



**UNITED STATES AIR FORCE
RESEARCH LABORATORY**

**ORGANIZATION AND COMPONENTS OF
PSYCHOMOTOR ABILITY**

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13. ABSTRACT (Maximum 200 words) We administered test batteries of general cognitive and specific cognitive information-processing ability along with two replications of a psychomotor battery sampling from Fleishman's (1964) taxonomy of psychomotor tasks (i.e. control precision, multi-limb coordination, rate control, and response orientation). All tests were administered via computer. Fleishman's a priori categories were not supported by structure modeling of the data. The psychomotor factors that were supported were a general psychomotor ability factor and a factor associated with practiced psychomotor performance. Cognitive factors overlapped considerably with the psychomotor factors. General cognitive and temporal processing ability accounted for more than half the variability in the general psychomotor factor, though the variability unaccounted for by cognitive ability was still reliable. In addition, practiced psychomotor performance (controlling for general psychomotor ability) was only related to processing speed. Our results suggest that 1) psychomotor ability is not a set of diverse orthogonal abilities (as suggested by past literature) 2) psychomotor measures are important adjuncts to selection batteries for jobs with psychomotor components 3) cognitive ability (both general and specific) overlap with psychomotor ability in theoretically meaningful ways.
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Abstract (from the journal article)

We investigated the organization and components of psychomotor abilities by administering a diverse set of cognitive and psychomotor tasks to a group of recent high-school graduates ($N = 161$). Confirmatory factor analyses identified two psychomotor factors: a general factor associated with all psychomotor tests, and an orthogonal psychomotor learning factor associated exclusively with practiced psychomotor tests. Path analyses suggested that the general psychomotor factor could be largely accounted for by two cognitive factors, general working-memory capacity ($r = .67$), and an orthogonal time estimation factor ($r = .32$). Most of the psychomotor learning factor variance was unique, but psychomotor learning was somewhat related to processing speed ($r = .49$). We conclude that initial psychomotor performance is constrained by working-memory limits and the ability to keep track of time. Practiced psychomotor skill is additionally limited by processing speed, consistent with the literature on the development of process automaticity. Discussion addresses (a) the small dimensionality of the psychomotor abilities space, (b) our discovery of the importance of time estimation and other cognitive factors in psychomotor learning, and (c) the changing nature of psychomotor skill with practice.

Organization and Components of Psychomotor Ability

Psychomotor ability is thought to underlie activities such as piloting, driving, playing video games, engaging in dentistry, surgery, mechanics, carpentry, and electrical repair work, using a keyboard, joystick, or mouse to interact with a computer, and athletic performances of all kinds. How do we characterize the ability common to these diverse activities? What cognitive abilities underlie successful psychomotor performance? Is there a general psychomotor ability? Is it distinct from general cognitive ability? Answering these questions would enable progress in addressing a variety of applied issues, such as personnel screening, training, and interface design for complex, real-world psychomotor tasks.

Definition

While no consensus exists on what psychomotor ability is, in this paper we will define psychomotor tasks as those that involve a significant perceptual and response load. A defining feature is the requirement for either complex perceptual discriminations or productions of a complex motoric response. The perceptual input on a psychomotor task could be of either a visual, auditory, or tactile nature, and the motor output could involve the manual (one or more limbs), ocular, or vocal motoric systems.

Some features associated with psychomotor tasks are their continuous nature, their time criticality, and their time-sharing requirement (doing multiple things at once). Not all psychomotor tasks contain all these features, but these features are ones that tend to increase perceptual or response load. Thus a classic psychomotor task may be one that stresses continuity (involves the translation of a continuous perceptual display into a continuous motor response), timing (requires the performer to time a response or to estimate time accurately), and coordination (is done in conjunction with another task).

What is known about psychomotor abilities?

