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The Cognition and Fine Motor Skills Test Batteries: Normative Data and Interdependencies

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Acronyms and Definitions

3-D ....3 dimensional
AIM....................................... Abstract Matching (version of the task, developed by Glahn)
AM ....Abstract Matching (NASA Cognition Test Battery Abstract Matching task)
BART....................................Balloon Analog Risk Test
CBT.......................................Cognitive Behavior Therapy
CCW ....counter clockwise
cm..centimeters
CSF ....contrast sensitivity function
CTB.......................................Cognitive Test Battery
CW ....clockwise
deg...degree(s)
DEMO...................................demonstration
DOD HRPP...........................Department of Defense Human Research Protection Program
DSST.....................................Digit-Symbol Substitution Test
ERT ....Emotion Recognition Test
F2B..Fractal 2-Back
FMS ....Fine Motor Skills
FMSTB ....FMS test battery
in ....inch
IRB..Institutional Review Board
LOT.......................................Line Orientation Test
MPT ....Motor Praxis Task
MRT......................................Matrix Reasoning Test
msec ....miliseconds
NASA....................................National Aviation and Space Administration
PI ....Principal Investigator
PVT ....Psychomotor Vigilance Test
RMS ....root mean squared
sec ....second(s)
STEM....................................science, technology, engineering or mathematics
UPENN ....University of Pennsylvania
UTAF ....Usability Testing and Analysis Facility (at NASA Johnson Space Center)
VOLT....................................Visual Object Learning Test
WCST ....Wisconsin Card Sorting Test

The Cognition and Fine Motor Skills Test Batteries: Normative Data and Interdependencies

Bettina L. Beard[1]

Space mission success and safety relies upon astronaut functional state. Since spaceflight stressors affect cognitive processing and fine motor skills, NASA requires that measures of performance of these things remain within clinically accepted values (NASA STD 3001). NASA is in the process of developing two test batteries for the assessment of crew cognitive and fine motor skills before, during and after spaceflight. Toward that goal, the current project collected normative scores in 91 "astronaut-like" military and civilian pilots.

The Cognition Test Battery (CTB) contains ten sub-tests that measure a range of cognitive abilities. For five of the ten CTB sub-tests, we propose scores to improve the battery's sensitivity. Among the ten sub-tests, response times were more highly correlated than accuracy scores. Principle component analysis of the correlations revealed that the first response time factor could explain over 40% of the total variance and appeared to represent the tendency of observers to try to respond more quickly. The first accuracy factor (explaining only 20%) gave a high weight to the higher level cognitive sub-tests and a negative weight to tasks associated with motor and lower level cognitive processing.

The Fine Motor Skills (FMS) test battery contains four sub-tests (Tracking, Pointing, Tracing, Rotating) performed on an Apple iPad tablet computer. Principle component analysis on the sub-test response time correlations revealed that the first two factors accounted for ~80% of the variance in performance. The first component captured overall speed on all four of the sub-tests. The second factor separated the sub-tasks into two groups (Drag-Point vs Trace-Rotate). Previous work found the first group response times correlated with that of a standard peg board task, while those of the other group did not.

Correlations were computed between the first FMS factor and the response time and accuracy scores from each CTB sub-task. Performing fine motor behaviors rapidly was significantly correlated with the ability to perform many of the CTB sub-tests rapidly. This ability cannot be simple motor speed since scores on the Psychomotor Vigilance Test (PVT) subtask did not correlate with the ability to perform the other tasks rapidly. Speed on fine motor skills correlated significantly with accuracy on the short-term-memory sub-test. We hypothesize that eye movements, which can be regarded as a fine motor skill, may explain this relationship.

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1. Introduction

During space flight extravehicular and intra-vehicular activities are physically and mentally demanding. Crewmembers must perform various tasks that require eye-hand-arm coordination, sustained and divided attention, memory, visual perception, task prioritization and decision-making. Cognitive processes are required to follow procedures, operate a robotic arm, follow schedules or respond to emergencies. Daily activities such as typing on a computer keyboard, interacting with iPads, instrument control, medical procedures, self-care or vehicle maintenance require fine motor skills. The combined contribution of both cognitive and fine motor abilities define overall performance on many tasks. It is critical for the crew's safety, and for mission productivity, to know if, and when, physical or mental performance are compromised so that countermeasures may be introduced.

NASA is in the process of developing a comprehensive set of performance indicators, or standard metrics, during space flight. To that end, two test batteries are being developed; one that assesses a range of cognitive abilities and a second that assesses fine motor skills. When developing test instruments several factors should be considered including length and ease of administration, participant burden, psychometric properties, generalizability to the population under study and availability of norms to infer appropriate comparisons (Mitrushina et al., 2005). The goals of this project are threefold: (1) to collect normative data on the Cognition Test Battery (CTB) in an astronaut-like population; (2) to collect normative data on two versions of the Fine Motor Skills (FMS) test battery in this same population; and (3) to identify to what extent the motor component of the cognitive tests contribute to the overall score. The importance of the first two goals will be discussed in the next section (Section 1.1) and the third goal's significance will be discussed in Section 1.2.

This project best addresses the following NASA Human Research Program Biomedical element research gap:

> CBS-*BMed2: We need to identify and validate measures to monitor behavioral health and performance during exploration class missions to determine acceptable thresholds for these measures.*

1.1. Test Batteries under Development at NASA

1.1.1. The Cognition Test Battery

NASA has been assessing crewmember cognitive function using the WinScat test battery (Kane et al., 2005). Because the WinScat sub-tests predominantly focus on one aspect of cognition, executive processes in working memory, it was decided to develop a more comprehensive battery. To better understand the vast range of human cognitive functions, a prominent theory of human information processing is briefly described in Box 1.

Box 1. Human Information Processing

Since the mid-1970s, information processing theory has driven research, learning theory and user interface design (Proctor et al., 1990). To simplify the conceptualization of how the human brain processes information, this theory proposes a set of discrete processes. Briefly, information enters the central nervous system via specialized sensory receptor cells. This information is temporarily stored and, if attended to, results in perception of the information. Once perceived, and if attended to, the information is then processed by working memory where an executive controller actively maintains, manipulates and organizes the information. Specifically, the executive controller:

- selectively attends to relevant information and filters distracting information
- inhibits inappropriate response tendencies
- directs attention to relevant stimuli by retrieving stored knowledge from long-term memory
- flexibly switches between tasks and restructures knowledge and information based on changing situational demands (task-switching)
- temporarily stores and manages information while learning
- works with information held in working memory (manipulation)
- uses context to determine whether an action is appropriate, or a thought is relevant (Bunge & Crone, 2009; Miyake et al., 2000)

Working memory processes are highly susceptible to interruptions, distractions and stressors. Vigilance also requires working memory resources. Long-term memory can be described as containing two types of knowledge: declarative and procedural (Cohen and Squire, 1980). Procedural memory refers to unconscious skills such as riding a bicycle, walking, flying an airplane or reading and is essential for the development of any motor skill or cognitive activity. Declarative memory, the second type of knowledge in long-term memory, refers to conscious memories used day-in and day-out, such as facts, personal experiences and internal maps of the environment. The hippocampus, part of the forebrain, is critical in the formation of declarative memories (Eichenbaum, 2001). Recalling information from declarative memory requires conscious effort. The hippocampus acts as a search engine, efficiently searching the stored memories that are essential for planning the future and generating creative ideas.

The CTB tests an extensive range of information-processing domains ranging from sensorimotor speed to abstract reasoning (see Methods for specifics). The CTB is based upon standardized clinical tests of cognition. Each sub-test has shown specific sensitivity to certain neurological diseases (Glahn et al., 2000), to reliably result in similar scores over repeated testing (Gur et al., 2001) and to be valid indicators of stages of cognitive processing (Gur et al., 2010).

1.1.2. The Fine Motor Skills Test Battery

Current training, scheduling, as well as payload and maintenance procedures, require crewmembers to use touchscreen devises on the International Space Station. The Fine Motor

Skills Test Battery, or FMS, was developed by the Usability Testing and Analysis Facility (UTAF) located at Johnson Space Center (JSC) to determine the effects of microgravity and other stressors on fine motor skills critical to the success of these operational tasks. The FMS is composed of four sub-tasks performed on an iPad:

- a multidirectional pointing task, in which the subject points to and taps on targets
- a dragging task, in which a target is repetitively dragged from one position on the screen to another
- a (circles and squares) shape-tracing task
- a pinch-rotate task, in which a geometric object is selected and rotated, using the touchscreen, to align with another geometric object presented on the screen. Touch, pinch and rotate operations are common tasks on modern touch interfaces and are similar to using the thumb and forefinger to pick-up objects and for writing.

To understand how comprehensive the chosen tests are requires a discussion. Fleishman (2010) developed a taxonomy of 52 human abilities. These 52 abilities, or metric classes, and their definitions are provided in Appendix A. Ten of these abilities are motor skills and four of those have been reported to correlate consistently with job performance (McHenry & Rose, 1988). These are finger dexterity, manual dexterity, wrist-finger speed and multiple (arm, wrist, hand) coordination. These four motor skills will now be briefly reviewed.

Finger dexterity refers to accuracy in finger movements. An earlier 3-D manual test of finger dexterity required repetitive insertion of rivets in a hole and to secure them with a washer (i.e., O'Connor Tweezer Dexterity test; O'Connor, 1998). The correlation coefficient of the O'Connor Tweezer task with job performance is approximately $r = 0.19$ (McHenry & Rose, 1988). Singh & Aggarwal (2016) developed an iPad application to measure finger dexterity where subjects place their thumb on a pivot point and trace an arc path (several radii are provided) with the index finger. They found that the iPad task correlated with job performance with correlation coefficients up to 0.34. The rotate aspect of the FMS pinch-rotate task emulates the Singh & Aggarwal task in assessing finger dexterity.

Manual dexterity refers to the speed of arm movements. An earlier test of manual dexterity involved unscrewing pegs from one board, turning them over and attaching them to another board (i.e., GATB Manual Dexterity Test, McHenry & Rose, 1988). The correlation coefficient for this task with job performance is approximately $r = 0.22$ (McHenry & Rose, 1988). Singh & Aggarwal (2016) developed several iPad applications to test manual dexterity that involve (a) tapping random locations on the screen as they appear and to (b) trace a triangle. The NASA FMS pointing task involves tapping a sequence of positions around a circle similar to the first Singh & Aggarwal manual dexterity task.

The second manual dexterity task developed by Singh & Aggarwal (2016) was tracing a triangle. The NASA FMS contains two tracing tasks: tracing a circle and tracing a square. The subject performs the tracings both clockwise and counterclockwise. Feedback is provided in the form of the pattern traced as compared to the original shape. On the FMS, subjects perform the pointing, tracing and dragging tasks both with their fingers and with a stylus. It is likely that conditions using a stylus would better reflect paper-based tracing performance. Five astronauts participated in a study involving pointing within specified regions of a touchscreen using a stylus (Fowler et al., 2008). The results were consistent with Fitt's (1954) law which states that the time needed to successfully execute an aiming movement increases linearly with task difficulty.

Wrist finger speed refers to the speed of wrist and finger movements. An example of a test of wrist-finger speed involves tapping as rapidly as possible (i.e., Large Tapping test, McHenry & Rose, 1988). The correlation coefficient for this task with job performance is approximately r = 0.18 (McHenry & Rose, 1988). Singh & Aggarwal's (2016) developed two iPad applications for this performance measure. The first involves pinching one circle to spatially coincide with another fixed circle. The second is similar to their finger dexterity task described above involving a pivot point, but here the arc was wider (analogous to screwing a light bulb into a socket). The NASA FMS contains a task that combines pinching and rotating where the subject pinches a diamond and rotates it to coincide with a fixed square. The subject is required to do this in two orientations. Therefore, the FMS combines a finger dexterity task with an assessment of wrist finger speed.

Multiple coordination refers to the proficiency in performing coordinated movements with two or more limbs. Sub-tests of the Purdue Pegboard test measure this ability. The correlation coefficient for this task with job performance is approximately r = 0.14 (McHenry & Rose, 1988). Singh & Aggarwal (2016) developed an iPad application for this ability where the subject must tilt the entire screen with both hands to guide a virtual ball along a course. The FMS does not assess multiple coordination, but it is unclear how this might be assessed in microgravity since the iPad uses linear accelerometers that require gravity input to determine tilt. In summary, the FMS includes sub-tests that sufficiently address key fine-motor skills.

The test-retest reliability of the FMS is excellent (r = 0.975). There are two versions of the test: one that requires approximately 15 minutes to complete (long version) and one taking approximately 5 minutes (short version). The short version was developed to accommodate post-flight crew-time constraints and was developed by removing some of the seemingly redundant aspects of the longer version.

1.2. Motor Contributions of each CTB Sub-test

Fine motor control has been assessed before, during and after both short and long-duration spaceflight. Reduced motor control abilities were reported on one Soyuz approach to the Mir space station (Manzey et al., 1993; 1995) and on many occasions in the first days and weeks after entering microgravity (Berger et al., 1997; Bock et al., 2001; Bock et al., 2003; Fowler et al., 2000; Heuer et al., 2003; Kubis et al., 1977; Manzey et al., 1998; Manzey et al., 2000; Newman & Lathan, 1999; Sangals et al., 1999; Schiflett et al., 1995; Semjen et al., 1998) that has been attributed to sensorimotor adaptation (Manzey et al., 2000). Reduced fine motor performance has also been reported later in the mission (Berger et al., 1997; Semjen et al., 1998). Manzey et al. (2000) found that in a single cosmonaut reduced motor performance in the last four days before return was aligned with evidence of more negative reports on mood and workload measures.

Neuropsychological measurement of cognitive processing speed is potentially problematic where deficits in motor performance are expected. Kreiner and Ryan (2001) and Joy et al. (2000) found that hand motor skill explained a large portion of the variance in Digit Symbol-Coding variance in clinical populations.

Another purpose of this project was to extend CTB validation by determining to what degree motor responses contribute to the overall score. This is important to know since there are known deficits in motor abilities associated with gravity transitions (e.g., Manzey et al., 1993). It is less clear if cognitive declines during the gravity transition period can be explained by these motor deficits since all CTB sub-tests contain a motor component. In addition, critical inter-dependencies exist between fine motor and cognitive processes.

1.2.1. Inter-Dependencies between Fine Motor and Cognitive Processes

Although cognitive and motor processes are often discussed as if they are independent functions (e.g., sensation as separate than executive processes or decision making as separate than motor responses), they are actually inter-dependent. An important correlation between psychomotor and cognitive abilities is often reported (Carretta, 1997; Penner-Wilger et al., 2007; Ree & Carretta, 1992). As examples:

- Even relatively simple sensory measures require the ability to comprehend directions, remember them and to sustain attention (Salthouse et al., 1996).
- Higher order processing is affected when the sensory image is degraded (Monge & Madden, 2016).
- Grooved pegboard performance relates more highly to cognitive than to motor involvement in Parkinson's disease (Bezdicek et al., 2014).
- Fine motor movements toward visual objects require attentional resources (Frens & Erkelens, 1991).
- Spatial working memory is involved in the execution of precise movements such as in grasping objects (Baldauf & Deubel, 2010).

Since Schmahmann's (1997) landmark publication, there has been an increasing interest in the cerebellum's role in emotion, cognition and motor processing (Diamond, 2000; Baillieux et al., 2008; Küper et al., 2011; Molinari et al., 2009). Neuroimaging studies have shown cerebellar activation during sensory acquisition and discrimination tasks (Gao et al., 1996). The motor cortex (Diamond, 2000; Georgopolous, 2000), cerebellum (Diamond, 2000; Rao et al., 1997), basal ganglia (Harrington et al., 1998) and dopamine receptors (Nieoullon, 2002) are crucial in the processing of higher order cognitive information. In fact, neuroimaging studies suggest that cognitive functions are distributed throughout the brain (McIntosh, 2000). It is the interactions between these regions that determine cognitive function. Feedback loops are ubiquitous throughout the brain. One theory of cognition states that mammalian brains evolved for adaptive action, not for cognition and thought. The human cerebral cortices evolved to perform cognitive processing, but only with guidance from the cerebellum.

A leading scientist in this field proposed an intriguing theory of the relationship between motor and cognitive processes (Koziol et al., 2012). Just as sensorimotor practice guides the development of internal models within the cerebellum that are then sent to the motor cortex for implementation, sensorimotor practice also forms internal models within the cerebellum that are projected to the cerebral cortex for executive functions, e.g., mental manipulations, rehearsal or pulling information from long-term memory storage.

Anatomically, much of the cerebellum is linked with motor systems, but a specific zone is linked with the cerebral cortex and therefore different aspects of cognition (Ito, 2014; Strick et al., 2009; Glickstein et al., 2011). Different zones of the cerebellum develop internal models in the same way (i.e., similar sets of neural fibers; Ito, 1993). New internal models develop in adjacent locations rather than overwriting previously stored models. This modular organization of internal models may support flexible adaptation depending on the context (Imamizu, 2014). Studies are underway to unravel these complex interrelationships.

There are several other lines of evidence suggesting an inter-dependency between fine motor skills and cognition. Terrestrial research shows that both fine motor and cognitive processes are disrupted by similar stressors. Table 1 shows a sampling of research demonstrating this relationship.

