor analytic research (discussed below), are listed in Table 1.

The second mental speed perspective is associated with experimental paradigms that employ chronometric measures of reaction and inspection time (Deary, 2003; Nettelbeck, 1994, 2003). The chronometric approach is based on the idea that "progress can be made in understanding differences in human intelligence if it can be shown that there are individual differences in basic cognitive processes that are correlated with higher level abilities as measured by mental tests" (Deary & Stough, 1996, p. 599). Carroll and Horn both recognized this second aspect of mental quickness in their respective models. Carroll (1993) included reaction and decision time abilities under a broad Decision/Reaction Time or Speed (*Gt*) ability. Horn's (Horn & Masunaga, 2000) analogous ability is called Correct Decision Speed (CDS), and is typically measured by recording the time an individual needs to provide an answer (either correct or incorrect) to a variety of tasks. Conceptually, Horn's CDS appears to represent a narrower ability than Carroll's more encompassing *Gt*. Conceptually, CDS, as defined by Horn, could easily fit under Carroll's *Gt*. The narrow (stratum I) abilities subsumed by *Gt*, which reflect the integration of recent factor analytic research (discussed below), are listed in Table 3.

More recently, both *Gs* and *Gt* have been investigated as key variables in explaining higher-level complex cognitive processing (e.g., *Gf, g*) (Kail, 1991; Lohman, 1989). A pivotal concept in information processing models is that human cognition is constrained by a limited amount of processing resources, particularly in working memory. "Many cognitive activities require a person's deliberate efforts and that people are limited in the amount of effort they can allocate. In the face of limited processing resources, the speed of processing is critical because it determines in part how rapidly limited resources can be reallocated to other cognitive tasks" (Kail, 1991, p. 152). In other words, faster processing of information permits reasoning to reach completion before the requisite information is lost.

Although a plethora of research studies have studied mental speed during the past decade, "factor analytic evidence concerning the status of a range of time-dependent constructs has been either piecemeal or nonexistent" (Roberts et al., 2000, p. 346). Unanswered questions remain such as "how many different speed abilities exist...what is their position in the hierarchy-that is, are they at the same stratum as broad organizations of the Gf/Gc theory or should they be placed at different strata?" (Stankov, 2000, p. 39). Attempts to answer these questions have been the focus of the largest number of in-depth CHC-related factor analysis investigations during the last decade. This focus is appropriate given the "general lack of clarity regarding different aspects of speeded processing" (Ackerman, Beier, & Boyle, 2002, p. 569). Also contributing to this lack of clarity has been the nearly universal omission (by most authors since 1993) of one of the three different broad speed factors presented in Carroll's seminal treatise.

Gs structural research. In addition to *Gs* and *Gt*, Carroll (1993) reported "a third category of second-order speed factors is what will henceforth be symbolized as *Gp* or 2P, interpreted as General Psychomotor Speed, in that it is primarily concerned with the speed of finger, hand, and arm movements, relatively independent of cognitive control" (p. 618). The influence of psychomotor speed in speeded tests in intelligence batteries (e.g., Wechsler Coding/Digit Symbol; WJ III Visual Matching; Flanagan et al., 2000) and the importance of sensory-motor functions in neuropsychological assessment (see Lezak, 1995 and Dean & Woodcock, 2003) dictates the need to recognize the complete speed trilogy (*Gs*, *Gt*, *Gps*), as well as to include the broad domain of psychomotor abilities (Psychomotor Ability; *Gp*)[8]. All speed and psychomotor abilities summarized by Carroll are represented in Figure 1.[9]

[8] *Gps* is used to designate the Broad Psychomotor Speed domain instead of *Gp* as used by Carroll (1993). This modification is due to the addition of a broad Psychomotor Ability domain (presented in a special chapter by Carroll) in the current paper. *Gps* (General psychomotor speed) and *Gp* (General psychomotor ability) are more logical factor codes.

[9] It is important to note that the psychometric abilities presented by Carroll, which are included in Figure 1, most likely represent only a small portion of the complete domain of psychomotor abilities. Carroll's review did not deliberately attempt to review the extant psychomotor ability literature. See Carroll (1993) for his discussion and references to other sources.