In the long history of interest in the psychomotor construct (Adams, 1987), a widespread perspective has been that there is no general psychomotor factor (Cronbach, 1970; Fleishman, 1954; Seashore, 1939). Support for this view came largely from early research showing low validity for simple psychomotor tests (e.g., rotary pursuit, finger tapping, rhythm reproduction). The research showed that although such tasks exhibited high reliability across occasions, they did not correlate with real-world psychomotor performances (e.g., athleticism; Seashore, 1930; managing yarn-winding machines at a cotton mill; Seashore, 1931). However, more recent research, using perhaps more complex psychomotor tests, has demonstrated higher validity against real world criteria such as performance on assembly-electrician work tasks (e.g., Levine, Spector, Menon, Narayanan, & Cannon-Bowers, 1996) and attrition from Air Force pilot training (Carretta and Ree, 1994; Melton, 1947, pg. 1013). It is probably fair to say that psychomotor ability, measured some ways, is important in some tasks or professions.

A widely accepted perspective on psychomotor ability is that it is not a single general factor but rather is made up of a set of independent "subfactors." This view largely reflects the work of Fleishman (1964) who suggested that there may be eleven or so psychomotor factors (e.g., reaction time, multi-limb coordination, response orientation). Fleishman's methodology was less than compelling, however. He did not conduct a single factor analytic study in which tests representing all the factors were administered to a single group of participants. Rather, because of the cost of such a study, a series of what he referred to as "interlocking" studies was conducted over a decade or so. What has not yet been attempted, due to machine and logistic limitations, is a study in which a wide range of both cognitive and psychomotor tests has been administered together. Current technology now makes such a study feasible.

The Latent-Structure Approach to Psychomotor Ability

It is useful to study broad behavioral constructs, like psychomotor ability, as "latent factors" underlying performance on a collection of tests. This factor-analytic approach is not new, but previous attempts such as Fleishman's relied on highly restrictive factor models (exploratory factor analysis) that were limited in their capability to address specific issues about the nature of psychomotor ability. Advances in latent structure modeling (including confirmatory factor analysis; Bentler, 1993; Joreskog, 1969) have allowed specific theory refinement and falsification to be introduced to psychometrics.

In this study we addressed several key issues from the psychomotor literature. We examined the hypothesis of a general psychomotor factor, the viability of Fleishman's taxonomy of psychomotor abilities, and the relationship between psychomotor abilities and other abilities, including cognitive, temporal, and processing speed. We also looked at the potential changing nature of psychomotor ability with practice.

Psychomotor Tasks and Fleishman's Taxonomy

We identified what appeared to be the four most important psychomotor factors from Fleishman's taxonomy, on the basis of the generality of the factors (as discussed in Fleishman, 1964), which was indicated by their published predictive validities with respect to piloting aircraft.

For each of our four target factors, we developed at least four computerized tests. At least one test in each factor was an implementation of an apparatus test originally analyzed by Fleishman. We chose the apparatus test with the highest factor loading on its intended factor as the test to develop. Other tests representing a factor were consistent with the factor descriptions taken from Fleishman (1964, and also briefly described in our procedure section for psychomotor tests.)

The four-factor organization of psychomotor tasks provided a starting point for an analysis. Initial confirmatory models were developed to reflect that organization, in addition to models of a general psychomotor factor common to all tasks. Comparison of model fits can help determine the viability of Fleishman's organizational scheme.

Cognitive Ability

We included cognitive tests in this study because we wanted to determine how much of psychomotor task performance is unique, and how much could be accounted for by cognitive factors, such as working memory capacity. We believe that this is an important step in determining the nature of psychomotor ability that was not evaluated in Fleishman's initial work. Our cognitive ability tests derive from the Cognitive Abilities Measurement (CAM) taxonomy, a broad taxonomy of general cognitive abilities. This taxonomy supposes that the structure of general cognitive abilities mirrors the major study areas of cognitive psychology, e.g. working memory, associative learning, procedural learning, and speed of elementary operations. Each area is a potential ability that can be assessed on different contents, spatial, verbal, and quantitative (for more discussion, see Chaiken, 1994, Kyllonen, 1991). Models derived from the taxonomy can indicate both general mental ability, and more specific factors.