Table 1. Example Publications Providing Evidence that Fine Motor and Cognitive Skills are Affected by Some of the Same Stressors

Stressor	***Fine Motor Performance***	***Cognitive Performance***
Physical workload	Straker & Mathiassen (2009)	Perry et al (2008)
Cognitive workload	Grant et al (2009)	Mehler et al (2010)
Vibration	Sanes & Evarts (1983)	Conway et al (2007)
G-forces	Ross (1991)	Grabher & Mast (2010)
Danger/Anxiety	Barnard et al (2011)	Barnard et al (2011)
Fatigue	Barker & Nussbaum (2011)	Flindall (2015)
CO_2	Manzey et al (1998)	Satish et al (2012)
Sleep deprivation	Scott et al (2006) Williamson & Feyer (2010)	Caldwell et al (2003) Williamson & Feyer (2010)
Acute hypoxia	Chen et al (2013)	Wilson et al (2009)
Decompression sickness	Webb & Pilmanis (2011)	Sausen et al (2001)
Reduced pressure	Seminara et al (1967)	Bahrke & Shukitt-Hale (1993)
Exercise	Raudsepp & Päll (2006)	Tomporowski (2003)
Hypoglycemia	Schächinger et al (2003)	Schächinger et al (2003)
Extreme temperatures	Ramsey (1995)	Hancock & Vasmatzidis (2003)
Normal aging	Seidler et al (2010) Krampe (2002)	Kramer & Madden (2008) Verhaeghen & Cerella (2002)
Extreme environments (simulations & spaceflight)	Newman & Lathan (1999)	Newman & Lathan (1999)

Note that crewmembers experience most of the stressors listed in Table 1. There are studies that have failed to find these negative stressor effects, and these differences need to be disentangled, however the majority of references identified show significant stressor effects.

Research on children has also demonstrated a significant relationship between motor skill development and cognition (Wassenberg et al., 2005) possibly linked to executive functioning, specifically (Roebers et al., 2014). Van der Fels et al. (2015) reported strong correlations between fine motor skills and visual processing and attention and moderate correlations between fine motor skills and working memory and executive functions in 4–16 year olds. Links between motor skills and cognitive abilities are also reported in children and adults with attention deficit hyperactivity disorder, developmental coordination disorder, and dyslexia or those who have suffered from hypocapnia (Dewey et al., 2002; Egeland et al., 2012; Gibson, 1978; Hamilton, 2002; Klimkeit et al., 2004; Mandich et al., 2003; Pitcher et al., 2003; Viholainen et al., 2002; Visser et al., 2014).

Attention is the cognitive ability most recurrently related to general motor control (Lajoie et al., 1996; Woollacott & Shumway-Cook, 2002). Strenge and coworkers addressed the relationship between cognitive functioning and manual ability in young healthy adults (Strenge et al., 2002). In that study, two pegboard tests and an attentional task were used. Results showed a moderate correlation between dexterity and attention.

There is also considerable research showing that both fine motor and select cognitive (e.g., response speed, problem-solving and goal-oriented action) task performance are enhanced after acute (Lambourne & Tomporowski, 2010; Reilly & Smith, 1986) and regular (Guiney & Machado, 2013; Kamijo et al., 2009) aerobic exercise as long as the exercise protocol does not exhaust or dehydrate the individual. Cai et al. (2014) found a reduction in motor skill loss with age in people who practice fine motor tasks and exercises. There are, of course, exceptions to this generalization (see McMorris & Graydon, 2000), but in a meta-analysis of the literature, Tomporowski (2003) suggested that the majority of the empirical data provide compelling support for improved fine motor and cognitive performance after exercise.

Objectives of the Current Project

Most U.S. astronauts have a Master's degree in science, technology, engineering or mathematics (STEM). Moore et al. (2017) collected data on the CTB in 96 Philidelphians (age range from 25 to 56 years) with at least a STEM Master's degree. Most U.S. astronauts and all European Space Agency astronauts are pilots. It would be expected that many fine motor responses will be automated in seasoned pilots, requiring relatively little cognitive demand. To resemble the current astronaut population, the current project obtained data in 91 certified pilots. It was predicted that those tasks that require scanning of objects and a choice will be strongly related: MPT (Motor Praxis Test), AM (Abstract Matching), MRT (Matrix Reasoning Test), and DSST (Digit-Symbol Substitution).

The current study also assessed the correlational relationship between the two test batteries (the CTB and the FMS) to disentangle how motor processes contribute to cognition test scores. If a crewmember is showing poorer performance on any of the CTB sub-tests, knowledge about what type of motor deficit versus cognitive deficit contribute to the decline can help pinpoint which countermeasures to employ. It was predicted that those tasks with similar motor response characteristics (swipe trackpad, position arrow, click trackpad, repetitive clicks, hit spacebar, point with index finger) will be most related. It was also hypothesized that the CTB and FMS test batteries will capture piloting skill as indicated by flight hours.

2. Methods

2.1. Participants

2.1.1. Age Range and Sample Size

Data were collected on n = 91 individuals. Power calculations determined that this sample size met the criteria for a reasonable chance (≥ 0.80) of detecting an age effect given a conventional level of alpha (.05) for a one tailed test—with a hypothesis that performance will decline with age for ages over 37 years old (e.g., Salthouse, 2007). Fifty of these participants were military pilots (i.e., U2 Dragonlady, C5 Galaxies, KC-10 Extenders, C-17 Globemasters, F/A-18E Super Hornet Fighter), 35 were private, corporate or commercial airline pilots and seven were military personnel with non-flying responsibilities within military aircraft (e.g., flight engineers, gunners, loadmasters, etc.).

Of the 91 participants, 88 collected data on the long version of the FMS, 84 on the short version of the FMS, and 89 on the CTB. There were 80 participants who collected data on all three test batteries.

Appendix B provides screen shots of the CTB and FMS questionnaires and a copy of a new seventeen item, computer-based questionnaire that was administered to all participants. Questions inquired about variables previously found to correlate with performance on various neuropsychological tests. Answers were either fill-in-the-blank, forced-choice, a list or ratings.

2.2. Equipment

Cognition software was run on a Hewlett Packard ZBook with Intel(R) Core™ i7-6820HQ CPU @ 2.70GHz processor. Display size was 34.29W x 17.78H with a brightness setting of 100%. The display resolution was set to 1920 x 1080. System latency was defined as 42.5 ms (keyboard) and 41.2 msec (mouse) based on the average latency determined by Pulsar Informatics on similar machines.

Fine Motor Skills Test Battery software was run on a MC707LL/A Version 9.3.5 iPad with a brightness setting at approximately 75%.

2.3. Procedures and Stimuli

To collect normative data, the Principal Investigator (PI) travelled to Beale Air Force Base, Lemoore Naval Air Station, Travis Air Force Base, and Edwards Air Force Base, spending a week at each military post. Testing locations were either a reserved conference room or office space. Data were also collected at NASA Ames Research Center in the PI's office.

Each testing session began with an explanation of the overall goal of the project and nature of the tasks. Written informed consent was then obtained as per the requirements set by the NASA Ames Research Center's Human Institutional Review Board (IRB). To ensure anonymity and confidentiality, each participant was assigned a random subject number that was associated with a randomized testing sequence of the Cognition, FMS-short or FMS-long test batteries (see Table 2). For example, subject 98 was tested first on the CTB, second on the FMS (long version) and finally on the FMS (short version). There were 41 instances when the short version, and 41 instances when the long version, was run first.

Table 2. Example of Randomized Test Sequences for Four Subjects

Randomized Participant Number	***Tested First***	***Tested Second***	***Tested Third***
98	Cognition	FMS long version	FMS short version
142	FMS short version	Cognition	FMS long version
176	FMS long version	FMS short version	Cognition
52	FMS long version	Cognition	FMS short version

Modification to Random Orders for Ten Participants

The PI agreed to also collect data for the Project entitled "Evaluation of tablet-based methods for vision assessment" (IRB #HRII-18-08) in a subset of pilots. This study uses a touch-screen-based application to measure the visual contrast sensitivity function (CSF) for the purpose of rapidly assessing crew vision changes (Mulligan, 2016). For these participants, the order of testing for the FMS-short, FMS-long, CTB, and CSF was randomized.

2.3.1. General Procedures

The PI sat in a position outside of the participant's field of view, but in a place that allowed the PI to assess adherence to directions. Each participant was given time to practice each task as many times as they needed to ensure they understood the task. This typically involved one repetition (occasionally two) of the brief training module. When the subject had successfully completed practice and did not have any questions about the task instructions, data collection began. The number of practice tests were recorded.

Commercial aviators were compensated for their participation. Military personnel were not allowed to accept compensation. There are very specific rules within the Department of Defense Human Research Protection Program (DOD HRPP) policies (DODI 3216.02) about compensation of active duty military personnel. On duty compensation is restricted to blood draws only; off duty, military personnel can be compensated for things other than blood draws but only if the source of the compensation is not federal funding. The exact wording from the policy is:

> "Federal personnel while off duty may be compensated for research participation other than blood draws in the same way as human subjects who are not Federal personnel (i.e., compensated for participation in a reasonable amount as approved by the IRB according to local prevailing rates and the nature of the research). However, payment to off-duty Federal personnel for research participation other than blood draws must not be directly from a Federal source (payment from a Federal contractor or other non-Federal source is permissible)."

Each sub-test was administered once requiring approximately one to 1.5 hours (including breaks). Data were obtained in 31 conditions: 12 (long version of FMS); 9 (short version of FMS); and 10 (CTB). Data collection on the CTB is discussed in Section 2.3.2 and on the FMS in Section 2.3.3.

2.3.2. Data Collection on the Cognition Test Battery

Table 3 lists the ten specific sub-tests of the CTB and their common abbreviation. The CTB software (Version 3.0.9-201710021500) always presented the sub-tests in the same order (i.e., MPT, VOLT, …PVT). As shown in the fourth column of Table 4 labelled “Randomized Stimuli,” six of the ten sub-tests present a predetermined set of stimuli, in the same order, each time the battery is run (from Cognition User Manual 09/01/2017). The remaining four sub-tasks dynamically generate random stimulus variation; i.e., MPT and LOT randomize the stimulus location, DSST randomizes which prompt stimulus is presented and the PVT randomizes the inter-stimulus interval.

Table 3. Cognition Test Battery Sub-tests, their Order of Testing and Whether the Stimuli within a Block of Trials are Randomized

Order of Testing	*Sub-test Name*	*Abbr.*	*Randomized Stimuli*
1	Motor Praxis Task	MPT	Yes
2	Visual Object Learning Test	VOLT	No
3	Fractal 2-Back	F2B	No
4	Abstract Matching	AM	No
5	Line Orientation Test	LOT	Yes
6	Emotion Recognition Test	ERT	No
7	Matrix Reasoning Test	MRT	No
8	Digit-Symbol Substitution Test	DSST	Yes
9	Balloon Risk Test	BART	No
10	Psychomotor Vigilance Test	PVT	Yes

For individuals taking the CTB repeatedly, there are 15 versions, referred to as “Batteries.” The current study used Battery 3.[2]

The University of Pennsylvania (UPENN) group had indicated that in previous studies they presented a 15-min familiarization video (https://upenn.box.com/s/83nl8kfqqc8fa1maq7 8bz0nz7ba44hmg) to each novice participant at the onset of CTB testing. Because of the large number of participants with limited time available for the current study, the information delivered in the video was provided using a pre-prepared set of PowerPoint slides depicting the test stimuli along with a composed, standard manuscript of instructions. These instructions are provided in Appendix C, Table C-1. Although all the instructions in the UPENN video were captured in the current, composed, standard manuscript, the wording was revised for clarity and supplementary information added based on questions asked by ten pilot (pilot as in preliminary)

[2] The UPENN group suggested Battery 3 because this was the most commonly tested version to date.

participants. In addition, rather than explaining all the tasks at the outset, as is done with the 15-minute video, in the current study, each task was explained immediately before the task was performed. As a result of these changes, participants had a firm grasp of the task requirements with a reduction in the time required for sub-task explanation from 15 to a total of ~6 minutes. Practice trials had to be completed successfully in order to start the test.

The following is a description of the ten CTB sub-tests.

Motor Praxis Test (MPT)

The MPT determines how well participants use the computer trackpad and is a measure of visual location identification, psychomotor speed and finger dexterity. Participants are shown 20 blue squares presented one at a time at a random location on the screen. Each square is successively smaller. As soon as a square appears, participants are to use the trackpad to rapidly move the cursor onto the square and then click using the trackpad button. As soon as the participant clicks on the square it disappears and another square is presented.

Visual Object Learning Test (VOLT)

The VOLT is a test of spatial image learning and working memory retrieval of visual images. Participants are asked to remember 10 images of wireframe objects with one facet colored blue. Each image is shown successively for 5 seconds. In the test phase participants are shown 20 images, one at a time. Half of these are sampled from the learning set, while the remaining half consist of novel objects. Participants end the presentation by clicking on one of four options labeled “Definitely Yes,” “Probably Yes,” “Probably No,” or “Definitely No” as to whether the image was in the learning set.

Fractal 2-Back (F2B)

The F2B test measures distractor effects on working memory maintenance and retrieval as well as sustained attention. Participants are shown 62 fractal patterns, one at a time, for 1.75 sec. They are to press the spacebar during the presentation if the pattern is the same as the one shown two patterns before. This requires remembering the last two patterns and comparing them to the current image while continuously updating their memory as the trials progress. Fifteen of the 62 test images satisfied the two-back criteria.

Abstract Matching (AM)

The AM test measures the ability to group stimuli in some meaningful way (abstraction) and to learn undisclosed, abstract concepts or rules based on feedback. Pairs of figures (circles, triangles, hexagons, crosses or stars) in one of three shades (light blue, dark blue or unfilled) are shown on the bottom of the screen. A single figure is shown in the center top of the screen. The task is to choose the figure pair at the bottom of the screen that best fits with the top figure. After clicking on their choice, the participant is provided feedback. They are to use the feedback during the 30 trials to learn the set of rules and therefore must exhibit cognitive flexibility.

Line Orientation Test (LOT)

The LOT is a perceptual task. The participant is shown two lines. The reference line (6.06 cm length) is shown in random orientations and positions on the screen. The test line is shown at a randomly assigned orientation with its centroid a constant distance (6.93 cm) from the reference line. The test line may be one, of four, line lengths (1.73; 3.46; 5.19; and 6.06 cm). The task is to rotate the test line, using arrows positioned on the lower screen, in set increments of 2 deg, until it is parallel to the reference line. There are twelve, self-paced trials.

Emotion Recognition Test (ERT)

In the ERT 20 three-quarter-head shots of adults (of various ages and ethnicity) are presented one at a time. The task is to categorize their expression from a list of five emotions ("Happy," "Sad," "Angry," "Fearful," or "No Emotion").

Matrix Reasoning Test (MRT)

The MRT measures the ability to examine an array of patterns containing one blank cell and to deduce relationships among the patterns that are satisfied by the best choice from five options to fill-in the missing cell. There are 12 trials.

Digit-Symbol Substitution Test (DSST)

In the DSST participants are shown a legend of nine reference symbol-digit pairs at the bottom of the screen. A series of test symbols are presented at the top of the screen one at a time. For approximately 90 seconds, the task is to select, using the top row number keys, the number associated with the test symbol.

Balloon Analog Risk Test (BART)

In the BART participants inflate 30 balloons, shown one at a time, as much as they can without popping them. Pressing an "inflate" button increases virtual earnings by $1 or pops the balloon. The participant may press a "collect" button, rather than continuing to inflate, to transfer the current earnings into a total winnings sum. If the balloon pops, the current earnings are lost, but the accumulated winnings are untouched. A probability distribution function defines when each of the 30 balloons will pop. Participants are not informed about the probability distribution characteristics.

Psychomotor Vigilance Test (PVT)

The PVT measures how quickly the participant can respond to the onset of a millisecond counter. The test continues for 3 minutes. Instructions include a warning not to respond before the counter begins (false start). To aid with fixation, a continuously presented box is shown at the center of the screen. The counter displays the last reaction time for 1 sec. The next counter appears at a time sampled from a uniform distribution over 1 to 4 sec.

2.3.3. Data Collection on the FMS

Table 4 provides a summary listing of the sub-tests on the long and short versions of the FMS. Data were collected in 82 participants on both the long and short versions. The FMS software includes a demonstration (DEMO) capability. The DEMO screen was shown to each participant at which time the Principal Investigator stated "The Fine Motor Skills battery contains 4 sub-tasks: a dragging, pointing, tracing, and a pinch-rotate task." The standard instructions used for each sub-task are provided in the third column of Table D-1 in Appendix D. Practice was provided for all sub-tests.

Table 4. Sub-tasks and Conditions included in the Long versus Short FMS Test Batteries

Sub-task	***Long Version***	***Short Version***
Drag (finger & stylus)	Horizontal Vertical	Horizontal Vertical
Point (finger & stylus)	Clockwise Counterclockwise 1.5 in 2 in	Clockwise Counterclockwise 1.5 in
Trace (finger & stylus)	Clockwise Counterclockwise Circle Square	Clockwise Counterclockwise Circle
Rotate	0 deg rotation 45 deg rotation	0 deg rotation

The FMS software provided a fixed order of testing for both the long and short versions. The fixed order of testing for the long version of the battery, followed by the number of trials within the testing block and the number of times that sub-test was tested are shown in Table D-2 in Appendix D. Table D-3 in Appendix D shows the fixed order of testing for the short version of the FMS. For all participants, the FMS short version always required data collection using a stylus first, followed by use of the finger(s). The long version, conversely, always required data collection using the finger(s) first, followed by the use of the stylus. Data were obtained with both the participant's index finger and a stylus for all but the Rotate test. The FMS long version included a repetition of all tests. The FMS short version excluded the 2 in Point test, the square Trace test and the 45-deg Rotate test.

The following is a description of the four FMS sub-tests.