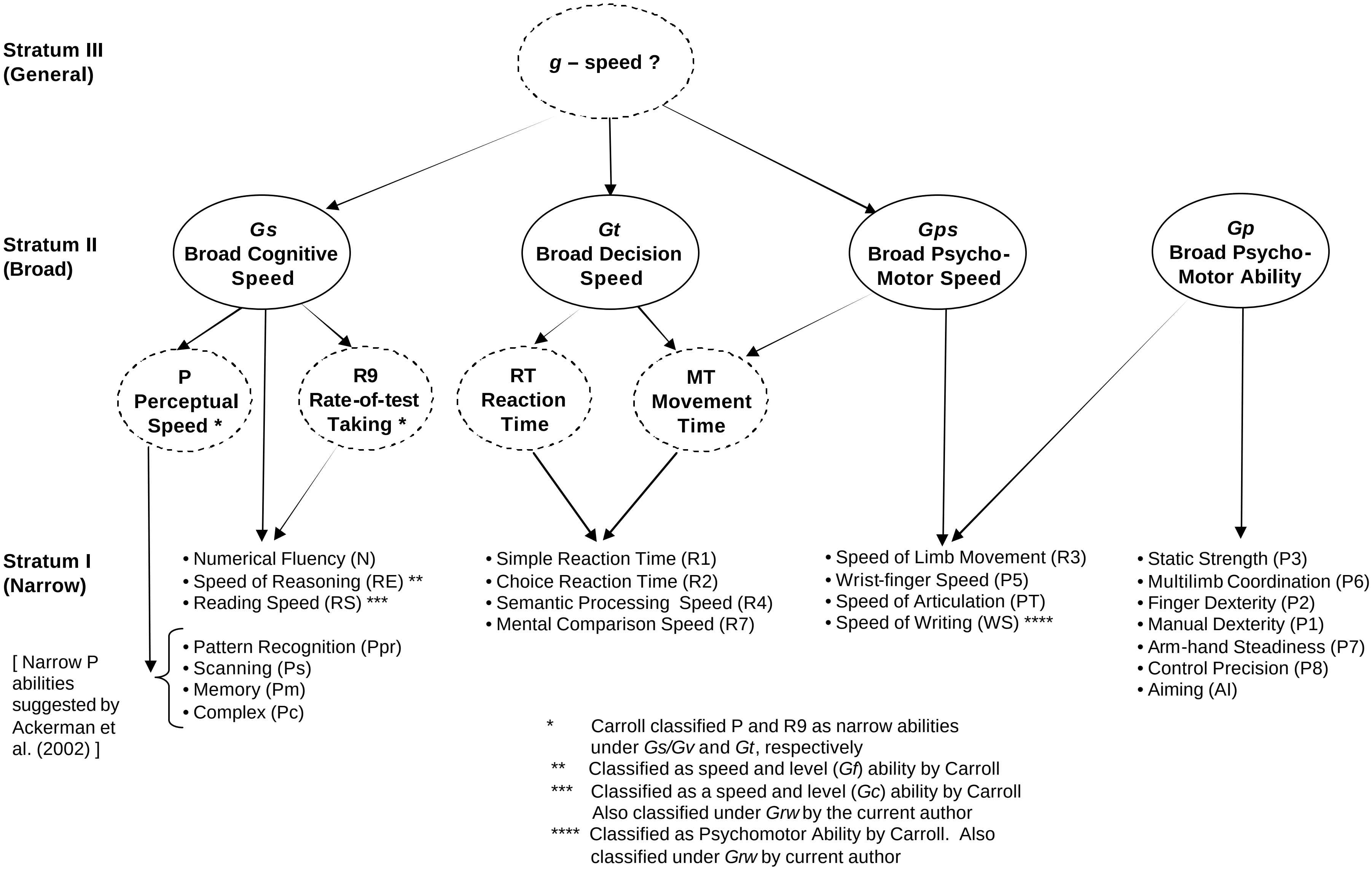

Figure 1: Hypothesized speed hierarchy based on integration of Carroll (1993) speed abilities with recent research (Ackerman, Beier & Boyle, 2002; O'Connor & Burns, 2003; McGrew & Woodcock, 2001; Roberts & Stankov, 1998; Stankov, 2000; Stankov & Roberts, 1997)