Provided general cognitive and psychomotor ability have been defensibly defined, more specific information-processing abilities (i.e., abilities with the effects of general cognitive ability, or *g*, removed) can be investigated as probes of psychomotor ability. Two examples of such abilities are temporal-processing and processing-speed ability. Temporal processing is the ability inherent in visual extrapolation tasks (e.g., Lyon and Waag, 1995) and time estimation tasks (e.g., Keele, Pokorny, Corcos, & Ivry, 1985). Processing speed is the ability to do simple cognitive operations (e.g. discrimination of differences, visual search) at a characteristic rate (Chaiken, 1994). The two specific ability classes have an a priori basis for being considered components of psychomotor ability.

Time estimation

There is evidence for the importance of temporal processing ability to motor performance. Keele, et al. (1985) found that the variability of periodic pulses tapped out with either hand or foot correlated with the ability to sense whether a short time interval between two auditory clicks was longer or shorter than a 400 ms standard. The correlation between timing production and perception tasks suggests a common timing mechanism. Consistent with this conclusion, they also showed that a psychomotorically gifted group--skilled piano players--were better at both time production and time estimation tasks than controls.

However, their conclusion of a common timing mechanism is open to criticism. First, all ability tests are positively correlated (Spearman, 1904), so the presence of a correlation between time-production and time-estimation, does not, by itself, demonstrate a "common-clock" or temporal processing ability distinct from general aptitude. Second, they did not find a correlation between time estimation and two other psychomotor "abilities," handwriting quality and asymptotic tapping speed. Third, the group differences in temporal processing for piano players and controls might have been due to piano players' practice at discriminating and producing short time intervals.

In the current study, we administered both temporal processing and cognitive ability tests. A temporal processing factor was defined after partialing out the contribution of general

cognitive ability in performance on the temporal processing tests (using the “nested factors” confirmatory factor analytic technique, Gustafsson and Balke, 1993). We then explored the role of cognitive and temporal processing abilities in performance of psychomotor tasks through (latent variable) regression analysis. Unlike Keele, et al. we can directly test the idea that temporal processing ability contributes to psychomotor performance beyond (or after partialing out for) general cognitive ability. This idea has been discussed in the literature but has not been demonstrated (c.f. Imhoff and Levine, 1980; Fleury, Bard, Gagnon, and Teasdale, 1992).

Processing speed

We employ the same methods to explore the role of processing-speed ability in psychomotor ability. One might expect an important role for processing speed, if psychomotor ability involves many elementary perceptual judgments happening in real time. The speed of making such judgments may remain important to performance even after extensive practice because visual feedback remains important in at least some psychomotor tasks (e.g., rapid aimed movements of the arm, Proteau, 1992). Because processing speed and temporal processing appear conceptually different from each other, it is also conceivable they would contribute to psychomotor performance in different ways.

Repeated testing

Finally, in addition to modeling *g* and specific information-processing abilities in relation to psychomotor performance, we also assessed the stability of such contributions with a modest amount of practice (c.f., Fleishman and Hempel, 1954). To accomplish this we administered our psychomotor test battery twice. We also selected a subset of the psychomotor battery (one test from each Fleishman factor) to be practiced 5 additional replications.

Method

Participants

Participants were run in weekly cohorts of 12-25 persons. Participants were 161 temporary-employment personnel (55 female), paid \$5 an hour, and were matched to the Air Force applicant pool by age, education, and vision (i.e. ages 18-27; high-school or higher, and corrected vision).

Apparatus

Participants were tested in the same room in separate study carrels. Testing stations were 486 50 MHz, 486 66 MHz, and Pentium 90 MHz machines, with 32, 54, and 75 participants run on each platform, respectively. There were no significant main effects of computer type on any composite scores used in analyses. Each testing station had a 17-inch color monitor, CH Products Flightstick with two buttons (a top-button and a trigger button on the distal side of the stick), and a CH Products Pro-pedals set to “plane mode”. Plane mode means the left-right

pedals were yoked such that “depressing” the left pedal entailed swinging the left pedal in (away from the participant) and the right pedal out (toward the participant). Tests were implemented in EGA mode (640 x 350 pixels).

Procedure

General administration

Participants attended 5 days of testing including other studies not described here. The two replications of the psychomotor battery occurred on days 1 and 3. One psychomotor session was given in the morning, and one after lunch. Each session required about 2 hours of testing and two 10-min breaks. For each cohort and at each replication, psychomotor tests were assigned randomly to morning and afternoon sessions with the constraint that sessions be balanced with respect to test type. Within a session test orders were randomized for each participant with the exception that tests requiring a two-flightstick configuration stay together.