Drag

The Drag test measures manual dexterity, or the speed of arm movements. The task is to push (i.e., place finger or stylus on a square and drag) a white square back and forth or up and down from one designated area on the screen to another. Each block contained 16 trials. Each participant ran in twelve blocks of trials (2 directions x 2 repetitions x finger/stylus) for the long version and (2 repetitions x finger/stylus) for the short version of the test.

Point

The Point test also measures manual dexterity. A ring of 16 squares is presented. The task is to tap the highlighted square. The top square is always highlighted first. An arrow indicates if the highlighted square will travel clockwise or counterclockwise around the ring. As soon as the participant taps the highlighted square, it is de-emphasized and the square on the opposite side of the ring is highlighted. Each block contained 18 trials. There were two distances; one where the distance between the squares was 1.5 in and the second where the distance was 2 in. Each participant ran in twenty blocks of trials (2 directions x 2 repetitions x 2 ring sizes x finger/stylus) for the long version and (2 repetitions x finger/stylus) for the short version of the test.

Trace

The Trace test also measures manual dexterity. The participant follows the outline of a geometric figure starting at the location of a small circle labelled “Start.” They trace along the outline in the direction indicated by an arrow. Feedback was provided on the path traced. Each block contained 5 trials. Each participant ran in twelve blocks of trials (2 directions x 2 repetitions x finger/stylus) for the long version and (2 repetitions x finger/stylus) for the short version of the test.

Rotate

The Rotate task measures finger dexterity and wrist-finger speed. In this test the participant places their index finger and thumb on two circles at the opposite corners of a blue square. They then pinch and rotate the square on the iPad screen to align with a 45-deg rotated inner black square. When the two squares are coincident, the participant lifts their fingers. The adjustable blue square location was provided as it is rotated. Each block contained 6 trials. Each participant ran in five blocks of trials (2 orientations x 2 repetitions) for the long version plus 1 repetition for the short version of the test.

3. Results

3.1. Pilot Demographics

Ninety-one pilots participated in this study. They ranged from 23 to 78 years of age (mean = 37.18; SD = 12.65). Seventy-eight participants were male and 11 were female. Seventy-four were right-handed, 9 were left-handed and 6 reported being ambidextrous (although they used their right hand for data collection). Highest level of education reports indicated 10 pilots with a high-school education; 43 with a bachelor’s degree; 35 with a Master’s degree; and one doctoral level degree. Estimated number of flight hours ranged from 55 to 21,000 (mean = 2272.26; SD = 3308.94) with a median of 1800 hours and mode of 3000 hours.

3.2. Normative Cognition Test Battery Scores

Figure 1 shows the average response times for the 89 participants in the present study and the corresponding scores from Moore et al. (2017). The ERT and BART were performed significantly more slowly in the present study. The LOT responses were faster in the present study.

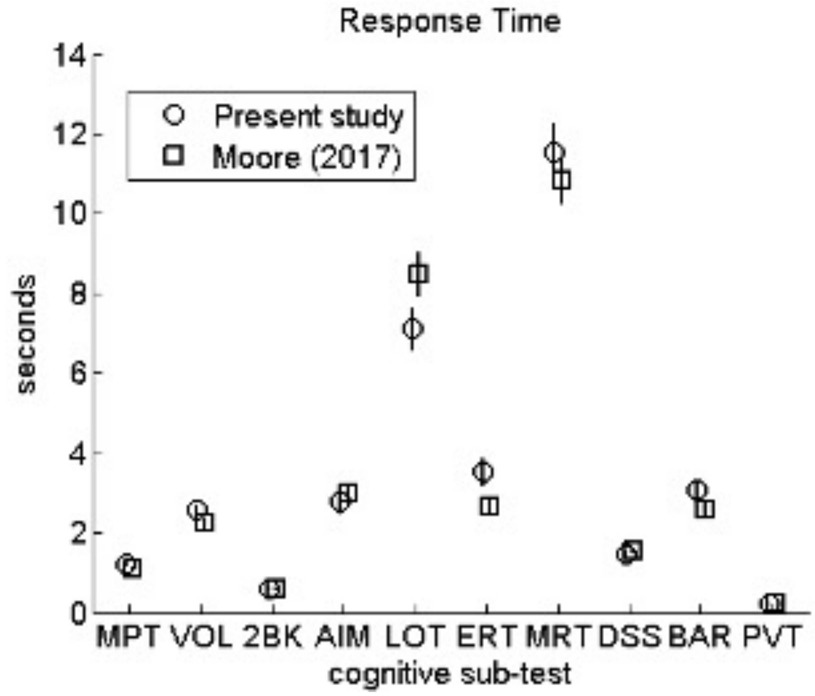

Figure 1. Mean response times for the present study and those of Moore et al. (2017).

New calculations are proposed for the MPT, LOT, and BART in Table 5. For the MPT the time is the time to the first response to simplify the measure. Previous measures were the time to the last response which sometimes included the time of position corrections. For the LOT, Moore et al. used the time to the final response. This includes trials that were nowhere near threshold. The proposed measure uses the response time for zero offset, and trials with offsets less than seven steps away from alignment that led to errors. For the BART, Moore et al. reported time to the last response of the trial.

Table 5. Cognition Test Battery Response Time Means and Standard Deviations (in parentheses) for 89 Participants.

Acronym	*Response Time (sec)*
MPT*	1.2165 (0.2056)
VOLT	2.5988 (0.5931)
F2B	0.6058 (0.0935)
AM	2.7671 (1.2158)
LOT*	0.8453 (0.2694)
ERT	3.5234 (1.5665)
MRT	11.5381 (3.2833)
DSST	1.4679 (0.2882)
BART	3.0700 (1.2308)
PVT	0.2153 (0.0182)

* Proposed measures are shown for the MPT and LOT.

Accuracy scores for the 89 participants in this study are shown in Figure 2. The MPT score is accuracy in pixels regardless of the box size (the average distance D of the response from the box center in pixels, transformed to make increasing scores better and the maximum score one, (50-D)/50), the VOLT score is based on only two categories (where "definitely" and "probably" categories are merged), the F2B accuracy formula is 0.5 * (Hit Rate - False Alarm Rate) + 0.5, the AM is percent correct, the LOT is average steps off at the conclusion of a trial, for ERT, MRT, DSST it is percent correct, for the BART score is the average number of pumps per trial divided by 4.5 and finally, the PVT score is the number of responses between 0.1 and 0.355 sec divided by the number of trials plus the number of anticipation responses. The comparable scores, calculated in the same manner, from Moore et al. (2017 are also shown. Our accuracy results are similar to Moore et al. for all but the ERT and the BART.

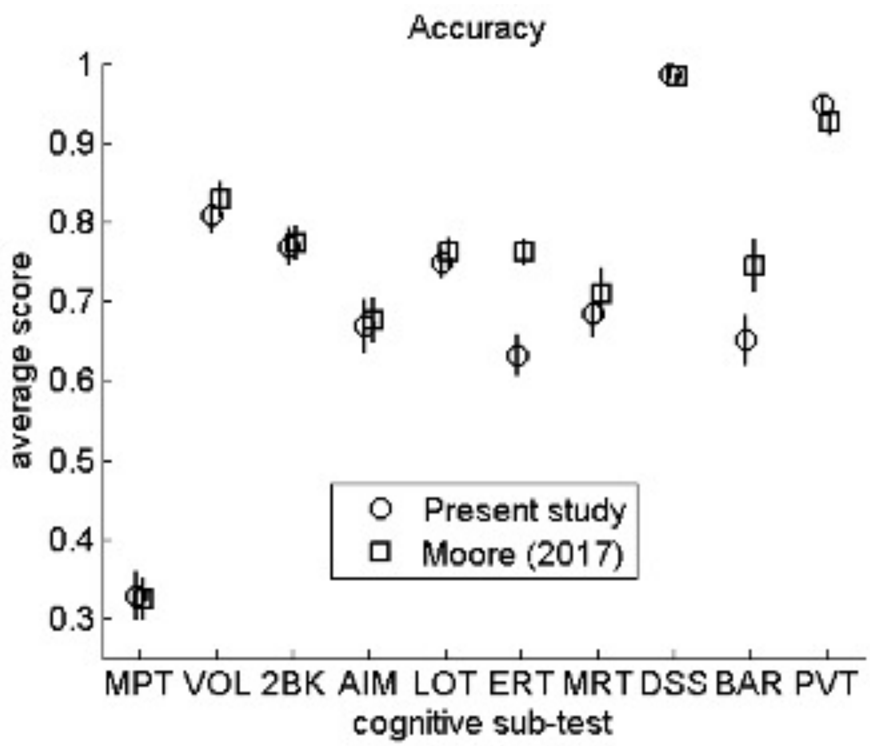

Figure 2. Mean accuracy scores for the present study and those of Moore et al. (2017).

Table 6 shows accuracy scores for the ten CTB sub-tests averaged over 89 participants. Five new accuracy scores—based on five new formulas—are proposed for measuring accuracy. Appendix E provides details about the calculations and the rationale for their use; namely, the data is used more efficiently thus improving sensitivity on those five sub-tests. Briefly, the MPT accuracy score takes box size into consideration. The VOLT score is the proportion correct when qualifiers "definitely" and "probably" are not ignored. The LOT score is the average absolute rotation error E in degrees of angle, transformed to make increasing scores better and the maximum score one (6-E)/6. The ERT is information transmitted. The BART score is 1-mean pumps on "collect."

Acronym	Accuracy Score (SD)	Measure	r
MPT*	-0.516 (0.096)	-Pixels/(0.5 box width)	0.96
VOLT*	0.865 (0.105)	ROC area	0.91
F2B	0.770 (0.107)		
AM	0.669 (0.162)		
LOT*	3.748 (0.958)	Model Std Dev, deg	0.60
ERT*	1.291 (0.274)	T(S,R), bits	0.90
MRT	0.685 (0.131)		
DSST	0.986 (0.025)		
BART*	3.249 (1.021)	Mean Non-Burst Payoff	0.98
PVT	0.949 (0.043)		

Table 6. Cognition Test Battery Mean Accuracy Scores and Standard Deviations (in parentheses) for 89 Participants

* New measures are proposed for the VOLT, LOT, ERT, and BART. The correlations between the original and proposed scores are in the rightmost column.

Immediately after sub-test completion participants are shown graphic feedback scores. Figure 3 (left) presents the ratio of the data response times to the feedback response times. The error bars are 95% confidence limits for the data means. Only the PVT time was significantly faster than the feedback standard. Our participants were significantly slower than the standard for 5 of the 9 tests. The right-hand side of Figure 3 shows the same ratio for the accuracy scores.

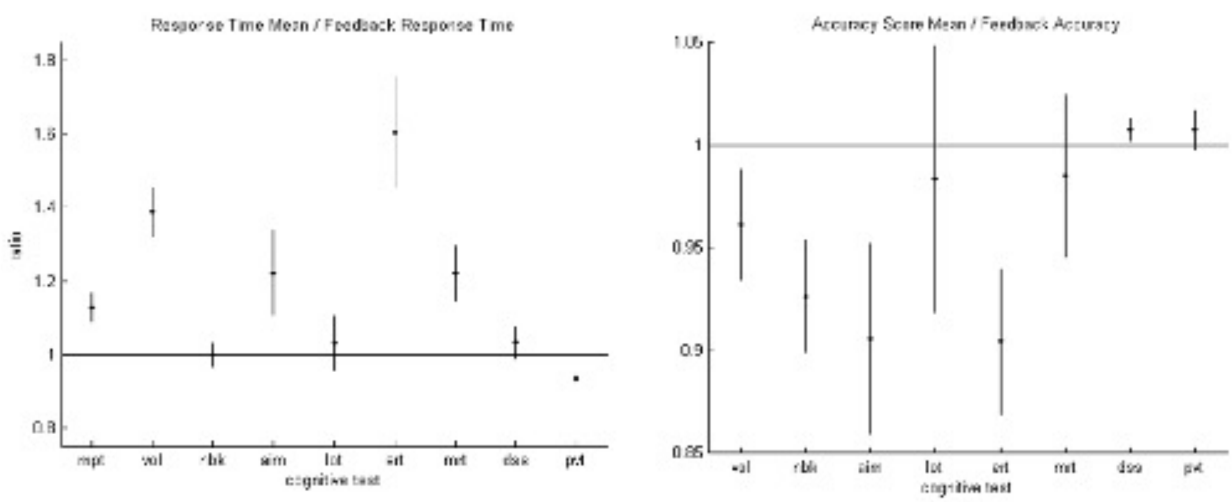

Figure 3. The left-hand side of the figure shows the ratio of the data response times to the feedback response times. Ratios greater than one indicate slower response times than the current CTB standard. The right-hand side shows the same ratio for the accuracy scores. Ratios less than one indicate lower accuracy than the current CTB standard. The error bars are 95% confidence limits for the data means.

Correlations among the accuracy and response times are shown separately in Table 7, with the accuracy correlations below the main diagonal and the response time correlations above. Double asterisks indicate correlations significantly different from zero at the 1% level (two-tailed). Single asterisks are provided for significant correlations at the 5% level. Only 2 of the 45 accuracy score correlations are significant at the 1% level, while 25 of the response time correlations are significant at that level, indicating a much higher level of commonality among the response times.

Table 7. Correlations among Response Times (above main diagonal) and Accuracy (below main diagonal) for each CTB Sub-test.

	MPT	VOLT	F2B	AM	LOT	ERT	MRT	DSST	BART	PVT
MPT	----	0.3377	0.251*	0.3859**	0.2816**	0.3404**	0.2071**	0.6379**	0.5004**	0.1961
VOLT	-0.0847	----	0.097	0.2626*	0.2781**	0.3962**	0.1723	0.3344**	0.2743*	-0.0104
F2B	-0.2170*	0.1368	----	0.1459	-0.0173	0.1668	0.1145	0.3529	0.0923	0.0805
AM	-0.172	0.2286	0.2295*	----	0.3999*	0.5698**	0.5844**	0.482**	0.4276**	0.1862
LOT	-0.2754	0.2551	0.1096	0.1616	----	0.4556**	0.4294**	0.4167**	0.4842**	0.1339
ERT	-0.0806	0.0991	0.1618	0.1292	0.0678	----	0.5623**	0.4326**	0.3188**	0.1746
MRT	0.0244	0.1325	0.3077**	0.2044	0.3219**	0.1617	----	0.2978**	0.3032**	0.1204
DSST	0.1131	-0.0172	-0.0471	-0.0706	-0.2439	-0.0219	0.1138	----	0.2953**	0.146
BART	0.0012	0.2831**	-0.0148	-0.0267	-0.0032	0.0148	0.062	0.2014	----	0.2469*
PVT	-0.0735	0.2264*	0.3017**	0.1174	-0.1234	0.1789	0.0331	-0.0322	0.0631	----

* = p<0.05; ** = p<0.01.

Principal component factor analyses were performed on both the speed and accuracy correlations. The proportion of variance accounted for by Factors 1 and 2 on response time were 0.4031 and 0.1195, and on accuracy were 0.2052 and 0.1304, respectively. The factor loadings on the first factor are shown in Figure 4. The high proportion on the first response time factor corresponds to the higher correlations among the response times. The first principal component of the accuracy scores mainly separates perceptual-motor tasks (MPT, DSST) from memory and reasoning tasks (F2B, AM, VOLT). The BART score is not really an accuracy score. The MPT, DSST, and PVT accuracy scores have such high mean proportions (0.98; 0.99; 0.95) that they are unlikely to be very reliable. The emotion recognition test (ERT) groups with the more cognitive tests. All of the response time measures have positive weighting on their first principal component.

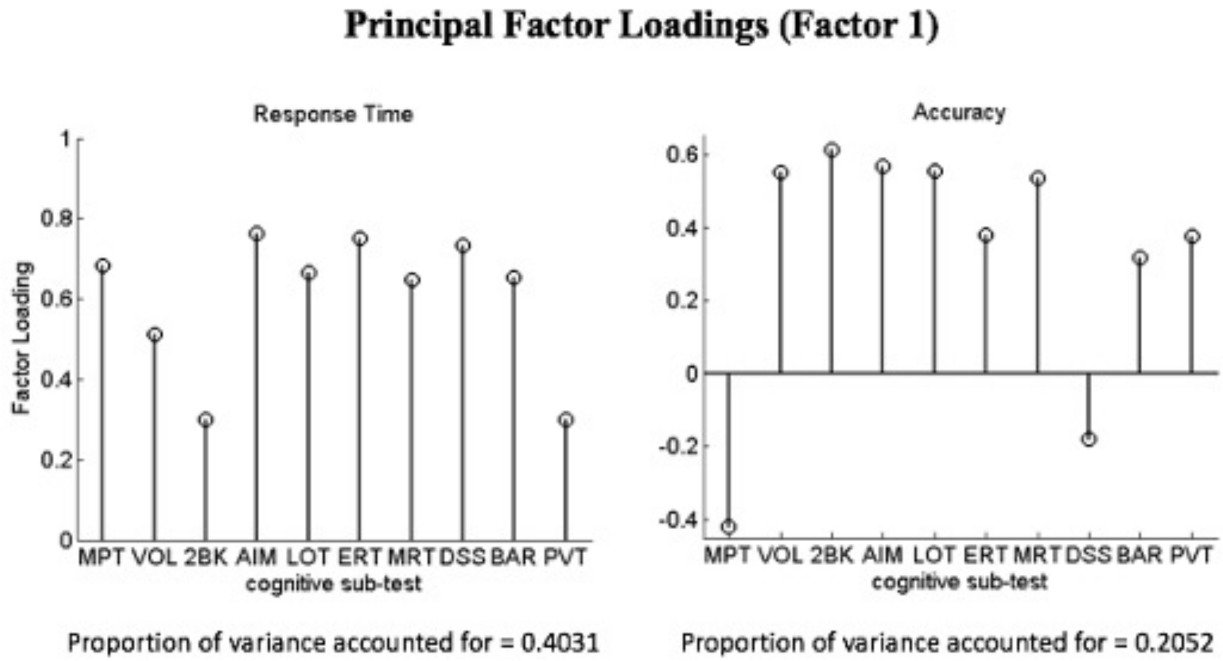

Figure 4. Factor loadings from principal component factor analyses on the response time and accuracy correlations.