In 1979, Ekstrom, et al., (1979), as part of the historical factor reference kit research, questioned whether more than one perceptual speed factor existed. Approximately 20 years later, a series of studies by Ackerman and colleagues (Ackerman et al., 2002; Ackerman & Ciancio lo, 2000) suggest that Ekstrom et al. (1979) were correct. The Ackerman group has demonstrated that the traditional Perceptual (clerical) Speed (P) ability may rest at the apex of hierarchy that includes a number of lower-order perceptual speed abilities. The Ackerman group has presented evidence for four different P factors, including the ability to: (a) quickly recognize simple visual patterns (Pattern Recognition; Ppr), (b) scan, compare, and lookup stimuli (Scanning; Ps), (c) perform tasks that place significant demands on immediate short-term memory (Memory; Pm), and (d) perform pattern recognition tasks that impose additional cognitive demands such as spatial visualization, estimating and interpolating, and heightened memory span loads (Complex; Pc)[10].

Although using different factor names than the Ackerman group, O'Connor and Burns (2003) presented factorial evidence for Perceptual Speed and Visualization (the time needed to complete tasks that included complex visualization of stimuli) factors that bear resemblance to Ackerman's Pattern Recognition (Ppr) and Complex (Pc) factors, respectively. Additionally, Stankov and colleagues (Stankov, 2000; Stankov & Roberts, 1997) reported an ability to perform speeded visual or auditory perceptual tasks (Tv/a) that resembles components of the Ackerman Pattern Recognition (Ppr) and Complex (Pc) Perceptual Speed abilities. In the model presented in Figure 1, these findings are reflected vis-à-vis the reclassification of Perceptual Speed (P) as an intermediate ability lying between the broad (stratum II) and narrow (stratum I) abilities. The four lower-order perceptual speed abilities (Ppr, Pm, Ps, Pc) are placed at the narrow ability level.

An additional proposed revision to the CHC speed hierarchy is the movement of the Rate-of-test Taking (R9) narrow ability to an intermediate level between stratum I and II. The rational for this reclassification (see Figure 1) is twofold. First, when attempting to classify the speeded psychometric tests in most intelligence batteries, McGrew and colleagues (McGrew, 1997; McGrew & Flanagan, 1998; Flanagan et al., 2000) found it difficult not to classify all speeded tests as measures of R9. Second, a closer reading of Carroll (1993) suggests that R9 is an ability that cuts across speeded tasks in multiple domains. Carroll (1993) stated that the R9 factor did "not appear to be associated with any type of test content" (p. 475) and "the speed factors associated with the major dimensions of level abilities may be thought of as factors of 'rate of test taking' " (p. 508). Furthermore, Stankov and colleagues (Stankov, 2000) identified a similarly described higher-order factor (Psychometric Time; PT) that subsumed a number of lower-order factors that varied across other broad CHC ability

[10] The abbreviations used for the Ackerman Perceptual Speed factors were developed for this paper by the current authors.

domains (e.g., time spent in working on inductive reasoning tasks; time spent in working on visual and auditory perceptual tasks). In their empirically-based speed hierarchy, Roberts and Stankov (1998) located the PT factor, a factor which has also been interpreted by others (O'Connor & Burns, 2003) as a test-taking speed ability, between the broad and narrow strata. Support for the general Stankov speed hierarchy has been provided by O'Connor and Burns (2003) who, based on the factor analysis of 18 speeded variables, concluded that the "data presented here are highly supportive of the model of mental speed proposed by Roberts and Stankov (1999) (p. 722). The similarity of Carroll's R9 and Stankov's higher-order PT factors argues for the placement of R9 as an intermediate ability between broad and narrow stratum (see Figure 1).