The first cognitive battery (working memory, skill learning, fact learning, induction) was given on the morning of day 2 and required 3 hours of testing with 2 five-minute breaks (outer thirds) and 1 ten-minute break (middle). Tests were given in a different random order for every participant.

The second cognitive battery (temporal processing, processing speed) was given in the afternoon of day 4 and required 2 hours of testing with a 10-minute break. Tests were given in a constrained random order with test classes (i.e. visual-search, temporal processing, inspection time) alternating.

Missing data across sessions were owing to three trends. First, some participants (19 of the 161 participants) left after the first day of testing (or missed a day of testing after the first day). Second, participants tended to be slower on the first day of psychomotor testing leading to fewer tests within a factor at day 1 (because participants were cut off before finishing all the tests). But because of our randomization procedures all tests were equally likely to be missing owing to slow finishing. Third, for one test (Hick’s task) a data-collection bug lead to the accidental overwriting of time 1 data by time 2 data (for the first cohort only, $n = 12$).

Psychomotor tests: general

Participants were instructed to use the hand of their choice and adopt the posture of their choice (e.g. placement of the flightstick on the desk or in their lap, placement of the rudder pedals, viewing distance). Once equipment was set up as desired, participants stayed at the same testing station. All tests had instructions with either part-task training and/or at least one practice trial. For tracking-type tasks, a 5-second warm-up period was given before data were collected on a trial.

Many psychomotor test trials were short periods of sustained performance (e.g. tracking an object for 35 seconds). For many such tasks feedback and enforced rest were given after

every trial. For most tests, participants advanced self-paced through feedback, affording additional rest time as needed. Except where noted, participant-feedback scores (aggregated across the task) were the same as those used in analyses.

Tests used flightsticks (hereafter sticks) and footpedals (hereafter pedals) to control screen objects in one of two ways. In isomorphically mapped control (hereafter, iso-mapped), stick or pedal placement consistently corresponded to some state of the object (e.g. a screen position or a rotation rate). In iso-mapping, the stick's rest position (i.e. vertical with no displacement) corresponded to the objects "resting state" (e.g. center screen or 0 rpm).

In speed-mapped tasks, keeping the stick tilted in a direction gave the yoked object a corresponding speed (proportional to tilt) and direction in screen space. For some speed-mapped tasks, releasing the stick or pedals (to rest) stops the object in whatever position it last reached. However, speed mapping is also used in compensation tasks, where the yoked object is not a rest but has speed. For such tasks, participants must cancel out an existing object speed or give the object a net speed (in a desired direction) to move the object purposefully. Compensation tasks used stick and pedals which could impart twice as much velocity (in a given dimension of travel) as the highest a priori velocity (in that same dimension).

Below are individual test descriptions for a single replication. The second replication is identical to the first except where noted. For task descriptions, we refer to left/right stick and object movements as "x" movements, and front/back stick movements and top/bottom screen-object movement as "y" movement.

Psychomotor tests: Control Precision

Tests in this class involve fine arm-hand and leg movements important in the operation of equipment that requires careful positioning. It is especially critical when movements require speed with precision. Rotary pursuit is a high marker of this factor. (Paraphrase of Fleishman, 1964).

1. Rotary pursuit (after Melton, 1947).

The participant followed a filled-in red circle (1.5-cm diameter) traveling in a circular path (14.5-cm diameter) using an iso-mapped stick to control a tracker. Twelve trials were given in a replication, six trials at 60 rpm and six at 30 rpm. Target-movement direction (clockwise or counterclockwise) alternated every trial, while speed alternated every 2 trials. An enforced rest of 15 seconds occurred after every trial during which our standard tracking feedback was given. This feedback displays the tracked object with the tracker at the average distance obtained by the participant during the trial.

2. Helicopter shoot.

The participant followed a helicopter-shaped icon using a stick with a speed-mapped sight. The helicopter moved at a rate of 80 x-pixel units per second along a complex sinusoid

from left to right sides of the screen (or vice versa). When the sight was on the target region (1 x 2.5-cm) for two seconds, the sight changed color to indicate a side-trigger click would shoot the target down. Premature firing lead to a "recoil" of the sight off the target and a restarting of the lock process. Participants did 4 sets of 6 trials and received number shot down and a 20-second rest after each set.