Correlation coefficients were determined between the ten CTB sub-test scores and participant's age. The MPT, AM, ERT, MRT, and DSST showed significant age trends in the response time data (see Figure 5). Figure 6 shows the only two significant age effects for accuracy scores on the F2B and MRT.

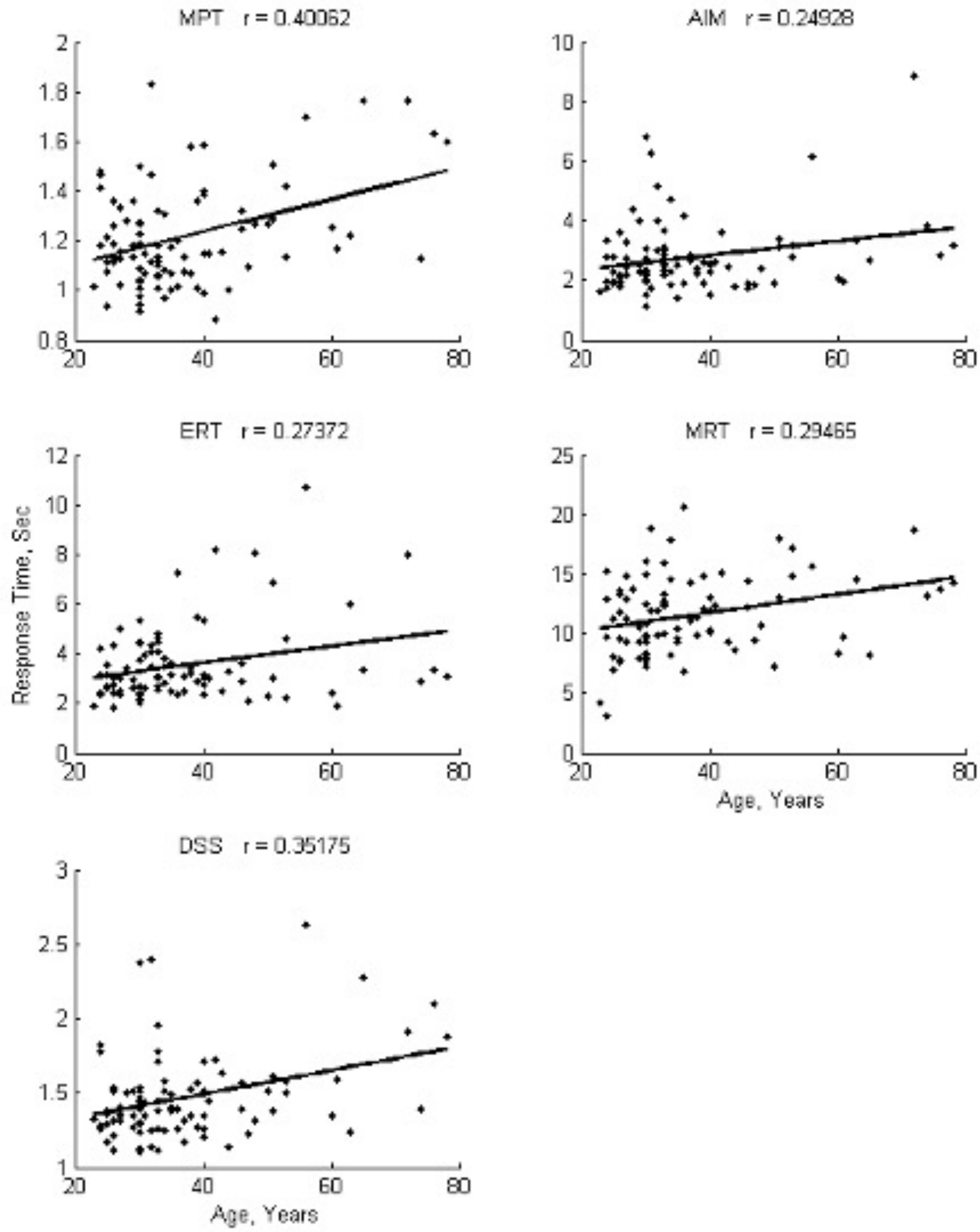

Figure 5. Response time as a function of age. Slopes are in sec/year.

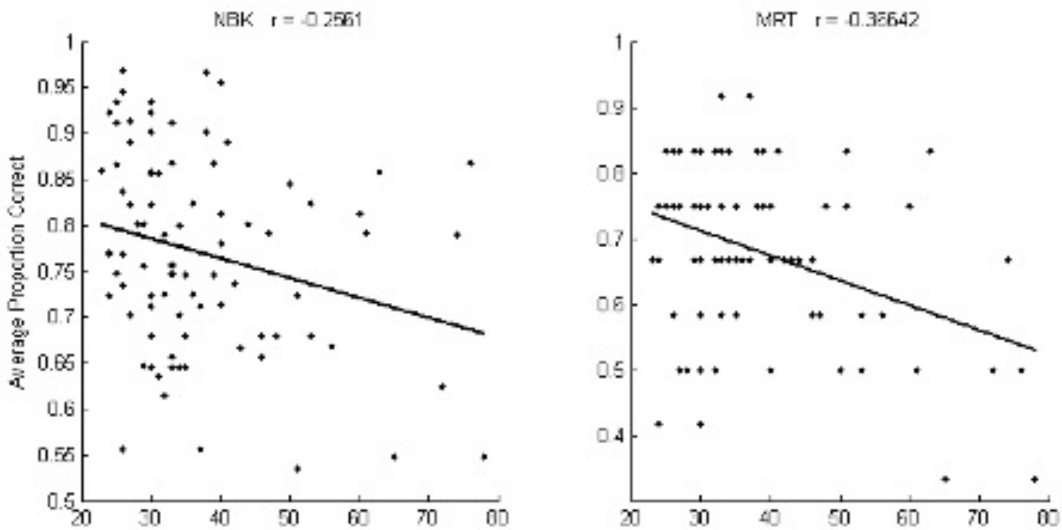

Figure 6. Average proportion correct as a function of age.

3.3. Normative Fine Motor Skills Test Battery Scores

Table 8 shows the total latency averages collapsed across non-significant differences. Participants were significantly faster using their index finger rather than the stylus for the Drag and Trace tasks. A stylus was not used in the Rotate task. The orientation of the square that was rotated did not significantly change the speed score. The larger ring diameter in the Point task took significantly longer as did tracing a square versus the circle.

Table 8. FMS Means of the Median Latencies (sec) and Standard Deviations for 82 Participants.

Sub-task (# Blocks)	***Conditions***	***Finger***	***SD***	***Stylus***	***SD***
Drag (12)	Horizontal	0.7102	0.1437	0.6999	0.1572
	Vertical	0.6823	0.1244	0.6797	0.1452
Trace (12)	CW & CCW Circle	3.2744	1.7344	3.3867	1.7791
	CW & CCW Square	3.7661	1.8311	3.9036	1.8862
Rotate (5)	0 & 45 deg rotation	2.4571	0.8563		
		Finger & stylus	SD		
Point (20)	CW & CCW 1.5 in	0.5063	0.0906		
	CW & CCW 2.0 in	0.5507	0.0992		

CW = clockwise; CCW = counter clockwise.

Table 9 presents average position variability scores collapsed across non-significant differences. For the Drag and Point tasks these averages are the standard deviation in the position the participant moved. In each tracing block there were five trials. The delta errors provided in the output file were not used. Rather, to determine a precise radial error, the average x and y error was corrected up to ½ pixel, thus providing information about whether the participant traced inside the circle (a negative number) or too far outside. To improve calculations, the square root of the two types of errors (inside and outside) were computed resulting in a proportion RMS (root mean squared) error (speed in pixels/sec). It was noted that while tracing the square, some participants did not abruptly change directions, rather they "cut the corners" staying on the inside of the square. Using the square root of the error (rather than 2 times it as was done in the FMS test battery output file) improves the estimates at the square's corners. Participants were worse at dragging with their finger, at pointing with their finger on the smaller ring and at tracing a square (versus a circle) clockwise. Appendix F, Table F-1, provides the average latencies for *all* 49 FMS conditions run by the 82 participants. The T-values and their significance levels are shown in Table F-2.

Table 9. FMS Error Scores and Standard Deviations for 82 Participants

Sub-task (# Blocks)	***Conditions***	***Finger***	***SD***	***Stylus***	***SD***
Drag (12)	Horizontal & Vertical	1.8916	0.4290	1.8012	0.4083
Point (20)	CW & CCW 1.5 in	2.0244	0.3911	1.9687	0.4289
	CW & CCW 2.0 in	1.6827	0.3700	1.6287	0.3748
		Finger & stylus	SD		
Trace (12)	CW Circle	3.8392	2.1333		
	CCW Circle	3.7277	1.8731		
	CW Square	3.8813	1.4166		
	CCW Square	3.8736	1.5661		

CW = clockwise; CCW = counter clockwise.

Correlations among the latencies and error scores are shown in Table 10. To summarize these results, principal component factor analyses were performed on the correlations. The results are shown for the latencies in Figure 7. The proportion of variance accounted for by Factors 1 and 2 are 0.295 and 0.242, respectively.

Table 10. Correlations among Response Times (above main diagonal) and Accuracy (below main diagonal) for each FMS Sub-test

	Drag Time	***Point Time***	***Trace Time***	***Rotate Time***	***Drag Error***	***Point Error***	***Trace Error***
Drag Time	----	0.5695**	0.1323	0.3179**	-0.4306**	0.0164	0.1387
Point Time		----	-0.1019	0.1573	-0.0528	0.1441	0.0685
Trace Time			----	0.4069**	-0.2735*	-0.2535*	-0.2133
Rotate Time				----	-0.1970	-0.0223	0.0752
Drag Error					----		
Point Error					0.3367**	----	
Trace Error					0.1001	0.2626*	----
Factor 1 Loading	0.7522	0.4266	0.5668	0.6329	-0.6969	-0.3205	-0.0878
Factor 2 Loading	0.4748	0.6519	-0.4699	0.0702	0.2208	0.6478	0.5896

* = p<0.05; ** = p<0.01.

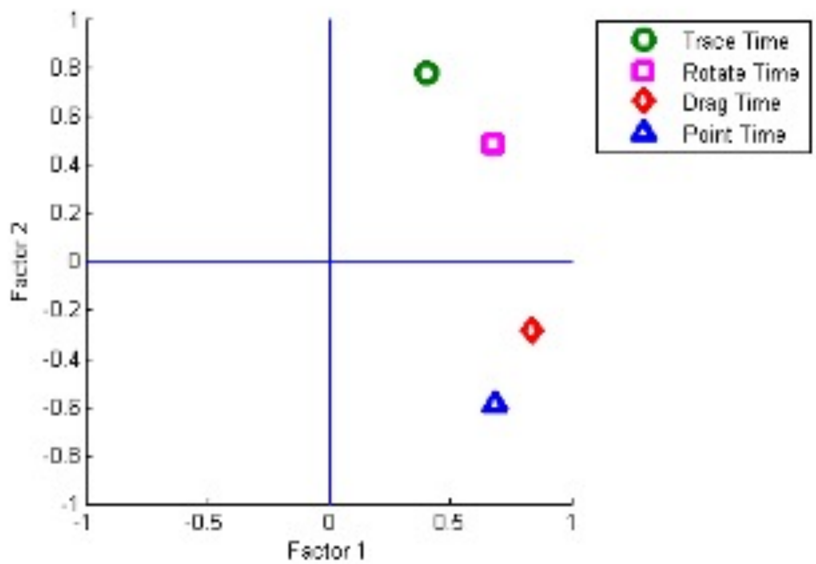

Figure 7. Factor loadings for mean time scores on the four FMS sub-tests.

The first principal component reflects a strong correlation among the tests likely reflecting the weighting the participants put on responding rapidly on the task. The second factor separates the Drag and Point tasks from the Trace and Rotate tasks.

This same analysis was performed on data obtained from Thompson et al. (unpublished manuscript) (see Figure 8). There is little difference between the finger and the stylus. Factor 2 differentiates between the dragging/pointing and the tracing/rotating sub-tasks.

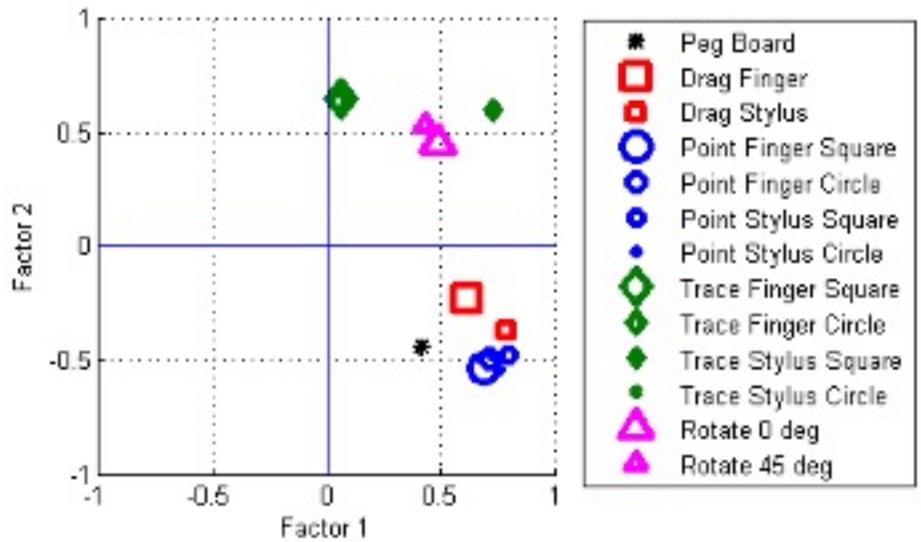

Figure 8. Factor loadings for mean times scores on the four FMS sub-tests based on data provided by Thompson et al.

The long version of the FMS included repetitions of the Drag, Point and Rotate sub-tasks. To determine the direction and strength of the relationship between repetition 1 and repetition 2, and between the clockwise and counterclockwise tracing tasks, correlations were determined (dragging – r = 0.883; pointing – r = 0 .909; tracing – r = 0.826; rotating – r = 0.695). The Rotate correlation is not as reliable since the participants only repeated this five times within a block of trials.

A linear regression analysis estimated a significant relationship between age and test z-scores (r = -0.378, p = 0.0005). Multiple regression was also performed on standardized scores where the amount of explained variance was 0.8679. As seen in the regression function in Figure 9, the age effect was highly significant, with older ages associated with longer response times and less accurate performance. Higher z-scores indicate better performance on the tests.

The relationship between flight hours and FMS z-scores was also examined. Flight hours were converted to z-scores and a regression analysis with age removed showed r = -0.1599, p = 0.1513. The FMS tests were not able to discriminate between flight experience (flight hours).

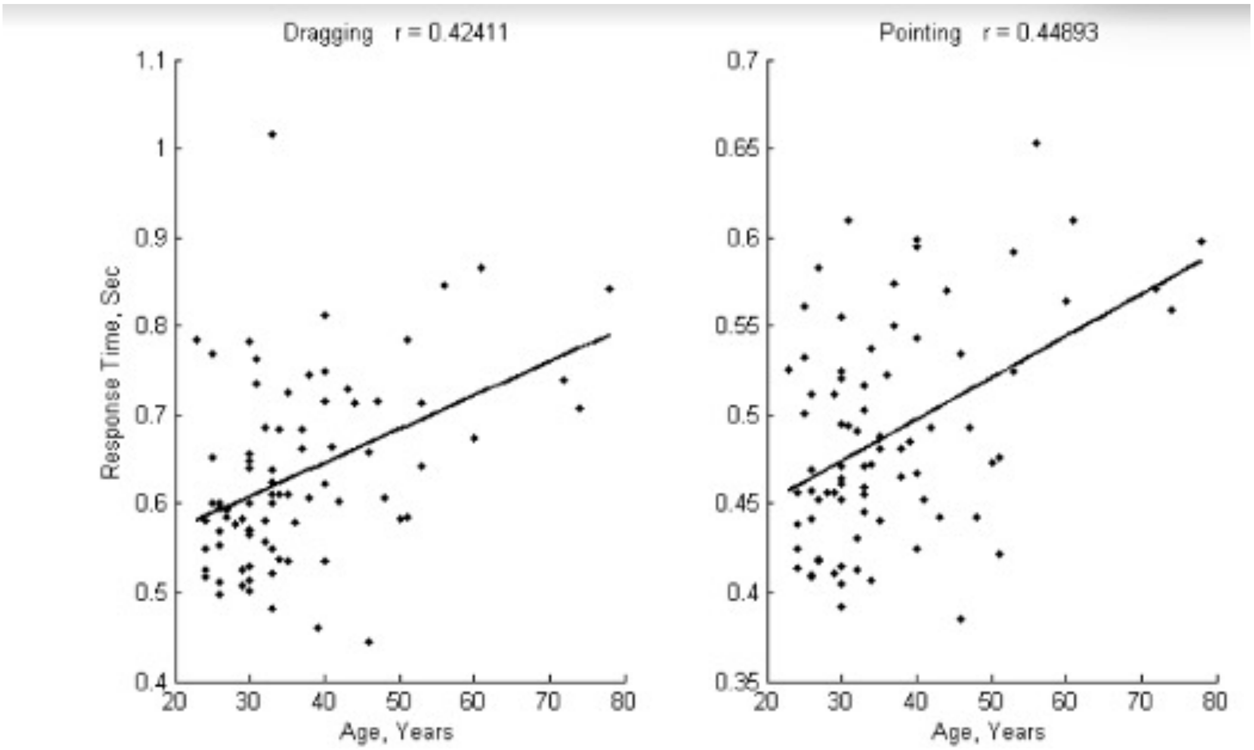

Figure 9. Response time (sec) as a function of age.