An additional proposed modification to Carroll's 1993 model is the listing of the Speed of Reasoning (RE) narrow ability under *both Gf* and *Gs.* The finding of a "time spent on inductive reasoning tasks" (Ti) factor under the Roberts and Stankov (1999) higher-order PT factor suggests that RE may tap more *Gs* than originally suggested. Evidence supporting the influence of speeded variables during complex task performance (e.g., *Gf*) has been provided by a diverse array of intelligence researchers (Jensen, 1987; Reed & Jensen, 1991, 1992; Vernon, 1987). A recent example is represented by Verguts, De Boeck and Maris' (1999) experimental investigation of performance on the Ravens Advanced Progressive Matrices (APM). Verguts et al. (1999) presented evidence in support of *rule generation speed* in solving complex reasoning tasks.

> Rule generation process plays a crucial role in solving the APM items. If (APM) rules are compared with balls in an urn, this means that people sample balls from an urn. Individual differences in the generation process can be thought of as sampling from different urns (qualitative differences) or at different rates (quantitative differences)…Given a limited time to solve the test, and given that the 'different urns effect' is cancelled out, this implies that fast persons (fast in the sense of generating many possible rules in a limited time) have a higher probability to solve a particular item correctly (p. 330).

The similarity between Carroll's RE ability, Stankov and Roberts Ti ability, and Verguts et al. (1999) rule generation speed ability, collectively suggest that Speed of Reasoning (RE) should play a more prominent role in contemporary CHC research and practice. Findings parallel to the *Gf*/RE pairing are also present in the domain of *Grw*. Carroll (1993), who categorized most all reading and writing abilities as *Gc*, placed Writing Speed (WS) under *Gps* due to the obvious speeded motor component. In well designed confirmatory studies conducted on large nationally representative samples (McGrew & Woodcock, 2001), tests requiring simple speeded writing (WJ III Writing Fluency) and reading (WJ III Reading Fluency) demonstrate dual factor loadings on both broad *Grw* and *Gs* factors. These findings are consistent with Carroll's (2003) subsequent interpretation of a combined exploratory and confirmatory factor analysis of the WJ-R norm data where Carroll reports that the WJ-R Writing Fluency test demonstrated salient loadings on *Gs* and a "Language" factor (similar to *Grw*). As a result, both Reading Speed (RS) and Writing Speed (WS) are included in the speed hierarchy presented in Figure 1.

The above proposed revisions to the CHC model are echoed by O'Connors and Burns (2003) who stated that "the inference drawn is that if a diverse battery was administered, there may be speed factors associated with each of the second order factors defined in Gf–Gc theory" (p. 722). Stankov and Roberts (1997) suggested the same hypothesis when they concluded that "the possibility cannot be ruled out that there may be as many disparate mental speed factors as there are factors among measures based on accuracy scores" (p. 73). Bates and Shieles (2003) arrived at the same conclusion when they stated:

> just as general effects on computational speed underpinning *g*, these additional group factors are also explained by variance in speed, but that the particular groups factors such as verbal and visuo-spatial reflect parcelled speed effects: speed variance reflected not across the whole brain but in a restricted set of processing modules. Some support for this notion is found in the already demonstrated finding that most or all of the abilities identified by Carroll (1993) are correlated with speed measures. Thus, for instance, "fluid'' ability is related to speed of reasoning, ''crystallized'' intelligence to reading speed, visual perception/spatial ability to perceptual speed, ideational fluency with retrieval ability, test-taking speed with cognitive speed, and, of course, reaction time with processing speed. The two abilities without a named speed correlate are memory and learning, and auditory perception. But of course working memory is associated with speed of rehearsal…and a growing literature supports a direct auditory analogue of IT for auditory stimuli (p. 284).[11]

Recent reaction time (Gt) structural research. There is little doubt that intelligence scholars have been enamored with the measurement of speed of basic information processing as measured by Reaction Time (RT) and Inspection Time (IT) paradigms (Roberts & Stankov, 1997; Nyborg, 2003). Literature reviews (Grudnik & Kranzler, 2001; Kranzler & Jensen, 1989; Nettelbeck, 1987) have established the relationship between IT and psychometric *g* in a range for .30 to .50 (Stankov & Roberts, 1997).[12] Despite this wide interest, researchers have been unable to reach a consensus on what RT and IT are measuring (Deary, 2000) and what implications these measures have for intelligence theory (Stankov & Roberts, 1997) and for applied practice (e.g., education) (Ackerman & Lohman, 2003).

