A Review of Taxonomies, Tests, and Task Mappings for Cognitive Abilities

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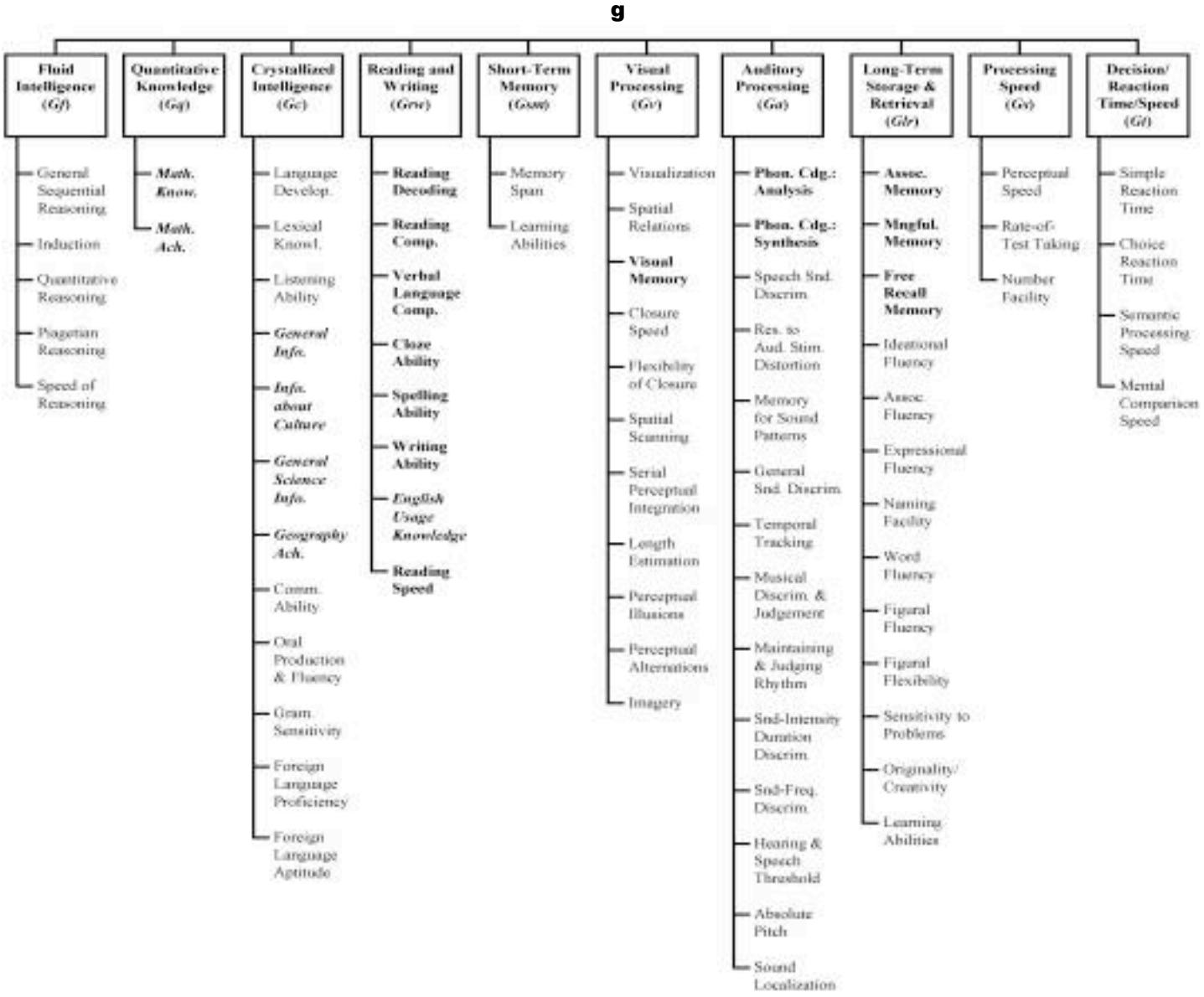
A goal set in the 2004 Cognition in Space Workshop was to "review the literature on predictors of individual performance in real-world tasks and develop a set of tests to be used during all NASA-funded research simulating space missions (e.g., bed-rest studies)." This literature review examines skill taxonomies, skill measures, and skill/task mappings.

Skill taxonomies can be derived from information processing models, psychometric models, or can be expert-derived. Information processing models show functionality by being able to replicate human performance in computer-based tasks. The information processing model ACT-R [1] organizes performance into declarative and procedural memory retrieval, perceptual and motor skills, working memory capacity [2], and knowledge compilation [3].

Psychometric models show construct validity by having independent factors derived from factor analysis of human performance. The model of Cattell, Horn, and Carroll [4,5] is a three-level hierarchy (Figure 1) with the top level having a general (g) intelligence, the next level having ten more specific abilities, and the next level having 64 even more specific abilities.