3.4. Motor Contributions for each Cognition Test Battery Sub-test

To evaluate the relationship between the CTB and the FMS, the correlations were computed between FMS Factor 1 (loading coefficients in Table 10) and the accuracy (Table 5) and response time (Table 6) scores from each CTB sub-task. The results are shown in Table 11. Significant correlations are given asterisks. The response time correlations are similar to the CTB response time factor loadings in Figure 4 except that here the PVT response time has a significant correlation. The VOLT and BART response times have a small correlation with Factor 1. The VOLT and MRT accuracy significantly correlates with FMS Factors 1 and 2, respectively.

Table 11. Correlations between FMS Factor1 and Factor 2 for the CTB Response Times and Accuracy for each CTB Sub-task

	Factor 1		*Factor 2*	
Sub-task	***Response Time***	***Accuracy***	***Response Time***	***Accuracy***
MPT	0.3551**	0.0251	-0.0191	-0.0966
VOLT	0.1618	-0.3552**	0.0350	0.1428
F2B	0.3855**	-0.2162	-0.1749	0.201
AM	0.3125**	-0.09	-0.0205	0.1252
LOT	0.2778*	-0.0942	-0.0499	0.1991
ERT	0.3311**	-0.1453	-0.1228	0.1171
MRT	0.5719**	-0.0406	-0.3857**	0.2888*
DSST	0.2863*	0.1836	-0.0317	0.0236
BART	0.0859	-0.0251	0.0136	-0.0266
PVT	0.3551**	-0.1474	-0.0191	0.1268

* = $p<0.05$; ** = $p<0.01$

4. Discussion

Normative scores in high-functioning (i.e., astronaut-like) individuals were determined on two test batteries; the Cognition (CTB) and Fine Motor Skills (FMS) test batteries. The CTB data will be discussed first.

4.1. Cognition Test Battery

The CTB normative data were consistent with Moore et al. (2017) for all but the ERT and the BART. This suggests that the present and the Moore et al data could be combined for the eight remaining tests to strengthen the power of the normative scores. The differences found between Moore et al. and the present study are likely due to the CTB versions used in their study as compared to ours. In an unpublished out-brief given at NASA Johnson Space Center, Basner (2017) presented significant version effects in 4 of the 10 tests for average reaction times (VOLT, ERT, MRT, and BART) and in 6 of the 10 tests for accuracy (VOLT, F2B, AM, ERT, MRT, and BART) lending support to the hypothesis that the difference found between Moore et al. and our scores may be explained by the use of different versions of the ERT and BART.

To reduce the version effects, to increase test reliability, or increase test validity, new measures were proposed for the CTB, response speed scores for the MPT and LOT and accuracy scores for the VOLT, LOT, ERT, and BART. The LOT response time score uses only the responses at zero offset or offsets near the discrimination threshold. The response times for clearly visible differences could be measured separately. The new MPT accuracy measure is relative to the decreasing target size, the mean based on pixels alone would be dominated by the large errors for the large squares. The new VOLT scores use all four response categories, instead of discarding the requested distinction between 'certainly' and 'probably' that was requested. If there were no information in the distinction, the two scores would have had the same average. The 4 category scores were significantly larger. Since the 1960s, psychophysicists have used signal detectability theory to measure sensitivity and bias separately in threshold measurements. Participants can get a small error score on their last judgment either by setting a strict criterion for when they are willing to say 'match' or by having little noise in their perceptual system. Our model makes the standard signal detectability theory assumptions, and we estimate these parameters from all the response data near threshold, not just the final response. Using information transmitted rather than proportion correct for the ERT accuracy measure gives the participant full credit for placing the emotions in consistent categories regardless of the labels, reducing the dependence on cultural background. The new BART accuracy measure was devised to lower the effect of different popping sequences in different versions. It has the property that if a participant has a fixed strategy it will report that strategy.

Intercorrelations among the CTB sub-tests were computed. There was a much higher level of commonality among the response times of most tests than for accuracy measures. This is consistent with Gur et al. (2010) who also reported high correlations among the speed measures for a different set of cognitive tests. The two tasks with the strongest motor component, the DSST and MPT, were highly correlated for speed. The PVT is a perceptual task with less of a motor component. The PVT showed only one significant speed relationship (at the 0.05 probability level) and that was with the BART. Neuchterlein et al. (2004) also reported that sustained attention tasks are separable from other neurocognitive tests. Only the VOLT, F2B, and the PVT showed non-significant relationships with other tasks on the speed measure. One explanation could have to do with the response time constraint of these three tasks. Participants are limited to responding within a 1.75 sec window in the VOLT task; in the F2B the stimulus is shut off (a disruption) when the participant responds. The F2B and PVT—where there is no speed-accuracy trade-off—also constrain how fast you can go. In addition, there are so few trials in the F2B that meet the criteria of a match (only 15 of the 62 trials). That only two of the 45 accuracy score correlations were significant at the 1% level supports the idea that the sub-tests are measuring different things. The significant relationship between the MRT and a F2B as well as the LOT accuracies may reflect the participants ability to focus, or concentrate, on a task.

Principle component analysis was used as a tool to explore the relationships between the sub-tests. The CTB accuracy data resulted in a first principal component that mainly separates perceptual-motor tasks (LOT, MPT, DSST) from memory and reasoning tasks (F2B, AM, VOLT). Cognitive abilities are highly interrelated, and performance on any test is dependent on the integrity of many different abilities and on the overall level of alertness.

Neuropsychological measurement of cognitive processing speed consistently show decline with advancing age. Significant age group differences were demonstrated on the MPT, AM, ERT, MRT and DSST tasks but not on the VOLT, F2B, LOT, or PVT. Hardy et al. (2007) examined age effects on psychomotor speed, information processing speed, attention, executive abilities, visual learning and memory in aircraft pilots between the ages of 28 and 62. A linear function best described the age trend for all but the visual memory task in which no age effect was found. We may have found significant age effects for some of these other tasks if we had run additional older people. There is a plethora of research on the topic of normal age-related declines in sensory function, visual perception, attention, central executive processes, memory, problem-solving, decision making as well as gross and fine motor movement (Baltes & Lindenberger, 1997; Clark, 1960; Gur et al., 2010; Henderson et al., 2011; Ketcham et al., 2001; Kramer & Madden, 2008; Krampe, 2002; Lindenberger, & Baltes, 1994; Lindenberger & Ghisletta, 2009; Salthouse et al., 1996; Salthouse et al., 1998; Valentijn et al., 2005; Verhaeghen & Cerella, 2002;

Yan & Chen, 2009). Nazeri et al. (2015) found an inverse relationship between superficial white matter functional anisotropy with age that may contribute to these findings.

4.2. Fine Motor Skills Test Battery

Normative data for the FMS test battery in 82 aircraft pilots were consistent with Thompson et al. (unpublished manuscript) who compared performance on the FMS sub-tests with the 9-Hole Pegboard Test in 33 adults (age range 20–67; mean = 9). Significant correlations were found between the Pegboard and the FMS pointing and vertical dragging tasks suggesting that these tasks are somewhat related to the pegboard test. The use of a stylus increased this relationship. Our latency data also show a significant difference between the Drag horizontal and Drag vertical conditions with more rapid responses using a stylus.

Principle component analysis on the FMS correlational data resulting in a first principle component that reflects a common component among the four tests while the second factor separates the Drag and Point tasks from the Trace and Rotate tasks (see Figure 5). This same relationship was found on another dataset provided by Thompson et al. (unpublished). Although the Singh & Aggarwal (2016) trace and pinch sub-tasks (discussed in Section 1.1.2 in the Introduction) are not identical to those in the FMS they appear quite similar. It can be inferred that a comparable, significant relationship would be attained between the Trace and Rotate sub-tasks of the FMS and manual fine motor tasks as that found for the trace and pinch sub-tasks used in the Singh & Aggarwal study.

Our parametric analysis showed a significant difference between the clockwise and counterclockwise Trace errors. This may be due to the unbalanced order in which they were tested (see Appendix D, Tables D-2 and D-3). Both latencies and errors were significantly different between the circle and square Trace scores suggesting that these two sub-tasks are fundamentally different. Performance on the square tracing showed large errors in the corners of the square. In addition, we found that finger speed scores were significantly slower than the stylus tracing speeds, tracing a circle was slower than tracing a square and clockwise tracing was slower than was counterclockwise tracing.

The FMS sub-tests are highly correlated. It would be advantageous to develop sub-tasks with theoretical underpinnings. A fine motor skills model should include what the astronaut is doing and how spaceflight stressors may affect those tasks. Unless predictions are guided by a model that postulates crew will lose dragging behavior more than pointing or counterclockwise tracing before clockwise tracing, then the test scores may not be characterizing anything of interest. It is recommended that NASA consider development of a sub-test that is more ballistic, such as a rotary pursuit task, where the participant tracks a randomly moving object using visual feedback. There is a great deal of data on this type of task and literature supporting its decline in early spaceflight.

The FMS is administered on an iPad. Touchscreens have been shown to effectively measure motor skills in children (Pitchford & Outhwaite, 2016) and in young (Wood et al., 2005) and older adults (Jenkins et al., 2016) as well as in microgravity (Adolf & Holden, 1996). Nevertheless, touchscreens do have limitations. When pointing with the index finger to one quadrant of the screen, the hand blocks other quadrants (Thomas & Milan, 1987). Finger widths can determine precision in pointing and the iPad capacitors are less sensitive to finger tips that are cold or dry (Jenkins et al., 2016). Arsintescu et al. (2017) reported that iPad touchscreens have a latency of around 75 ±30 ms, which is similar to ZBook latencies. The ZBooks currently used for CTB measurements are calibrated, and a correction factor is used for those tests measuring reaction time. In addition, there are statistically significant individual differences of 10 to 20 ms possibly dependent on skin moisture or skin electrical qualities (Arsintescu et al., 2017). Because simple reaction times are on the order of 200 to 250 ms in a young and healthy adult (Woods et al., 2015), these latencies should not be a problem for FMS score interpretation. One distinct advantage of computerized touchscreens over traditional tests using three-dimensional objects is the standardization afforded in setting up the equipment, conducting the experiment and reporting scores.

4.3. CTB and FMS Intercorrelations

The Fine Motor Skills Drag and Point task principle component significantly correlate with the speed scores on the CTB perceptual-motor tasks (LOT, MPT, DSST) and the AM, ERT, and MRT. These relationships underscore that the ability to perform motor behaviors rapidly makes a significant contribution toward the ability to perform many of the CTB sub-tests rapidly. This ability cannot be simple motor speed since the PVT does not correlate with the ability to perform the other tasks rapidly. It only received a small loading on the first factor extracted from the cognitive test score speeds and it has a small correlation with the first FMS time factor.

Eye movements are a fine motor skill that are used to obtain visual information. Several lines of evidence suggest that cognitive processing and eye movement patterns are linked (Binello et al, 1995; Thomas & Lieras, 2007). For example, successful problem solvers move their eyes in a pattern that represents the problem's solution (Grant & Spivey, 2003; Hayes et al., 2011; Just & Carpenter, 1985). Several of the CTB sub-tasks are oculomotor working memory tasks. NASA should attempt to untangle the contributions of eye movements to these complex, multidimensional tasks. The significant correlation between the FMS Factor 1 component and the VOLT accuracy scores likely reflects eye movement patterns since saccades and hand movements appear to use a common mechanism in visual search tasks requiring a motor response (Frens & Erkelens, 1991; Liversedge & Findlay, 2000).

There are several improvements that could be implemented to improve the CTB and the FMS. In the following section we discuss the CTB and FMS questionnaires, the AM, the ERT, the DSST, the BART, and the FMS.

4.4. Some Observations about the Sub-tests

To aid test result interpretation, in its current iteration, the CTB has a 4-item questionnaire. Questions include hours slept, hours since awakening, psychotropic drug consumption in the past 6 hours and an 11-option alertness scale. The FMS also has a 4-item questionnaire which includes a 5-option alertness scale, questions about previous-hour activities and current location, and an open-ended comment space. To further aid score interpretation, the test-taking protocol (standard metrics) could include measures of the local CO_2 concentration and temperature, a question about the day's/week's workload, a record of unusual or dangerous events in the near schedule and changes in the schedule that may affect circadian rhythms since these factors can influence scores (Graw et al., 2005; Horowitz et al., 2003; Satish et al, 2012). The differential contribution of recent, transient factors during a mission can shed light on performance patterns.

4.4.1. CTB Observations

The AM test measures executive function, specifically the ability to group stimuli according to rules based on feedback. Practice effects are especially prevalent in executive function tasks (Bornstein, Baker, & Douglass, 1987). Recall of previously generated strategies from experience during the first test administration make the neurocognitive skills assessed by an executive function task after an intervention quite different from those assessed at baseline. Each of the 15 AM versions use the same set of rules. It was noticed that some pilots in the current study learned three of the five rules in the first session. This suggests that scores in future sessions may assess something different than abstract learning (e.g., memory for what was learned in the first session). It may not be meaningful to have repeated measures on the AM sub-test.

There are concerns regarding computerized assessments including equivalence with paper and pencil methods (Feldstein et al, 1999). The AIM (Glahn et al., 2000) is based on the Wisconsin Card Sorting Test (WCST) which requires participants to sort a series of cards onto four key cards. Feedback provides the correct matching rule. The correct matching rule on the WCST changes after ten consecutive correct responses, thus requiring inhibition of the previously learned rule and the flexibility to generate a new rule. This latter aspect of the WCST task was not conserved in the PENN CNB AIM or the NASA CTB AM. Thus, perseverative errors are not assessed in the computerized version. Glahn et al. (2000) did not find a significant correlation between the computerized AIM and WCST categorization scores supporting the idea that the AM is measuring something different from the well validated WCST. Here we suggest that the AM be modified to include the measurement of perseverative errors. A terrestrial example of a perseverative error is forgetting to stop at the store on your way home when you had intended to do so. Major commercial airline accidents have been caused by the pilot forgetting to return to an intentionally postponed procedural step. An example of a perseverative error that has repeatedly cost NASA millions of dollars is when an engineer forgets to turn off an oven that is assessing a piece of hardware's tolerance to the high heat of space. During interviews and in the Crew Notes, astronauts have revealed times that they forgot to do something that had been deferred due to a distraction or interruption from the Mission Control Center. It is suggested that this aspect of the WCST task be instituted in the AM since perseverance is a daily requirement in all walks of life.

Another aspect of the PENN CNB AIM that is not instituted in the NASA CTB AM is a 500 msec delay between the target stimulus and the shape choices on some trials. These trials require maintenance of the target stimulus in working memory. Since the Fractal 2-Back measures working memory maintenance, this addition may be duplicative.

There are several improvements that could be made to the LOT sub-task. First, very few trials contain useful information since the initial offset typically is not close to threshold, making the test longer than it needs to be. Second, it is unclear if the long or medium length lines are producing an aliasing confound. Antialiasing errors depend on whether the center point of line is on a pixel or not. It may be tricky to implement an anti-aliasing scheme during long duration space flight (since you would either need to know the current gamma of the display or perhaps jitter the stimulus). Third, Basner et al. (2015) define the mean rotation error by averaging over all the line lengths. Since orientation thresholds change as a function of line length (Mäkelä et al., 1993), it would provide more information to compute mean rotation error for each line length. Finally, a much more sensitive way to obtain orientation discrimination thresholds is by simultaneously flashing the two lines for a set duration and require the participant to respond yes or no as to whether they were aligned. The subsequent trials orientation offset should be dependent on the participant's decision—whether it was right or wrong. Each decision would be informative if you are near the orientation threshold.

The ERT contains two uncontrolled variables, both pertaining to information availability. People discriminate static face emotions using the mouth area (Blais et al., 2012; Kontsevich & Tyler, 2004). Other aspects of the image, such as the eyes, are also used only when there is uncertainty about the expression (Baron-Cohen et al., 1997). The stimuli used in the current study (CTB version 3) were composed of 11 low intensity and 5 medium intensity emotions. None of the expressions were of high intensity emotion, making some faces difficult to categorize. This resulted in some participants reportedly using aspects of the image other than the mouth, such as the shoulders. It is recommended that the test images selectively show only the actor's face in order to exclude unintentional cues. Secondly, because the test is self-paced, trial duration is variable between participants. Some participants make rapid discriminations while others ponder about the subtle expressions. It is recommended that the face stimuli be presented for a set duration so that all participants are performing the same task.