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[11] See Parker, Crawford, & Stephen (1999) for an example of research regarding auditory inspection time.
[12] The reaction and inspection time literature is too voluminous to treat in this paper. See Deary, (2003) and Nettelbeck, (2003) for recent summaries.

When traditional speeded psychometric measures are factored together with measures of reaction and inspection time (RT/IT), relatively robust and separate reaction time (RT) and movement time (MT) factors emerge (O'Connor & Burns, 2003; Roberts & Stankov, 1999; Stankov, 2000; Stankov & Roberts, 1997). The RT/MT dichotomy reflects the two phases of reaction time as measured by various elementary cognitive tasks (ECTs) (see summaries by Deary, 2003; Nettelbeck, 2003).

Given the robust finding of separate RT and MT components across different reaction time paradigms, and the emergence of distinct higher-order RT and MT factors that subsume lower-order reaction time factors in empirical studies (see Roberts & Stankov, 1999; Stankov, 2000), a logical, theoretical, and operational decision was made to classify the RT and MT factors as intermediate factors between the broad and narrow ability strata (see Figure 1). An intriguing set of findings warranting future research are the reported significant correlations between DT and broad memory (*Gy* as per Carroll, 1993) and reasoning (*Gf*), and MT with *Ga* (Roberts et al., 2000). The *Ga*/MT correlation "is most interesting because it suggests possible links among natural tempo, psychomotor performance, and audition" (Roberts et al., 2000, p. 351).

In a study designed specifically to evaluate the role of IT in structural models of intelligence, Burns and Nettelbeck (2003) conducted a Carroll-type exploratory factor analyses of chronometric IT measures together with select tests of *Gsm, Gs, Gv*, and *Gf* from the WJ-R and WAIS-R. These exploratory analyses were followed by confirmatory factor methods. The results unambiguously found that IT loaded on the psychometric broad *Gs* processing speed factor. IT did not load on any other first-order CHC factors. Burns and Nettelbeck (2003) concluded that "IT, to be sure, somehow taps the same processes as those that contribute to performance on tests of clerical speed" (p. 249).

Finally, although using different terminology, the research of Stankov and colleagues (Roberts & Stankov, 1998; Stankov & Roberts, 1997; Stankov, 2000) suggests that a model of human cognitive abilities that includes a general speed ability (*g*-speed; see Figure 1) at the same level as *g* is plausible. According to Stankov (2000), "the structure of mental speed may be as complex as the structure of all other cognitive abilities and the Gt factor may analogous to a putative general factor based on accuracy scores (i.e., psychometric g)" (p. 41).

External CHC Structural Extensions

"For any taxonomic model of human cognitive abilities to be complete, all sensory moralities must be encompassed within its framework (Carroll, 1993; Roberts et al., 1999; Stankov, Seizova-Cajic, & Roberts, 2001)" (Danthiir, Roberts, Pallier & Stankov, 2001). Currently, a significant gap exits in the CHC taxonomy regarding the human sensory domains of tactile, kinesthetic, and olfactory abilities (Danthiir et al., 2001). Recent factor analytic research argues for the expansion of the CHC taxonomy to include a number of additional broad ability constructs.