It has been recognized that the CHC model is missing concepts of attention and executive function [6]. Other psychometric models focus exclusively on these concepts. Mirsky's model of attention [7] has sub-abilities to focus-execute, sustain, shift, and encode, while Zomeren's model of attention [8] has selectivity (with sub-abilities of focused and divided attention) and intensity (with sub-abilities of altertness and sustained attention). Miyake's model of executive function [9] has sub-abilities of shifting, updating, and inhibition. Fleishman and Quaintance's model of cognitive abilities [10] includes attention in the taxonomy. The model has sub-abilities of communication, conceptual, reasoning, and speed-loaded abilities (see Table 1).

Communication:	Oral Comprehension, Written Comprehension, Oral Expression, Written Expression
Conceptual:	Memorization, Problem sensitivity, Originality, Flexibility of ideas, Flexibility of closure, Selective attention, Spatial orientation, Visualization
Reasoning:	Inductive reasoning, Category flexibility, Deductive reasoning, Information ordering, Mathematical reasoning, Number facility
Speed-loaded:	Time sharing, Speed of closure, Perceptual speed & accuracy, Reaction time, Choice reaction time

Table 1: Cognitive Ability Taxonomy from Fleishman and Quaintance [10]

The expert-derived ability taxonomy of O'Donnell et al. [11] includes attention (sustained, divided, directed, and blindness), memory (working, declarative, procedural, and prospective), language/semantics, decision making, planning, problem solving, task multiplexing, spatial visualization, math functioning, problem sensitivity, cognitive flexibility, situation awareness, time/velocity estimation, and visual-motor control. This taxonomy appears to be the most complete, but it lacks empirical validation.

Tests of cognitive abilities include neuropsychological tests and computer-based batteries. Neuropsychological tests (see Table 2) have typically been designed to measure a specific ability without regard to tests for other abilities. Computer-based batteries use neuropsychologically-dervied tests and are typically designed to cover areas of abilities.

- General intellectual function
  - * Wechsler Adult Intelligence Scale-III (WAIS-III)
  - * Kaufman Brief Intelligence Test (K-BIT)
- Language
  - * Controlled Oral Word Association (COWAT)
  - * Boston Naming Test (BNT)
  - * Aphasia screening exam
  - * Token Test
- Attention and scanning
  - * Visual
    - o Trailmaking Test
    - o Symbol Digit Modality Test
    - o Cancellation tasks
    - o Tests of Variable Attention (TOVA)
    - o Symbol Search (WAIS-III)
    - o Useful Field of View (UFOV)
  - * Verbal
    - o Serial Verbal Learning
    - o Digit Span (WMS/WAIS-III)
    - o Letter-Number sequencing (WMS/WAIS-III)

- o Paced Auditory Serial Addition Test (PASAT)

Memory
- * Wechsler Memory Scale (WMS-III)
- * California Verbal Learning Test-II (CVLT)
- * Selective Reminding Test
- * Benton Visual Retention Test
- * Memory for Designs Test
- * Tactual Performance Test (TPT)
- * Rivermead Behavioral Memory Test (RBMT)

Visuospatial reasoning and constructional ability
- * Block Design (WAIS-III)
- * Rey-Osterrieth Complex Figure (ROCF)
- * Tactual Performance Test (TPT)
- * Judgment of Line Orientation Test (JLO)
- * Ravens Progressive Matrices
- * Hooper Visual Organization Test (HVOT)

Executive function
- * Wisconsin Card Sorting Test® (WCST)
- * Halstead Category Test
- * Porteus maze test
- * Proverb interpretation (e.g., Proverbs test)
- * Similarities (WAIS-III)
- * Abstract word tests
- * Stroop (color word test)

Motor speed and dexterity
- * Finger Oscillation Test
- * Grooved Pegboard Test

Psychomotor speed
- * Assorted reaction time tasks (simple vs. recognition vs. choice)

Table 2: Typical neuropsychological tests (from Yale et al. [12])

The computerized Automated Neuropsychological Assessment Metrics (ANAM) battery [13] consists of the following tests: 2-Choice Reaction Time, 4-Choice Reaction Time, Code Substitution, Demographics, Digit RT, Dual Task (Track / Memory), Logical Relations, Grammatical Reasoning, Manikin, Matching to Sample, Matching Grids, Mathematical Processing, Mood Scale 2-Revised, Mood Affect Score, Mental State Exam, Procedural Reaction Time, Pursuit Tracking, Reaction Time, Relative Judgment, Running Memory CPT, Simple Reaction Time, Stanford Sleepiness Scale, Spatial Processing, Standard CPT, Memory Search (Sternberg), Stroop Test, Switching, Symbolic Reaction Time, Tap Left, Tap Right, Tower Puzzle, and Tracking. Normative data from the ANAM battery exists from a number of studies [14-21]. To test the construct validity of the ANAM battery, performance on a subset of tests (Simple Reaction Time, Sternberg Memory, Math Processing, Spatial Processing, and Matching to Sample) was subjected to factor analysis [22]. Table 3 shows the resulting factors of Processing Speed, Resistance to Interference, and Working Memory.