The NASA CTB BART has several differences from other instantiations including a single level of reward ($1 for each pump), a low explosion break point (~4 pumps), few total balloons (30 balloons) and fictitious total winnings. These features make the present BART findings specific to this version of the task. Most versions of the BART reward 5 cents per pump, use several additional reward values, have average break points up to 64 pumps and use 60 or 90 balloons. There have been other studies using 30 total balloons (Aklin et al., 2005; Crowley et al., 2006; Hunt et al., 2005; Killgore, 2007; Lejuez et al., 2003a,b, 2005, 2007; Skeel et al., 2007), but in these there are actual rewards. As examples, Lejuez et al. (2003b) motivated participants with cash rewards, Lejuez et al. (2002) gave a gift certificate for the amount earned and Hunt et al. (2005) provided a gift certificate to the participant who earned the most money. Without an incentive, it is not clear if the CTB version of the BART is measuring risk taking. As an example, three participants stated that their aim was to pop the balloon. However, similar to Lejuez et al. (2002), the majority of the present study's participants behaved cautiously. This may have been a reaction to the high number of balloons that popped after two or three pumps and especially since the first balloon popped after one pump.

Basner and his colleagues have used a fixed battery approach that advocates administration of a semi-comprehensive battery of tests to all crew in invariant order. The advantage of this approach is in systematic acquisition of data, thus building an extensive spaceflight database. This approach minimizes the probability of missing an early stage problem. However, administration of an extensive battery to all crew, regardless of individual needs and presence of stressors can lead to excessive testing and uneconomical expenditures of resources. In addition, the accuracy of the assessment is compromised if the fixed battery does not include tests sensitive to the deficits in specific functional domains suspected during spaceflight. What may be better is a flexible battery approach where the specific battery is tailored for the respective environmental stressors present (high CO_2 – memory) and a model of the stressor's effects on performance. Based on the pattern of weaknesses identified and a priori-generated hypotheses, additional tests might be administered to specifically address the extent and nature of the deficits. These hypotheses could guide test battery development.

The PVT used in the current study was the 3-minute version that has a reduced inter-trial interval[3] that is determined by a uniform distribution (Basner et al., 2015). With a uniform distribution, as time passes, the event (in this case the counter starting) is more and more likely. So as time passes the participants expectation of the event grows, improving vigilance. In typical vigilance tasks exponential ITI distributions are used which have the property that as time passes the chance of the event happening is constant. The participant, therefore, has no way of knowing when the counter will start and is therefore more likely to suffer a lapse of attention. Since a brief test is preferred, a truncated exponential is a possibility, however NASA should investigate how a truncated exponential distribution would interact with expectations.

4.4.2. FMS Observations

In the FMS data output files, roundoff errors made it difficult to understand the actual location of the stimulus or how the delta error was calculated. Greater precision could be obtained if the delta errors had not been rounded in the output file. This output unnecessarily reduces the sensitivity of the test. Precision would be even more affected by rounding for inaccurate tracing behaviors.

It was assumed that the circle's radius was 230 pixels with zero at the center. The output file provided the absolute values of the delta tracing error. This is not recommended since the person's strategy (staying inside versus outside of the target circle) would be unknown without the signage information.

NASA may investigate if the DSST is adequately accounting for the residual variance in motor tasks performed by crewmembers. Ebaid et al. (2017) found a significant correlation between the Purdue pegboard and a symbol substitution task. This suggests that the Drag and Point tasks, which are highly correlated to each other, may not provide enough novel data to include in a set of standard measures. Within the FMS tests, you may use the principle components to predict which combination of the different tests would provide equally reliable measures. If you want a certain reliability you can either use the long or short versions until you get an acceptable reliability. It is suggested that a regression analysis be done between the DSST data, FMS short and long and real world crew skills. All of them will have some unreliability. The one that correlates most highly to real world behavior through regression analysis would win.

The FMS test battery output file provide error scores that were calculated differently depending on whether the participant traced inside versus outside of the square. Presumably, outside errors were used when the participant traced both inside and outside of the square. When only inside tracing was done, the smaller of the errors was used. Participants who traced only on the inside of the square would be at an advantage.

[3] The PVT Data Dictionary states that the ITI ranges from 2 to 5 sec, but in fact it is 1 to 4 sec.

5. Conclusions

NASA has developed two test batteries to measure and monitor astronaut cognitive and fine motor skills. The Cognition Test Battery contains 10 sub-tests that assess cognitive behaviors ranging from low level visual perception to high level learning and memory. The Fine Motor Skills test battery contains 4 sub-tests that assess finger dexterity and wrist-finger speed. This study determined acceptable norms for both batteries in an astronaut-like sample of certified pilots. In addition, the extent to which the cognitive test scores reflect fine motor skills was determined. These data are essential for establishing potential declines in crew performance during spaceflight.

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Appendix A. Fleishman's (2010) Taxonomy of 52 Human Abilities

Arm-hand steadiness	Ability to keep the hand or arm steady. It includes steadiness while making an arm movement as well as while holding the arm and hand in one position. This ability does not involve strength or speed.
Auditory attention	Ability to focus on a single source of auditory information in the presence of other distracting and irrelevant auditory stimuli.
Category flexibility	Ability to produce many rules so that each rule tells how to group a set of things in a different way. Each different group must contain at least two things from the original set of things.
Control precision	Ability to move controls of a machine or vehicle. This involves the degree to which these controls can be moved quickly and repeatedly to exact positions.
Deductive reasoning	Ability to apply general rules to specific problems to come up with logical answers. It involves deciding if an answer make sense.
Depth perception	Ability to distinguish which of several objects is more distant from or nearer to the observer or to judge the distance of an object from the observer.
Dynamic flexibility	Ability to bend, stretch, twist, or reach out with the body, arms and/or legs, both quickly and repeatedly.
Dynamic strength	Ability of the muscles to exert force repeatedly or continuously over a long time period. This is the ability to support, hold up or move the body's own weight and/or objects repeatedly over time. It represents muscular endurance and emphasizes the resistance of the muscles to fatigue.
Explosive strength	Ability to use short bursts of muscle force to propel oneself or an object. It requires gathering energy for bursts of muscle effort over a very short time period.
Extent flexibility	Ability to bend, stretch, twist, or reach out with the body, arms or legs.
Far vision	Capacity to see distant environmental surroundings.
Finger dexterity	Ability to make skillful coordinated movements of the fingers of one or both hands and to grasp, place or move small objects. This ability involves the degree to which these finger movements can be carried out quickly.
Flexibility of closure	Ability to identify or detect a known pattern (such as a figure, word, or object) that is hidden in other material. The task is to pick out the disguised pattern

Fluency of ideas	Ability to produce a number of ideas about a given topic.
General hearing	Ability to detect and to discriminate among sounds that vary over broad ranges of pitch and/or loudness.
Glare sensitivity	Ability to see objects in the presence of glare or bright ambient lighting.
Gross body coordination	Ability to coordinate the movement of the arms, legs and torso together in activities in which the whole body is in motion.
Gross body equilibrium	Ability to keep or regain one's body balance or stay upright when in an unstable position. This ability includes maintaining one's balance when changing direction while moving or standing motionlessly.
Inductive reasoning	Ability to combine separate pieces of information, or specific answers to problems, to form general rules or conclusions.
Information gathering	Ability to follow correctly a rule or set of rules to arrange things or actions in a certain order. The rule or sets of rules used must be given. The things or actions to be put in order can include numbers, letters, words, pictures, procedures, sentences, and mathematical or logical operations.
Manual dexterity	Ability to make skillful coordinated movements of one hand, a hand together with its arm, or two hands to grasp, place, move or assemble objects, such as hand tools or blocks. This ability involves the degree to which these arm-hand movements can be carried out quickly. It does not involve moving machine or equipment controls, such as levers.
Mathematical reasoning	Ability to understand and organize a problem and then to select a mathematical method or formula to solve the problem. It encompasses reasoning through mathematical problems to determine appropriate operations that can be performed to solve problems. It also includes the understanding or structuring of mathematical problems. The actual manipulation of numbers is not included in this ability.
Memorization	Ability to remember information, such as words, numbers, pictures, and procedures. Pieces of information can be remembered by themselves or with other pieces of information.
Multiple coordination	Ability to coordinate movements of two or more limbs (for example, two arms, two legs or one leg and one arm), such as in moving equipment controls. Two or more limbs are in motion while the individual is sitting, standing or lying down.
Near vision	Capacity to see close environmental surroundings.

Night vision	Ability to see under low light conditions.
Number facility	Involves the degree to which adding, subtracting, multiplying, and dividing can be done quickly and correctly. These can be steps in other operations, such as finding percentages and taking square roots.
Oral comprehension	Ability to understand spoken English words and sentences.
Oral expression	Ability to use English words or sentences in speaking so others will understand.
Originality	Ability to produce unusual or clever ideas about a given topic or situation. It is the ability to invent creative solutions to problems or to develop new procedures to situations in which standard operating procedures do not apply.
Perceptual speed	Involves the degree to which one can compare letters, numbers, objects, pictures or patterns, quickly and accurately. The things to be compared may be presented at the same time or one after the other. This ability also includes comparing a presented object with a remembered object.
Peripheral vision	Ability to perceive objects or movements towards the edges of the visual field.
Problem sensitivity	Ability to tell when something is wrong or is likely to go wrong. It includes being able to identify the whole problem as well as the elements of the problem.
Rate control	Ability to adjust an equipment control in response to changes in the speed and/or directions of a continuously moving object or scene. The ability involves timing these adjustments in anticipating these changes. This ability does not extend to situations in which both the speed and direction of the object are perfectly predictable.
Reaction time	Ability to give one fast response to one signal (sound, light, picture) when it appears. This ability is concerned with the speed with which the movement can be started with the hand, foot or other parts of the body.
Response orientation	Ability to choose between two or more movements quickly and accurately when two or more different signals (lights, sounds, pictures) are given. The ability is concerned with the speed with which the right response can be started with the hand, foot or other parts of the body.
Selective attention	Ability to concentrate on a task one is doing. This ability involves concentrating while performing a boring task and not being distracted.

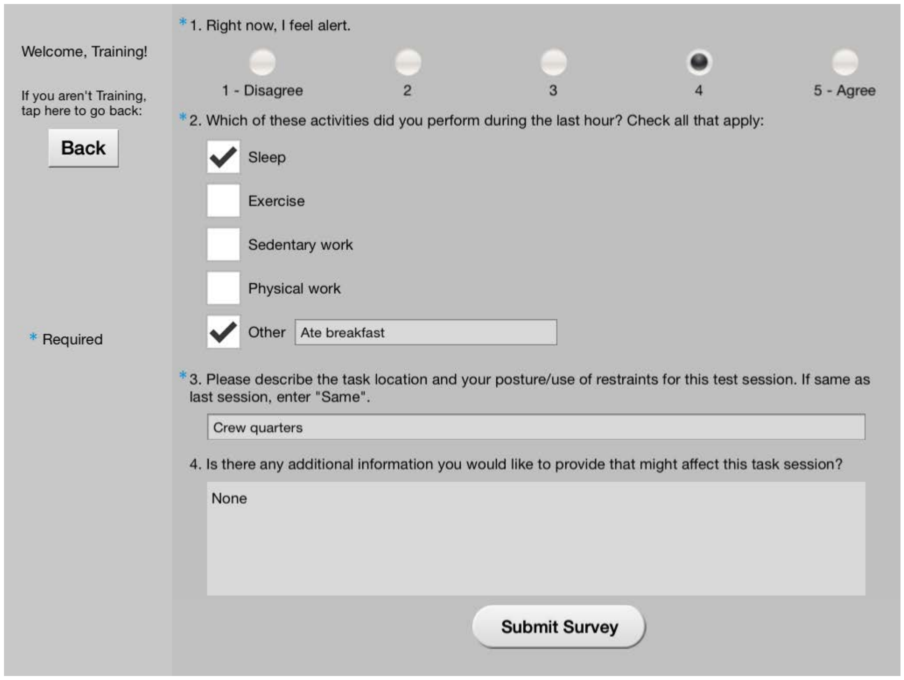
Sound localization	Ability to identify the direction from which an auditory stimulus originated relative to the observer.
Spatial orientation	Ability to tell where you are in relation to the location of some object or to tell where the object is in relation to you.
Speech clarity	Ability to communicate orally in a clear fashion understandable to the listener.
Speech hearing	Ability to learn and understand the speech of another person.
Speed of closure	Involves the degree to which different pieces of information can be combined and organized into one meaningful pattern quickly. It is not known beforehand what the pattern will be. The material may be visual or auditory.
Speed of limb movement	Involves the speed with which a single movement of the arms or legs can be made. This ability does not include accuracy, careful control or coordination of movement.
Stamina	Ability of the lungs and circulatory systems of the body to perform efficiently over long time periods. This is the ability to exert oneself physically without getting out of breath.
Static strength	Ability to use muscle force in order to lift, push, pull or carry objects. It is the maximum force that one can exert for a brief period of time.
Time sharing	Ability to shift back and forth between two or more sources of information.
Trunk strength	Involves the degree to which one's stomach and lower back muscles can support part of the body repeatedly or continuously over time. The ability involves the degree to which these trunk muscles do not fatigue when they are put under such repeated or continuous strain.
Visual color discrimination	Capacity to match or discriminate between colors. This capacity also includes detecting differences in color purity (saturation) and brightness (brilliance).
Visualization	Ability to imagine how something will look when it is moved around or when its parts are moved or rearranged. It requires the forming of mental images of how patterns or objects would look after certain changes, such as unfolding or rotation. One has to predict how an object, set of objects or pattern will appear after the changes are carried out.
Wrist-finger speed	Ability to make fast, simple repeated movements of the fingers, hands and wrists. It involves little, if any, accuracy or eye-hand coordination.

Written comprehension	Ability to understand written sentences and paragraphs.
Written expression	Ability to use English words or sentences in writing so others will understand.

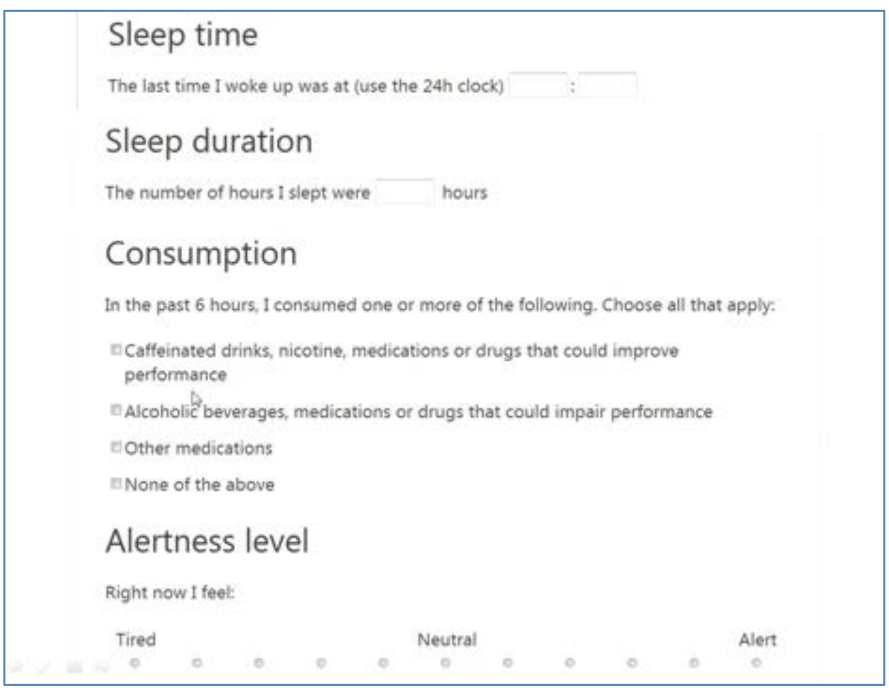
Appendix B. Questionnaires Administered in this Project

Both the FMS and the CTB have brief questionnaires coded into the software. Subjects fill these in before data collection can commence. Screen shots of these questionnaires are provided below.

The FMS questionnaire:



The CTB questionnaire:



An additional two-page questionnaire containing 17 questions was administered.

NORMATIVE DATA STUDY: PARTICIPANT DEMOGRAPHICS

1. Your age is _____.

2. ____ Male ____ Female

3. Are you:

____ Left-handed ____ Right-handed ____ Ambidextrous

4. Y or N

____ Do you typically wear corrective lenses for reading a computer monitor?

____ Are you currently wearing corrective lenses?

5. Your current education level:

___ High School graduate or equivalent

___ Bachelor's Degree or equivalent Bachelor's degree in ______________________________

___ Master's Degree or equivalent Master's degree in ______________________________

___ Doctorate or equivalent Doctorate degree in ______________________________

6. Your mother's education level:

___ High School graduate or equivalent

___ Bachelor's Degree or equivalent Bachelor's degree in ______________________________

___ Master's Degree or equivalent Master's degree in ______________________________

___ Doctorate or equivalent Doctorate degree in ______________________________

7. Your father's education level:

___ High School graduate or equivalent

___ Bachelor's Degree or equivalent Bachelor's degree in ______________________________

___ Master's Degree or equivalent Master's degree in ______________________________

___ Doctorate or equivalent Doctorate degree in ______________________________

8. Are you a pilot? (If "No" continue to question 10.)

List all A/C you have flown _________________________________

____

____

____

____

____

9. Total Flight Time: ______________ hours

10. Have you crossed time zones in the past two weeks? Yes____ No ____

When did you do this? ________ days ago

Did you travel east or west of your base? East ____ West ____

11. In the past week have you worked:

Night or evening duty? Yes ____ No ____

Overtime? Yes ____ No_____

12. Have you been diagnosed with a concussion in the past few months? Yes____ No ____

13. How often do you play video games?

____ every day

____ every 2-3 days

____ every week

____ rarely or never

14. How often do you exercise vigorously?

____ every day

____ every 2-3 days

____ every week

____ rarely or never

Mark an X on the scale where it applies.