3. Fitts task (after Fitts, 1954).

The participant used an iso-mapped stick to move a sight between screen "response plates" as quickly as they could. The participant made 14-correct consecutive swings for each set. If an undershoot or overshoot occurred, an error message alerted the participant and they restarted the set. A "time-remaining" message was given after each error as participants had a 3-minute deadline before advancing automatically to the next set. At set completion, total swinging time on the correct series was presented in the context of their past best and worst times. If they beat their best they were congratulated; if they did poorer than their worst they received: "Sorry, this is your slowest time so far."

Participants did 5 sets in each cell of a 2 x 2 design varying precision (plate width: 1.2 cm vs. 3.5 cm) and amplitude (plate separation: 12 cm vs. 24.5 cm). The 4 conditions were blocked and presented in a random order for each participant. Scores are derived from successfully completed sets only.

4. Grids.

The participant used an iso-mapped stick to move a sight to a colored grid cell (target) in a large grid containing many unlit cells. Once the sight was placed within the target, a side-trigger click "extinguished" it and a new cell became target. Participants did 5 sets on a grid that was 16 x 16 cells (cell-side of 1 cm) and 5 sets on a grid that was 32 x 32 cells (cell-side of .5 cm). Consecutive targets were randomly chosen with the constraint that no two targets be within half a grid side (e.g. 8 or 16 cell lengths). Other aspects of the procedure were the same as the Fitts task.

Psychomotor tests: Multi-limb coordination

Tests in this class involve simultaneous coordination of two or more limbs especially when operating devices with several controls. High loaders include the Mashburn task (referred to by Fleishman as the "Complex-coordination task") and Two-hand coordination tasks.

1. Center the ball.

The participant used a speed-mapped stick and pedals to keep a filled-in circle (ball) at center screen. Pedals compensated for x-drift of the ball while the stick compensated for the y-drift. Ball drift (speed and heading) was replaced every 4 seconds by a new drift selected from a fixed set. Participants did two sets of 36 four-second-drift compensations with feedback similar to rotary pursuit. An enforced 90-second rest was given between sets.

2. Mashburn Task (after Mashburn, 1934).

The Mashburn stimulus looks like an upside-down T whose (former) top has become the base and whose (former) leg supports the concave part of an arc (i.e. an upside-down anchor). Each component (i.e. base, leg, and arc) was composed of a red and green bank of 13 lights each, either one atop the other (base and arc) or side by side (leg). The computer presented a target light in the red bank of each component and participants matched 3 lights under their control in the green bank. The pedals controlled placement of the base light by iso-mapping pedal-movement range into the 13 light positions and the 14 "spaces" around the lights. Hence, when the pedals corresponded to a position between lights no bottom light would show. The arc and leg light banks were similarly mapped into the x and y motion of the stick, respectively. Once participants matched their lights to the computer's for 2 seconds, a new trial was presented.

Participants received 1 minute of practice and did five 2-minute periods. A number-completed score followed each period along with a 45-second forced rest, after which the next period automatically started. Trials cycled through a fixed set of 40 (selected from the original apparatus task), continuing where the last set left off and returning to the beginning of the set if needed.

3. Two-armed coordination.

Two blocked tasks were used in an order balanced across participants. In two-arm tracking (loosely after Melton, 1947) participants used two iso-mapped sticks to keep a sight close to a target moving on a visible path. Half the time, the path was a circle 14.5-cm in diameter, and half the time a "tri-circle" -- three 8.3-cm diameter circles tangent to each other and arranged in an upside triangular formation. The right-stick controlled the y-movement while the left-stick controlled the x-movement of the tracker. Moving a stick in an inappropriate direction caused the other stick's appropriate movement to become less effective (in proportion to the amount of inappropriate movement), and participants were made aware of these effects prior to starting the task. Participants did 12 trials with feedback after each trial as in rotary pursuit.