Factor	ANAM Measures
Processing Speed	Reaction Times for Spatial Processing, Math Proc., and Sternberg
Resistance to Interference	Accuracy for Spatial Processing, Math Proc., and Sternberg
Working Memory	Accuracy for Matching to Sample

Table 3: Factors from ANAM Measures in Bleiberg et al. [22]

In another study, the ANAM subtests Logical Reasoning, Code Substitution, Delayed Matching to Sample, Math Processing, Running Memory Continuous Performance Test, Spatial Processing, and Sternberg Memory Search were subjected to factor analysis [23,24]. Table 4 shows the resulting factors of Working Memory/Complex Attention, Other Cognitive Processing, and Paired Associate Learning. Neuropsychological tests (WAIS-R (Arithmetic, Digit Span, Digit Symbol), California Verbal Learning Test, Trail Making Tests A&B) were then added to the ANAM tests for a factor analysis. Table 4 also shows the resulting factors of Processing Speed/Efficiency, Information Retention, and Working Memory.

Factor	ANAM Measures
Working Mem./Complex Attention	Accuracy for Running Memory CPT, Logical Reasoning, Match to Sample, and Sternberg
Other Cognitive Processing	Accuracy for Spatial Processing, and Math Processing
Paired Associate Learning	Accuracy for Code Substitution
Factor	**ANAM+Neuropsych Measures**
Processing Speed/Efficiency	Reaction Times for Logical Reasoning, Code Substitution, and Math Processing; Digit Symbol, Accuracy for Running Memory CPT; Trails B; Throughput for Matching to Sample
Information Retention	Percent Retained for CVLT; Recall for Code Substitution; Accuracy for Sternberg
Working Memory	Arithmetic; Accuracy for Math Processing; Digits Backwards

Table 4: Factors from ANAM and Neuropsychological test in Kabat et al. [23,24]

To test the external validity of the ANAM battery, several studies have shown correlations between performance in a subset of ANAM tests and brain injury [25-31], stress [32-34], fatigue [35], ADHD [36], decompression [37], radiation exposure [38-40], and medication [41-42].

The ANAM Readiness Evaluation System (ARES) [13] was designed to run on a PDA and consists of the following tests: Code Substitution, Four-Choice RT, Logical Relations, Matching to Sample, Math Processing, Matrix Rotation, Memory Search, Mood Scale, Profile of Mood States, Pursuit Tracking, Running Memory, Simple Reaction Time, Sleep Scale, Synthetic Work, and Vigilance. The ARES battery has been used to examine the effects of fatigue on cognition [43].

The Windows Space Cognitive Assessment Test (WinSCAT) [44,45] consists of the following ANAM-derived tests: Code Substitution (learning, memory), Running Memory, Mathematics, and Match to Sample. The WinSCAT battery has been used in space and has measured decrements in CPT accuracy and Math accuracy, presumably due to fatigue [46].

The Performance Assessment Workstation (PAWS) [47,48] consists of the following ANAM-derived tests: Visual Analog Mood Scale, Critical Tracking, Spatial Matrix, Memory Search, Continuous Recognition, Switching Task, Dual Task, and Fatigue Scale. The PAWS battery has also been used in space and has measured initial decrements in tracking performance, presumably to do microgravity, and later adaptation with better performance [47]. PAWS has also measured decreased performance in Switching Task in space, presumably due to fatigue [47]. On Earth, PAWS found no effect of bed-rest on cognitive performance [49].

The MiniCog battery [50] was designed to run on a PDA and consists of the following tests: Attention (Vigilance, Filtering, Divided), Working Memory 2-Back Task (Verbal, Spatial), Cognitive Set Switching, 3-Term Reasoning, Mental Rotation, and Perceptual Reaction Time. The MiniCog battery has been used to measure the effects of hypoxia on Mount Everest [50], the utility of caffeine and exercise to counteract fatigue [45], and the effect of relaxation techniques to cope with noise stress [45].

The CogScreen battery [51-53] consists of the following tests: Backward Digit Span, Math, Visual Sequence Comparison, Symbol Digit Coding, Matching to Sample, Manikin, Attention (Divided, Shifting), Auditory Sequence Comparison, Pathfinder, and Dual Task. Studies of flying performance have used the CogScreen battery to show the effects of age [54-57], medication [58,59], HIV [60], and brain injury [61-63] on cognition and flying performance.