15. Describe today's workload

Very high Very low

____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____

16. Quality of your sleep last night

Good Poor

____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____

17. Right now you feel:

Happy Unhappy

____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____

Sick Healthy

____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____

Energetic Physically exhausted

____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____

Not stressed at all Very stressed

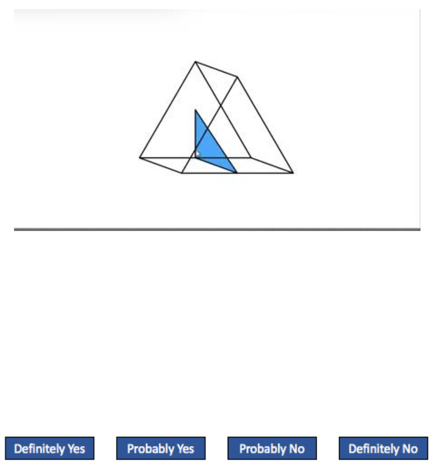
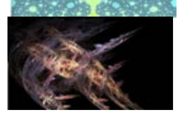
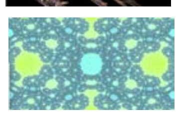
____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____

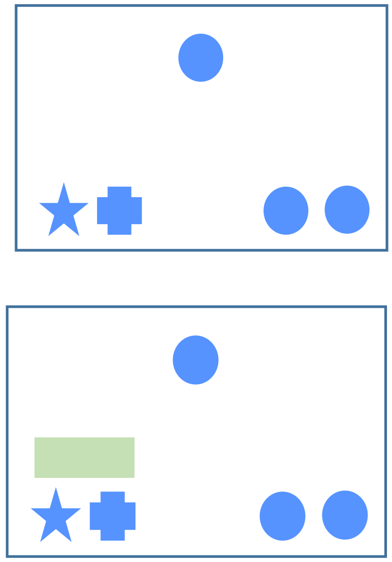
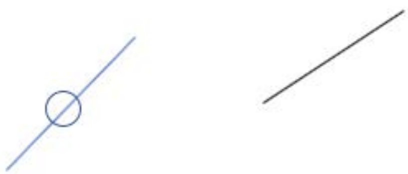
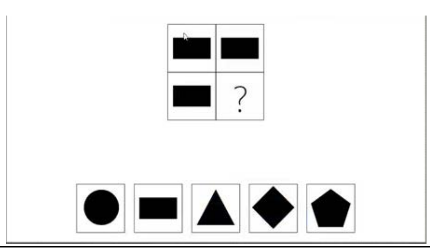
Very depressed	Not depressed at all
_______ ______ ______ ______ ______ ______ ______ ______ ______ ______ _______	
Mentally sharp	Mentally fatigued
______ ______ ______ ______ ______ ______ ______ ______ ______ _______ _______	

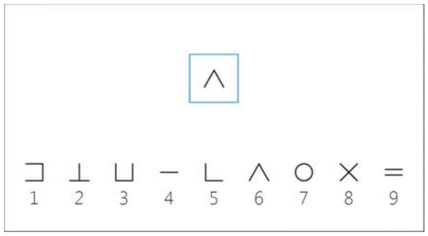
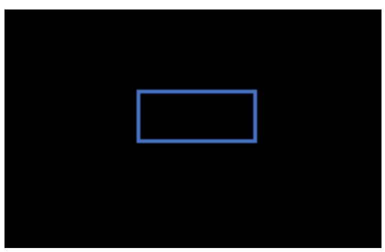
Thank you.

Let's collect some data!

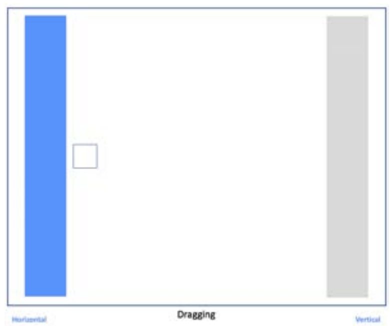
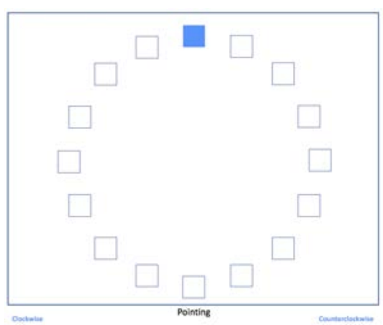
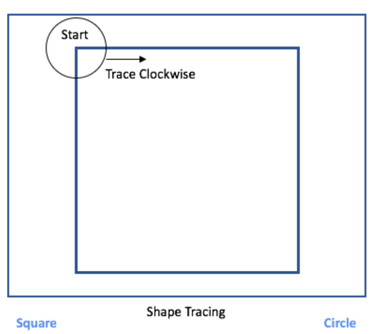
Appendix C. Instructions used for the CTB

Table C-1. Instructions used for the CTB		
	Stimuli Shown (.ppt)	**Instructions as Stated by the PI**
Motor Praxis Task (MPT)		"This test measures how well you can use the ZBook trackpad." "You will see a sequence of blue squares, presented one at a time. As soon as a square appears, use the trackpad to rapidly move the cursor onto the square and then click using the leftmost trackpad button." "Immediately after you click on one square, another, slightly smaller square, will appear in a different location. This will be repeated multiple times." "Questions?" "You may now practice the task."
Visual Object Learning Task (VOLT)		"This is a test of your memory for visual objects." "You will see 10, different Euclidean shapes that you are to remember. They will be similar to this one, containing a clear contour and an inner blue form. You are to remember the entire shape. The computer will advance through the ten shapes automatically, one at a time. You are to remember these ten initial shapes." Afterward you will be shown a series of shapes, one at a time. For each of these shapes, you are to determine if you saw it in the initial set of 10 by responding DY, PY, PN or DN. Respond as quickly and accurately as you can." "Questions?" "This task does not provide practice, so be sure to read the instructions as you go."
Factal 2-BACK	Screen 1  Screen 2  Screen 3  Screen 4  Screen 5 	"This is a test of your working memory." "You will be shown a sequence of fractal patterns, such as these, one at a time. For each picture, press the spacebar if the picture on the screen is the same as you saw two screens before." "In this example, you would press the spacebar when you see picture 4 because you saw the same picture 2 screens ago (on screen 2). You would also press the spacebar during screen 5 since this test is continuous and not resetting. That means that you must keep remembering the last two pictures you saw, even if you pressed the spacebar. Respond as quickly and as accurately as you can." "Questions?" "You may now practice the task." [After practice, if there are no more questions] "The actual test goes faster than the practice, there will be no feedback and there will be 62 images shown."

Abstract Matching (AM)		"This is a test of your ability to learn abstract rules." "You will be shown two sets of objects on the bottom of the screen and a single object at the top. You are to choose the set at the bottom that best fits with the top object." After your choice, you will be provided feedback (correct in green or incorrect in red). Because you are learning abstract rules, they may at first seem illogical. Try to learn the set of rules that you have been assigned. Respond as quickly and as accurately as you can." "Note that the feedback is always shown over the left-hand set, so don't let the location of the feedback confuse you." "Questions?" "You may now practice the task."
Line Orientation Task (LOT)		"This is a test of line orientation discrimination." "You will be shown two lines. Your task is to rotate the blue line until it is parallel to the black line using arrows provided at the bottom of the screen. Please keep your head upright and remain at the same distance from the screen as you are right now." "Questions?" "You may now practice the task. Respond as quickly and as accurately as you can."
Emotion Recognition Test (ERT)		"This is a test of emotion recognition." "You will be shown 20 faces. Your task is to determine if the person appears H, S, A, F or is showing no emotion. Respond as quickly and as accurately as you can." "Questions?"
Matrix Reasoning Task (MRT)		"This is a test of reasoning skills." "You will be shown a matrix at the top of the screen that contains a missing cell. You are to select from the options at the bottom, the best choice to fill-in the missing cell." "Questions?" "You may now practice the task. The practice trials will provide feedback."

Digit-Symbol Substitution Task (DSST)		"This is a test of visual scanning and eye-hand coordination." "You will be shown a single symbol at the top of the screen. Here it is the "carot" symbol. You are to locate that symbol from the nine options shown at the bottom and as quickly and accurately as possible press the corresponding number associated with it. Here it would be the "6" key, using the number keys located along the top of the keyboard. Please use only your dominant hand." "Questions?" "You may now practice the task." "Note that the first three trials provided feedback. This will be true for the real test. This feedback forces a slower rhythm. On the fourth trial and on, you can go pretty fast."
Balloon Analog Risk Task (BART)		"You will be shown 30 balloons, one at a time. Inflate each balloon as much as you can without popping it. Each time you press the 'inflate' button, the reward goes up by a dollar. [PI points to the 'reward']. The larger the balloon, the greater the reward. When you press 'collect', the reward for that balloon moves into the 'total winnings'. You want to inflate each balloon as much as you can, but press collect before the balloon pops."
Psycho-motor Vigilance Test (PVT)	 	"This is a test of your reaction time. You will see a blue rectangle in the center of a black screen. " "After a brief amount of time, numbers will start counting up from one. As soon as you see the numbers appear, hit the space bar. In this example, this person hit the space bar after 180 msec. So, on this test, you can see your own reaction times." "Questions?" "You may now practice the task. "

Appendix D. Instructions used for the FMS and Fixed Order of Testing for the Short and Long Versions of the Battery

<table>
<tr><th colspan="3">Table D-1. Instructions used for the FMS</th></tr>
<tr><th></th><th>Stimuli
(as Shown on DEMO page)</th><th>Instructions</th></tr>
<tr><td>Dragging</td><td>
</td><td>“In the dragging task, you push the white square from the gray bar to the blue bar. When you reach the blue bar, you must lift your finger off of the screen for it to register, the bars will then change colors, and you quickly push the square to the other side. You are always pushing the square from a gray to a blue bar. [The PI then demonstrated the actions to be taken during a dragging task.]
“You will be tested in the horizontal and vertical orientations.”
Speed and accuracy are important.”</td></tr>
<tr><td>Pointing</td><td>
</td><td>“In the pointing task, you point to and touch the blue square, which always starts at the top, and then jumps to the opposite side as soon as you touch it. An arrow will tell you if the blue square will travel clockwise or counterclockwise.” [The PI then demonstrated the actions to be taken during a pointing task.]
Speed and accuracy are important.”</td></tr>
<tr><td>Tracing</td><td>
</td><td>“In the tracing task, you will trace either a circle or a square, clockwise or counterclockwise. You start at the location of the small circle labelled ‘Start’ and trace in the direction indicated by the arrow. Speed and accuracy are important.”</td></tr>
</table>

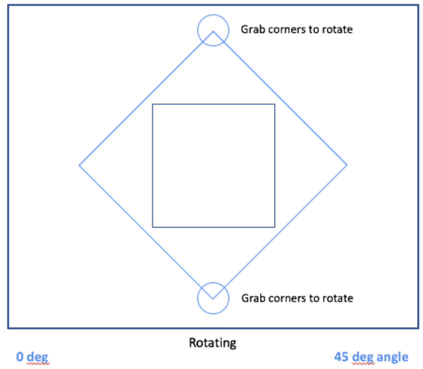
Pinch-rotate		"In the pinch-rotate task you place your pointer and thumb on the two circles [the PI demonstrates]. Then, pinch and rotate to outer blue square to align with the inner black square. Finally, you lift your fingers off of the screen. [The PI then demonstrated the actions to be taken during the pinch-rotate task.] You will be tested on two orientations." "Speed and accuracy are important."

Table D-2. Fixed Order of Testing for the Long-version of the FMS								
Testin g Order	Sub-task	#Trials /Block	Sub-Task Count		Testing Order	Sub-task	#Trials /Block	Sub-Task Count
Finger					Stylus			
1	Dragging Horizontal	16	D1 Rep 1		21	Pointing Counterclockwise Small	18	P1 Rep 1
2	Rotating Diamond	5	R1 Rep 1		22	Tracing Square Counterclockwise	5	T1
3	Rotating Square	5	R2 Rep1		23	Tracing Circle Counterclockwise	5	T2
4	Pointing Clockwise Small	18	P1/2 Rep 1		24	Dragging vertical	16	D1 Rep 1
5	Tracing circle Counterclockwise	5	T1		25	Tracing Square Clockwise	5	T3
6	Pointing Clockwise Large	18	P2 Rep 1		26	Pointing Counterclockwise Large	18	P2 Rep 1
7	Pointing Counterclockwise Small	18	P3 Rep 1		27	Tracing circle Clockwise	5	T4
8	Pointing Counterclockwise Small	18	P4 Rep 2		28	Pointing Counterclockwise Small	18	P3 Rep 2
9	Dragging Vertical	16	D2 Rep 1		29	Dragging Vertical	16	D2 Rep 2
10	Rotating Square	5	R3 Rep2		30	Dragging Horizontal	16	D3 Rep 1
11	Pointing Counterclockwise Large	18	P5 Rep 1		31	Pointing Counterclockwise Large	18	P4 Rep 2

12	Tracing Square Counterclockwise	5	T2		32	Pointing Clockwise Large	18	P5 Rep 1
13	Pointing Counterclockwise Large	18	P6 Rep 2		33	Pointing Clockwise Small	18	P6 Rep 1
14	Pointing Clockwise Small	18	P7 Rep 2		34	Dragging Horizontal	16	D4 Rep 2
15	Pointing Clockwise Large	18	P8 Rep 2		35	Pointing Clockwise Small	18	P7 Rep2
16	Tracing Square Clockwise	5	T3		36	Pointing Clockwise Large	18	P8 Rep 2
17	Dragging Vertical	16	D3 Rep 2					
18	Dragging Horizontal	16	D4 Rep 2					
19	Tracing Circle Clockwise	5	T4 Rep 2					
20	Rotating Diamond	5	R4 Rep 2					
Grand total # trials: 476 Approximate time to complete: 18 min								

Table D-3. Fixed order of testing for the short-version of the FMS.							
Testing Order	Sub-task	#Trials/ Block	Sub-Task Count	Testing Order	Sub-task	#Trials /Block	Sub-Task Count
Stylus				**Finger**			
1	Dragging Horizontal	16	D1	7	Rotating Square	5	R1
2	Tracing Circle Counterclockwise	5	T1	8	Pointing Clockwise Small	18	P1
3	Dragging Vertical	16	D2	9	Tracing Circle Counterclockwise	5	T1
4	Tracing Circle Counterclockwise	5	T2	10	Tracing Circle Clockwise	5	T2
5	Pointing Counterclockwise Small	18	P1	11	Dragging Horizontal	16	D1
6	Pointing Clockwise Small	18	P2	12	Pointing Counterclockwise Small	18	P2
				13	Dragging Vertical	16	D2
Grand total # trials: 161 **Approximate rime to complete: 8 min**							

Appendix E. Proposed Analyses Rationale

New performance measures are proposed for five of the CTB tests.

E.1 MPT – Include size of square: Not discarding data

E.2 VOLT – Utilize all the categories: Not discarding data

In the Visual Object Learning task (VOLT), a series of 10 images are shown followed by 20 images where the participants choose one of four categories regarding whether they have seen the image before (yes definitely, yes probably, no probably and no definitely). There is little difference between the d' and percent correct scores ($r = 0.9051$). However, if a participant were to change their use of the categories, then the area under the Receiver-Operating-Characteristic (ROC) curve would provide a more stable estimate.

The original accuracy score for the VOLT test is the average of the proportion of correct responses on memorized objects and the proportion of correct responses to new objects. The definitely-probably distinction was ignored by Moore et al. (2017) when deciding whether a response was correct or not. The ROC curve is a plot of the hit rate, PH, against the false alarm rate, PFA. The area under the ROC is a convenient measure of signal detectability. Figure E-1 shows the case of using only two response categories, where the ROC curve runs from (0, 0) to (PFA, PH) to (1, 1). The area under the curve is that of two triangles and one rectangle, PA = 0.5 (PFA PH) + 0.5 (1-PFA)(1-PH) + (1-PFA) PH = 0.5 + 0.5 (PH – PFA), which is the same as the average of the two correct proportions, hits and correct rejections.

0.5(PH + PCR) = 0.5(PH + (1-PFA)) = 0.5 + 0.5 (PH – PFA).

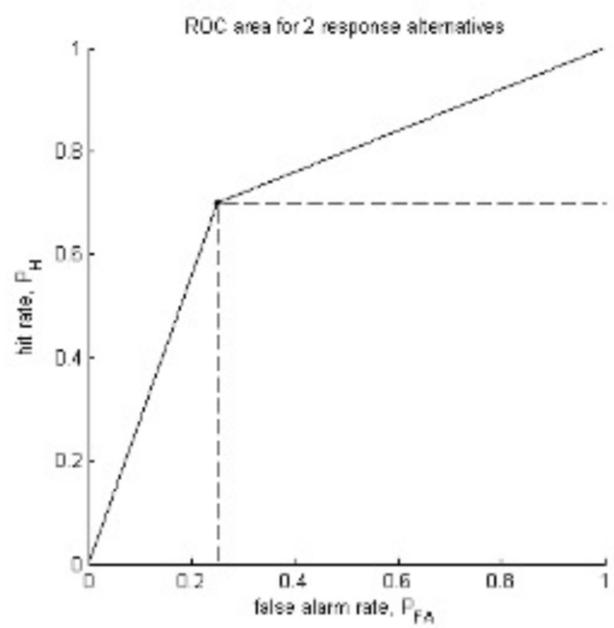


Figure E-1. ROC area when the "definitely-probably" distinction is ignored.