Tactile (Gh) and kinesthetic (Gk) abilities

Despite the historical and frequent use of measures of tactile and kinesthetic abilities in neuropsychological assessment settings (e.g., Dean-Woodcock Neuropsychological Battery, Dean & Woodcock, 2003; Halstead-Reitan Neuropsychological Test Battery, Reitan & Wolfson, 1985; Luria-Nebraska Neuropsychological Test Batteries, Golden, Hammeke & Purisch, 1985), and the importance of understanding how these processes are used by individuals with visual impairments to navigate in the absence of on non-visual cues (Klatzky, Golledge, Loornis, Cicinelli, & Pellegrino, 1995), the structural evidence for these domains has been meager (Carroll, 1993). Since Carroll's factor analytic meta-analysis, a handful of new studies (Li, Jordanova & Lindenberger 1998; Pallier, Roberts, & Stankov, 2000; Roberts, Stankov, Pallier & Dolph, 1997; Stankov, Senzova-Cajic & Roberts, 2001) have factored sets of tactile and kinesthetic variables together with cognitive variables. Collectively, these studies have tentatively suggested that separate broad kinesthetic (*Gk*) and tactile (*Gh*))[13] abilities should be included in a more comprehensive CHC taxonomy (Stankov, 2000).

The Stankov group isolated three different abilities at the narrow (stratum I) ability level. The TP (Tactile Performance) factor reflected the ability to perform complex tactile-kinesthetic tasks. The complexity of the TP ability was due to the inability of these researchers to "disentangle" TP from the higher-order influences of *Gv* and *Gf*. In terms of practical test interpretation issues, Stankov (2000) concluded that the interpretation of the complex Halstead-Reitan tactile and kinesthetic tasks may be problematic as it was not possible to isolate separate tactile and kinesthetic factors distinct from *Gv*. "In other words, the processes involved in complex tactile and kinesthetic tasks seem to activate visualization abilities during their performance, a finding in agreement with the experimental literature (e. g., Livesey & Intili, 1996)" (Stankov, 2000, p. 42).

The Stankov group also identified separate Tactile (TS) and Kinesthetic (KS) abilities. TS abilities "require processing that depends on fine discrimination of pressure on the skin" while KS abilities involve "the awareness of (passive) movements of upper limbs and the ability to visually recognize path that individuals follow while blindfolded" (Stankov, 2000, p. 43). The kinesthetic (KS) and tactile (TS) factors were found to be weakly correlated with higher-stratum cognitive abilities (e.g., *Gv, Ga, Gf*, etc.; Stankov et al, 2001). The common variance among the cognitively

[13] *Gk* = kinesthetic; *Gh* = tactile ("h" stands for "haptic") as per the Stankov research group notation.

simple KS and TS factors "cast doubt on the existence of a broad ability that spans the kinesthetic and tactile domains" (Stankov et al., 2001, p.25).

In a sample of 179 middle age adults, Li, Jordanova and Lindenberger (1998) isolated two tactile discrimination abilities (i.e., Tactile Pressure Sensitivity and Texture Discrimination) and one tactile similarity (Arc-Part part whole matching) ability. All three factors bear resemblance to the TS ability described by the Stankov group. Given that each of Li et al.'s (1998) three factors were based on multiple scores from each of the three different tasks, it is possible that these three factors may represent singlet test factors and not separate abilities. Until replicated, the differentiation of TS into sub-abilities is not encouraged.[14]

Olfactory (Go) Abilities

Carroll (1993) cited only one study (Jones, 1957) that investigated the structure of the olfactory domain. Although largely ignored in structural investigations of human cognitive abilities, olfactory abilities are important to study given the use of the olfactory sense by blind or partially sighted people, and experts such as "gourmets, wine connoisseurs, coffee experts, and the like" (Danthiir, Roberts, Pallier, G. & Stankov, 2001, p. 357). In addition, recent clinical research has suggested that declines in olfactory abilities may be associated with a variety of clinical disorders and diseases ranging from Alzheimer's, idiopathic Parkinson's, alcoholism and drug abuse, attention deficit/hyperactivity disorders, severe-stage anorexia nervosa, Down's syndrome, head trauma, multiple sclerosis, restless leg syndrome, seasonal affective disorder, and others (see Doty, 2001, for a complete review)

Carroll's (1993) analysis of the Jones (1957) olfactory sensitivity data suggested a possible hierarchical structure with four odor-specific narrow abilities (O1, O2, O3, O4) and two unnamed higher-order factors. More recently, in a study of university students, Danthiir et al. (2001) identified a stratum I Olfactor Memory (OM) ability that was independent of other higher-order CHC abilities and only weakly related to simple olfactory sensitivity (Stankov, 2000). Danthiir et al. (2002) concluded that the "OM factor can be considered as part of the taxonomy of cognitive abilities, apparently not dependent on simple olfactory acuity" (p. 355).