In two-arm navigation participants used independent (i.e. non-interfering) speed-mapped sticks to control the x (left stick) and y (right-stick) speed of a small boat as it moved through a 6-pointed star-like canal. The boat was a solid-white circle .3 cm in diameter and the canal was .65 cm. in width. When the boat "hit" a canal wall, it stuck for 2 seconds (accompanied by a buzz and a small "x" appearing on the boat). Participants traversed the path as quickly as possible and got feedback after every traversal in the style of Fitts. Participants did 12 trials on 12 15-degree rotations of the star-canal, with representative starting locations and alternating travel directions.

4. Pop the balloons.

Participants popped a randomly moving target balloon (purple circle) among randomly moving non-targets (yellow circles). Participants used a speed-mapped stick and pedals to

respectively control the y and x-movement of a sight so that it could be placed on the target and popped (trigger-click). If the participant did not pop the target in 8 seconds, it turned red, as a warning, and then popped itself 2 seconds later. After popping, one of the non-targets turned purple and the process repeated until the set was popped. Participants did 5 sets of 3 to 8 balloons in that order, with feedback (average time between pops) and participant-determined rest after each set. Total number of participant-popped balloons across sets (the test score) was given at the end of the test.

Psychomotor tests: Rate Control

Tests in this class involve continual corrections to motor responses to keep in synchrony with a variably speeded object or to avoid collisions with objects. High loaders are 2-wheel avoidance (a.k.a. "Motor judgment task") and arc pursuit (a.k.a. "Rate control test").

1. Arc pursuit (after Melton, 1947).

The stick's x-movement was speed mapped into a 140-degree arc-shaped window (4-cm height and 26 cm horizontal distance between outer-arc endpoints). The stick controlled 2 yellow lines which connected the inner and outer arcs with 5 degrees separation (i.e. these lines would project back to the arc window's center). The participant moved the yellow lines to keep them as close to (or around) a single solid-red line (also projecting to center). The target moved in the arc-window at varying rates in the same direction, but reversed direction at left/right window boundaries. For each trial, target movement was constructed by randomly combining 7 levels of speeds (35 to 140 degrees per second) and 3 levels of duration (900 to 1900 msec) with the constraint that no two consecutive speeds be identical. Each trial lasted 35 seconds and was followed by feedback in the style of rotary pursuit. Participants did one practice and 10 test trials.

2. Wheel avoidance.

Two versions were given with the simpler version preceding. The simple version had a single screen-centered wheel 10-cm in diameter that rotated from +25 to -25 rpm. The wheel attained a target speed (picked from a fixed set of speeds) at a gradual rate (+3 or -3 rpm every second) and then moved to the next target speed. The wheel had 3 gray and 3 black uniformly distributed 60-degree segments. The participants controlled the rotation rate of a green arrow pivoted at circle-center to avoid the gray segments (where the arrow turned red). Arrow rate was iso-mapped (from +38 to -38 rpm) into the y-movement of the stick. After a 30 second practice trial, participants did 5 two-minute trials with percent time-in-black and a participant-determined rest given after each set.

The harder version (after Melton, 1947) used two wheels of alternating red and black segments (10-cm in diameter). Each wheel had roughly 80 degrees red, 70 black, 30 red, 80 black, 30 red, and 70 black. The circles rotated at 10 and 8 rpm and had centers approximately 7 cm to either side of screen center. At screen center a green arrow's rotation rate was controlled (between 8 and 50 rpm, clockwise only) by the iso-mapped y-movement of the stick. During a

trial, participants maximized the number of arrow rotations without touching a red segment of either circle. Participants received 30 seconds of practice before doing five 2-minute trials. Fifteen seconds of enforced rest with feedback was given after each trial before continuing without pause. Feedback was number of error-free rotations minus the number of error-rotations.

3. Circle pursuit.

One half of the stick's y-movement (from neutral to maximum tilt towards the screen) was speed-mapped into a circular path (15-cm in diameter). The stick controlled a sight's speed along the path in one direction only (i.e. stopping was possible but not going in reverse). The participant kept the sight as close as possible to a filled-in red circle that also traveled in one direction along the circle but at varying rates (between 60 and 204 degrees per second). All other aspects of this task are the same as in Arc pursuit.