The battery of O'Donnell et al.[11] consists of the following tests: Continuous Memory, Dichotic Listening, Digit Span, Manikin (low/high training), Match to Sample, Math Processing, Motion Inference, NovaScan C (Manikin+Continuous Memory), Precision Timing, Peripheral Information Processing, Rapid Decision Making, Reaction Time (choice, simple), Relative Motion (Join-Up), Sternberg (letters, symbols), Stroop, Tower of Hanoi (low/high training), Tracking (pursuit, unstable), Visual Vigilance, and Wisconsin Card Sorting. The construct validity of the tests was determined by having experts rate how much performance on each test was dependent on each cognitive ability in the O'Donnell taxonomy. Table 5 shows the highest rated tests for each ability.

Abilities	Highest Rated Tests
Sustained/Focused Attention	Relative Motion (Join-Up), Tracking, and Visual Vigilance
Divided Attention	Motion Inference
Selective Attention	Dichotic Listening, Stroop
Directed Attention	Dichotic Listening, NovaScan C (Manikin+Cont. Memory)
Working Memory	Continuous Listening, Digit Span, Math Processing, Sternberg (symbols), Tower of Hanoi (low training)
Declarative Memory	Sternberg (symbols)
Procedural Memory	Tower of Hanoi (high training)
Language/Semantics	Stroop
Decision Making	Rapid Decision Making, Tower of Hanoi (low training)
Planning/Problem Solving	Tower of Hanoi (low training)
Task Multiplexing	NovaScan C
Spatial Visualization	Manikin (low training)
Math Functioning	Math Processing
Problem Sensitivity	Rapid Decision Making
Cognitive Flexibility	Wisconsin Card Sorting
Situation Awareness	NovaScan C
Time/Velocity Estimation	Motion Inference, Relative Motion
Visual-Motor Control	Precision Timing, Relative Motion, Tracking (unstable)

Table 5: Highest Rated Tests for Abilities (from O'Donnell et al. [11])

The external validity of typical neuropsychological tests has been shown in studies showing the effects of cardiovascular disease [64-66], age [67-80], medication [81], intoxication [82,83], and brain injury [84-88] on cognition and driving performance, as well as effects of cognitive performance on flying performance [89-92]. Some driving studies focus on executive functioning [93-96] which can be measured by the Stroop task [97-103]. Studies have also found the effect of cognitive impairment on driving can be lessened with compensation strategies [104,105].

Many of the tests of cognitive ability appear to have high external validity, but the construct validity of the batteries has only been empirically tested with smaller subsets of tests within the battery. The number of necessary tests depends on the task(s) of interest.

In order to determine what abilities are needed for tasks, the U.S. Department of Labor has sponsored development of the Occupational Information Network (O*NET) Content Model [106,107], which builds on the work of Fleishman and Mumford [108]. O*NET contains ratings of abilities used in 950 occupations. Cognitive abilities used by O*NET include Comprehension (oral, written), Expression (oral, written), Fluency of Ideas, Originality, Problem Sensitivity, Reasoning (deductive, inductive), Information Ordering, Category Flexibility,

Mathematical Reasoning, Number Facility, Memorization, Speed of Closure, Flexibility of Closure, Perceptual Speed, Spatial Orientation, Visualization, Selective Attention, Time Sharing. The highest rated cognitive abilities for airline pilots and aerospace engineers can be seen in Table 6.

Cognitive Skill	Ratings for Airline Pilots
Problem Sensitivity	85
Spatial Orientation	85
Oral Expression	80
Oral Comprehension	75

Cognitive Skill	Ratings for Aerospace Engineers
Deductive Reasoning	91
Problem Sensitivity	91
Mathematical Reasoning	88
Written Comprehension	84

Table 6: Highest O*NET cognitive skill ratings for airline pilots and aerospace engineers.

Occupations were related to test batteries by Anderson et al. [109], who asked experts to rate abilities measured by a subset of the ANAM and CogScreen batteries that were needed for 350 occupations. The tests used from ANAM were Digit Set Comparison, Matching to Sample, Math Processing, Running Memory CPT, and Logical Relations Test. The tests used from CogScreen were Symbol Digit Coding, Pathfinder, Shifting Attention Test, Dual Task Test, and Visual Sequence Comparison.

In conclusion, "a set of tests to be used during all NASA-funded research simulating space missions" should be informed by a validated taxonomy of abilities to test and should depend on the abilities needed to perform particular tasks in space. A taxonomy with good validity and completeness appears to be Fleishman and Quaintance's [10]. This taxonomy is used by O*NET [106,107] to map occupations to abilities, which may be helpful in mapping space-related tasks to abilities. For mapping abilities to tests, the expert ratings of O'Donnell et al. [11] appear to have good coverage (but still need empirical validation).

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