Collectively, the structural research of Carroll (1993) and Danthiir et al. (2002), as well as basic and clinical studies of the olfactory system, suggests that a broad olfactory ability domain (*Go*) should be

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[14] It is important to note than Li et al (1998) included their tactile factors, together with visual and auditory acuity factors, as causal variables with direct effects on *g*, which in turn was represented by a measurement model consisting of five latent factor cognitive variables. The tactile variables where factored separately. As a result, it is not possible to determine the structural relations between the tactile factors and the five cognitive factors in a manner similar to that of the Stankov group. The Li et al. (1998) study was focused on exploring the causal relations between sensory abilities and *g*, not the structural characteristics of cognitive abilities.

included within a comprehensive CHC taxonomy. Although the *Go* structural research is sparse, the recent development of sophisticated psychophysical measurement technologies and easy-to-use olfactory function tests, some with relatively large norm samples, will soon likely lead to a better understanding of the cognitive component of *Go*.[15]

Summary and Conclusions:

Human intelligence is multidimensional. The past decade has witnessed the accumulation of evidence that supports the broad strokes of the hierarchical multi-ability CHC theory of human cognitive abilities (McGrew, in press). This new evidence validates the inclusion of the broad (stratum II) abilities of *Gf, Gc, Gq, Grw, Glr, Gsm, Gv, Ga, Gs*, and *Gt* in the CHC taxonomy. In addition, the extant research suggests the need to attend to, and possibly incorporate, knowledge of additional broad domains (*Gps, Gp, Gk, Gh, Gkn, and Go)* in future research, measurement, and assessment activities.

The cognitive speed ability research reviewed here serves as a cautionary tale that should ward off the tendency to succumb to a "premature hardening of the CHC categories." The importance of this caveat was clearly demonstrated this past decade vis-à-vis the structural research on the domain of cognitive mental speed, where research now suggests a domain characterized by a complex hierarchical structure with a possible *g*-speed factor at the same stratum level as psychometric *g*
The suggested revisions, additions, and extensions to the CHC taxonomy are based on a reasoned review and evaluation of research spanning the last decade. However, the proposed CHC taxonomic enhancements summarized here require additional research and replication. Reanalysis of Carroll's 460+ datasets with contemporary procedures (viz., confirmatory factor analysis-CFA), combined with both CFA and Carroll EFA-based exploratory procedures of post-Carroll (1993) datasets, will help elucidate the validity of current and future proposed revisions of the CHC taxonomy.

The structural research of the past decade demonstrates the dynamic and unfolding nature of the CHC taxonomy. Additional research is needed to better elucidate the structure of abilities in the broad domains of *Gkn, Gk, Gh,* and *Go.* In addition, Carroll's primary focus on identifying an overall structural hierarchy necessitated a deliberate ignoring of datasets with small number of variables

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[15] The interested reader should consult Doty's (2001) review for information on new olfactory assessment instruments. These include tests such as the 40-odor University of Pennsylvania Smell Identification Test (UPSIT ; known commercially as the Smell Identification Test), the 12-odor Brief-Smell Identification Test (also known as the Cross-Cultural Smell Identification Test), the 3-odor Pocket Smell Test, the 12-item Odor Memory Test, the Odor Confusion Matrix Test, the San Diego Odor Identification Test , the Scandinavian Odor Identification Test, the "Sniff 'n Sticks" test, the Viennese Olfactory Test Battery, an 8-odor identification test, and the T&T olfactometer test.

within a single broad domain (Carroll, 1994). We believe that more focused “mining” within each broad stratum II domain is rich with possible new discoveries, and will be forthcoming soon. The parochial *Ga*, *Gv*, *Gs* factor research reviewed here illustrates how studies with a molar focus on a small number of variables within a single broad CHC domain can provide valuable insights into the structure and relations of narrow abilities within a broad domain.

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