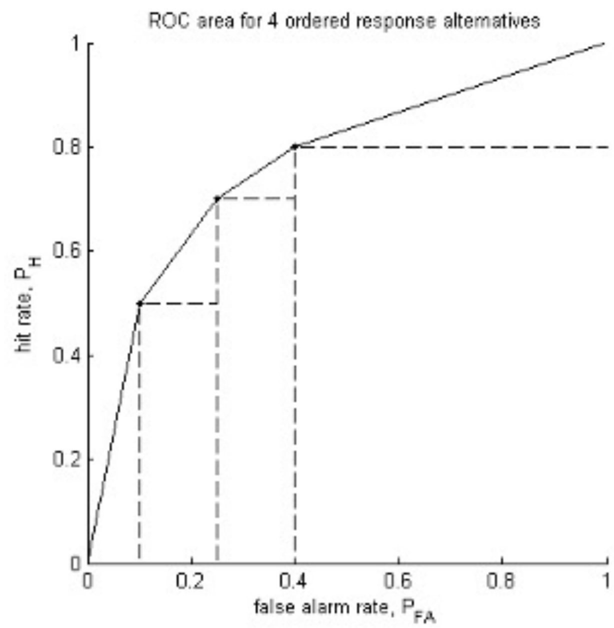


Figure E-2. ROC area when the "definitely-probably" distinction is used in the calculation.

Figure E-2 shows how the area is computed when there are four response categories so that there are three hit and false alarm rates (P_{H1}, P_{FA1}), (P_{H2}, P_{FA2}), (P_{H3}, P_{FA3}), computed by using each boundary in turn to define correct and incorrect. The area under the ROC is then that of four triangles and three rectangles,

$$P_A = 0.5\, P_{FA1}\, P_{H1}$$
$$+\ 0.5\,(P_{FA2}-P_{FA1})(P_{H2}-P_{H1}) + 0.5\,(P_{FA3}-P_{FA2})(P_{H3}-P_{H2}) + 0.5\,(1-P_{FA3})(1-P_{H3})$$
$$+\ (P_{FA2}-P_{FA1})\ P_{H1} + (P_{FA3}-P_{FA2})\ P_{H2} + (1-P_{FA3})\ P_{H3},$$

which simplifies to

$$P_A = 0.5\,((P_{FA1}\, P_{H1}) + (P_{FA2}-P_{FA1})(P_{H2}+P_{H1}) + (P_{FA3}-P_{FA2})(P_{H3}+P_{H2}) + (1-P_{FA3})(1+P_{H3})).$$

The use of all four response categories would provide more information for so few trials (10 signals and 10 no-signals).

E.3. LOT – Estimate the Slope of the Frequency of Seeing Curve: Not Discarding Data

The original accuracy measure for the Line Orientation Test (LOT) was average number of rotation steps away from equality in either direction when the participant responded that the orientations matched. For the new measure of accuracy, the response series was reduced to a 3x7 table of the number of times Nsr each of the stimuli were within 7 steps of the match (s = 0, 1, …, 6) and the response was "match," "move closer," or "move farther" (r = M, C, or F). The participant was modeled as having an internal response for each stimulus with a Gaussian distribution centered at the stimulus with standard deviation s, and symmetric criteria (-c, c) about the mean of the match distribution for deciding if a stimulus was a match. The model is illustrated in Figure E-3. The example signal has an offset of 1 step. The gray area is the probability that the sensation is between the criteria, resulting in the M response (and termination of the sequence). The green area is the probability of a sensation falling above the upper criterion, resulting in the C response (next stimulus is 0 offset), and the red area is the probability of the F response (next stimulus offset will be 2 steps).

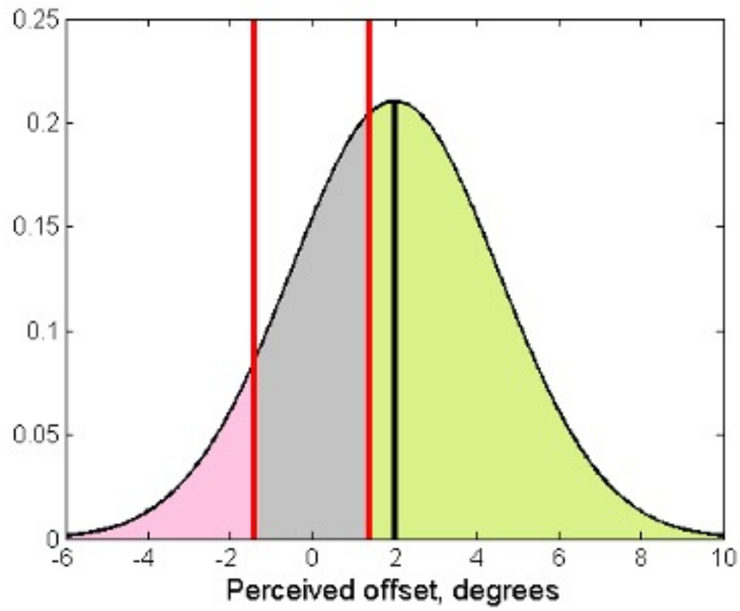


Figure E-3. Model of the participant's internal response to the line stimulus.

If we denote the standard normal cumulative distribution with mean m and standard deviation s by F(x; m, s), if the offset is 0, the probability of response M

$p(M|0) = 1 – F(-c; 0, s) – (1 – F(c; 0, s) = 1- 2 F(-c; 0, s)$,

and, since you cannot move closer to 0,

$p(C|0) = 0$ and $p(F|0) = 1 – p(M|0)$.

If the stimulus is t steps away with t>0,

$p(M|t>0) = 1 – F(-c; t, s) – (1 – F(c; t, s))$,

$p(C|t>0) = 1 – F(c; t, s)$, and $p(F|t>0) = 1 – p(M|t>0) – p(C|t>0)$.

The natural log of the likelihood of the stimulus-response table (n(S, R) , S = 0, 1, … , 5; R = M, C, F) is given by

$\ln L = \Sigma\ S, R\ n(S, R) \ln p(S, R)$.

Estimates of sigma and c in stimulus steps were found by maximizing the log likelihood of the response table using the Matlab Routine 'fminsearch' with the initial values s=1 and c=1.

A mean response time was also computed for the stimuli in the table for which not all the responses were C ("closer").

E.4. ERT – Identify Categorizing Ability

For the ERT, the performance was also evaluated by the information transmitted in bits T(S, R) for the participant's stimulus response table given the number of times n(S, R) that emotion category S resulted in response category R. A formula for T(S, R) is

$$T(S, R) = H(S) + H(R) - H(S, R),$$

where, the n's are the row and column sums and the grand sum

$$n(S) = \sum_{R} n(S, R) \; ; \; n(R) = \sum_{S} n(S, R) \; ; \; n = \sum_{S, R} n(S, R) \; ,$$

and the three information terms are the information in the S-R table and the two marginal tables.

$$H(S, R) = \log_2 n - (1/n) \sum_{S, R} n(S, R) \log_2 n(S, R) \, ,$$

$$H(S) = \log_2 n - (1/n) \sum_{S} n(S) \log_2 n(S) \, ,$$

$$H(R) = \log_2 n - (1/n) \sum_{R} n(R) \log_2 n(R) \, .$$

E.5. BART – Estimate the Quality of the Strategy: Not Discarding Data: Make Measures Less Sensitive to the Specific Sequence that was Used

The original measure of performance for the Balloon Analog Risk Task (BART) test is the average number of pumps per balloon series. Suppose the participant has a fixed number P of pumps that will be made before he/she stops pumping and collects. That number would be revealed as the number of pumps made when he/she collected before the balloon burst. The average number of pumps would be less and a function of the pop distribution for the test sequence truncated by the value P. If the participant has a distribution of P values the statistic R, the mean number of pumps on collection sequences will be less than the mean of P because the higher values will have increased burst exposure, but it will still characterize the strategy.

For our BART test, R and the average number of pumps are almost perfectly correlated. This is likely because the sequence of when the balloons would pop was constant (rather than randomized). All participants ran in the following sequence:

2 4 7 3 2 8 6 5 6 7 8 2 3 4 8 9 3 2 3 8 7 2 4 1 6 8 2 8 3 9

In other words, the first balloon popped after two pumps, the second after four pumps, etc. The frequency count for the number of pumps before the balloon would pop is shown in Figure E-4. If the distribution were a random sample from the uniform, the expected winnings as a function of P for 30 trials is 30 (P+1)(1-P/9). This has an optimal expected winnings of $83.33 at P = 4. For a random sample from the actually used distribution, the optimal value is $84 at P = 5. The frequency distribution was a single sample from the uniform distribution.

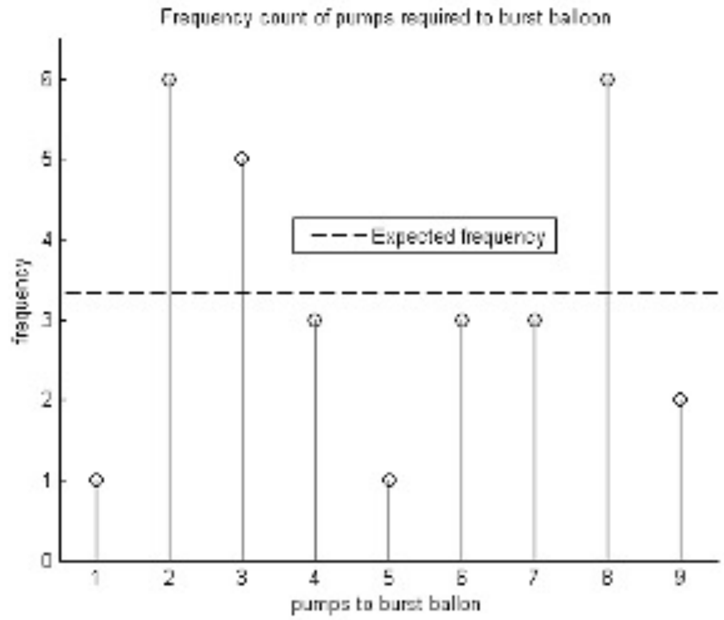


Figure E-4. The frequency distribution for Battery 3 of the BART.

E.6. Trace

In each tracing block there were five trials. The delta errors provided in the output file were not used. Rather, to determine a precise radial error, the average x and y error was corrected up to ½ pixel, thus providing information about whether the participant traced inside the circle (a negative number) or too far outside. To improve calculations, the square root of the two types of errors (inside and outside) were computed resulting in a proportion RMS (root mean squared) error (speed in pixels/sec). It was noted that while tracing the square, some participants did not abruptly change directions, rather they "cut the corners" staying on the inside of the square. Using the square root of the error (rather than 2 times it as was done in the FMS test battery output file) improves the estimates at the square's corners.

Appendix F. Average Latencies for the Short and Long Versions of the FMS

Average latencies for each of the 49 conditions averaged over 82 participants.

Table F-1. FMS Means of the Median Latencies (sec) and Standard Deviations for 82 Participants								
	FMS Long				**FMS Short**			
Conditions	**Finger**	**SD**	**Stylus**	**SD**	**Finger**	**SD**	**Stylus**	**SD**
DRAG								
Horizontal	0.755020561	0.16866049	0.688932146	0.12439917	**0.7101883**	0.1436706	0.69988109	0.15718068
Horizontal	0.706654707	0.12297997	0.676371232	0.11291277				
Vertical	0.699907024	0.12374764	0.671527439	0.11563522	0.69988109	0.15718068	0.67971713	0.14517589
Vertical	0.703993902	0.12212789	0.652935268	0.13492374				
POINT								
CW 1.5 in	0.536394988	0.12353127	0.504558902	0.09944554	0.49712467	0.08836004	0.5042534	0.0928031
CW 1.5 in	0.4982195	0.07467993	0.504264207	0.10093491				
CW 2 in	0.542486415	0.09385933	0.562442451	0.09154194				
CW 2 in	0.557744549	0.09750036	0.567042024	0.11200134				
CCW 1.5 in	0.502426793	0.06711641	0.504564378	0.08070933	0.50046005	0.07600406	0.53284959	0.11403998
CCW 1.5 in	0.49134011	0.07420447	0.499249293	0.09587459				
CCW 2 in	0.540008122	0.09621981	0.546533878	0.08201829				
CCW 2 in	0.538543402	0.11255711	0.550792	0.10811224				
TRACE								
CW Circle	3.138226829	1.70573017	3.384892683	1.80623854	3.31310976	1.59753946	3.27190244	1.73195574
CCW Circle	3.329031707	1.98144486	3.4787	1.80341266	3.31712195	1.65293049	3.41112195	1.77488203
CW Square	3.678209756	1.78095572	3.906997561	1.90239945				
CCW Square	3.854009756	1.88130491	3.900260976	1.86995047				
ROTATE								
45-deg	2.67110178	0.82187894						
45-deg	2.245047573	0.80609314						
0-deg	2.610758244	1.02310152			2.59837741	0.93898767		
0-deg	2.160268976	0.69124332						

CW = clockwise; CCW = counter clockwise.

Table F-2. T-statistics on the Latency Means for the Four FMS Tests		
Analysis	**T-statistic**	**Probability**
DRAG		
Finger vs Stylus	4.31412	0.00004
Horizontal vs Vertical	3.90967	0.00019
Rep1 vs rep2	2.68749	0.00873
FMS-Long vs FMS-short	-0.23464	0.81508
Learning 1 vs 3	6.93295	0.00000
Learning 2 vs 3	2.35487	0.02095
POINT		
Finger vs Stylus	-1.12057	0.26578
CW vs CCW	1.98670	0.05034
Rep1 vs rep2	1.20432	0.23197
1.5 in vs 2 in ring	-11.67388	0.00000
FMS-Long vs FMS-short	-0.60897	0.54425
Learning 1.5 in only 1 vs 3	6.59529	0.00000
Learning 1.5 in 2 vs 3	3.29115	0.00148
Finger vs Stylus	-1.12057	0.26578
TRACE		
Finger vs Stylus	-2.14448	0.03499
Circle vs Square	-7.33055	0.00000
CW vs CCW	-1.62680	0.10766
CW vs CCW just Circle	-0.96868	0.33559
FMS-Long vs FMS-short	-0.03511	0.97208
Learning time circle only 1 vs 3	-1.20221	0.23279
Learning time circle only 2 vs 3	-0.36080	0.71918
ROTATE		
Square vs Diamond	1.75701	0.08269
Rep1 vs rep2	6.82170	0.00000
FMS-Long vs FMS-short	-1.30478	0.19566
Learning (time) square only	5.88817	0.00000
Learning (time) square only	1.97305	0.05190

Table F-3. FMS Errors and Standard Deviations for 82 Participants.								
	FMS Long				FMS Short			
Conditions	**Finger**	**SD**	**Stylus**	**SD**	**Finger**	**SD**	**Stylus**	**SD**
DRAG								
Horizontal	1.99696794	0.43729032	1.87038113	0.40869287	1.7834797	0.40483348	1.86581928	0.42735317
Horizontal	1.85362874	0.43624609	1.8451404	0.4521433				
Vertical	1.9476867	0.45654743	1.77673084	0.36031446	1.92348329	0.43060642	1.7305432	0.42430873
Vertical	1.84449885	0.4085928	1.71841476	0.37727978				
POINT								
CW 1.5 in	1.98037234	0.39212284	2.0087983	0.43916339	1.9576954	0.42162649	1.90894474	0.44527403
CW 1.5 in	2.03797589	0.4225359	2.03082151	0.42536719				
CW 2 in	1.65759891	0.38828766	1.65433967	0.32931588				
CW 2 in	1.70880001	0.3558525	1.59255411	0.40066106				
CCW 1.5 in	2.03790421	0.38318648	1.97384032	0.37658735	2.11643772	0.33250612	1.9681143	0.44393022
CCW 1.5 in	2.01611494	0.39476465	1.92161968	0.44326189				
CCW 2 in	1.66184545	0.33895608	1.6258944	0.400931				
CCW 2 in	1.70267138	0.3970554	0.550792	0.10811224				
TRACE								
CW Circle	4.35276684	2.20965968	4.40062224	2.95471539	3.35272439	1.66017146	3.25081951	1.70881449
CCW Circle	4.27728387	1.85012344	4.06321024	2.28722803	3.31949512	1.64637037	3.82521707	2.75040613
CW Square	3.80961565	1.30990668	3.95296877	1.52332857				
CCW Square	3.78948888	1.71173695	3.95763767	1.42039085				

CW = clockwise; CCW = counter clockwise.

Table F-4. T-statistics on the Mean Errors for the Four FMS Tests		
Analysis	**T-statistic**	**Probability**
DRAG		
Finger vs Stylus	3.83312	0.00025
Horizontal vs Vertical	1.87066	0.06500
Rep1 vs rep2	3.10622	0.00261
FMS-Long vs FMS-short	1.05723	0.29355
Learning 1 vs 3	2.76843	0.00698
Learning 2 vs 3	1.81556	0.07314
POINT		
Finger vs Stylus	2.72537	0.00787
CW vs CCW	-0.05799	0.95390
Rep1 vs rep2	3.43281	0.00094
1.5 in vs 2 in ring	-9.98252	0.00000
FMS-Long vs FMS-short	0.54810	0.58513
Learning 1.5 in only 1 vs 3	0.84524	0.40046
Learning 1.5 in 2 vs 3	0.02720	0.97837
TRACE		
Finger vs Stylus	-1.14506	0.25556
Circle vs Square	-0.16256	0.87127
CW vs CCW	2.37718	0.01980
FMS-Long vs FMS-short	2.21590	0.02950