4. Lane Tracking.

Participants had a drivers-eye view of the front of a car heading down the right lane of a straight two-lane / two-direction highway. The car is subjected to high winds either from the left or right, which push the car off the road or into the opposing lane (with the appropriate perspective rendering as this occurs). Participants used the speed-mapped x-movement of the stick to compensate the winds and keep as close to the center of their lane as possible. Participants did one practice trial for 30 seconds and eight test trials for 1 minute each. In four test trials wind-speed shifted every second and in the other four twice a second. Trial types alternated. Feedback was a 3-d static rendering of the car's distance from the target lane's centerline. Other aspects are similar to Arc pursuit.

Psychomotor tests: Response Orientation

Tests in this class involve rapid selection, independent of precision or coordination, of the correct motor response corresponding to a discrete stimulus. High loaders are direction control test, red-green orientation test (a.k.a. "Discrimination reaction time"), and sounds and lights test (a.k.a. "Choice reaction time").

1. Sounds and lights (after Fleishman, 1964).

Participants viewed a 2 x 4 cm black rectangle for a random foreperiod of 3.5 to 4.5 seconds. Either a high tone, low tone, red-rectangle fill, or green-rectangle fill occurred to which participants moved pedals left, right, pressed the top-stick button, or stick-trigger, respectively. Participants studied the response rules (15 seconds each) and received two practice sets of blocked pedal and stick responses (20 trials). Participants next received 9 blocks of 12 randomly ordered mixed trials, of which the last 6 blocks had the consecutive-correct constraint as in Fitts. All incorrect responses received feedback that told the correct answer. A participant-determined rest and feedback was given between sets. The task score was the average response time within a (consecutive-correct) set.

2. Red and Green Orientation (after Melton, 1947).

Participants viewed a 2 x 2 array of white unfilled circles. A red and green circle replaced one of the array's rows or columns. The participant then indicated how the red circle was oriented to the green one by pressing the appropriate arrow key on the number-pad (e.g. left arrow, number pad 4, for to the left of; up arrow, number-pad 8, for above). After studying the rules to representative stimuli and experiencing 4 practice trials, participants did eight blocks of 16 trials. When an error was made the trial remained on screen until the correct response was given (after which a blank screen occurred). The task score was total cumulative responding time per block (i.e. errors added time to ones score).

3. Direction control (after Melton, 1947).

Participants viewed four types of arrow-like stimuli and made spatially analogous responses. If an arrow stimulus pointed with an angle integrally divisible by 45, the participant swung the stick in the two directions implied by the stimulus (e.g. pointing to the upper left screen corner would imply a leftward and upward swing of the stick in any order). If an arrow pointed straight up or down, or directly to the left or right, the participant swung the stick in the direction pointed and pressed either the top button (for up/down stimuli) or the side-trigger (for left/right stimuli) in any order. After studying the rules (15 seconds for each of 8 stimuli), participants received 24 practice and 3 blocks of 24 balanced test trials. Pedagogical feedback occurred on error or after a (10-second) time-out, requiring a trigger-click from the participant to resume the task. The score used was average time to finish the correct responses across blocks.

4. Hick's task (variant of Hick, 1954).

Participants switched to 286-based platforms with touch-screens for this test only. Participants received two conditions. In one condition, participants viewed 7 empty cells arranged in a horizontal arch that subtended the (14-in) screen with a home key roughly at arch center. After the participant's index finger was at the home key for 1 second and after a random foreperiod (750 to 1250 msec), an arch cell filled. The participant lifted from the home key and touched the target as quickly as possible. A correct response extinguished the cell and restarted the process; an incorrect response did nothing and a response longer than 3 seconds caused a time-out message (requiring a key-press to resume). The second condition displayed the target in a random two-cell subset of the 7-cell condition (the other cells being blanked out), so that only two-possible locations were identified during the pre-target waiting interval. After 10 practice trials, both conditions were given in 4 mixed blocks of 42 balanced stimuli. The score used was the average of movement and decision time for all conditions.

Extended Practice

A subset of the psychomotor battery was administered for 5 additional replications on the morning of Day 4 (i.e. after the second administration of all the tests). The subset consisted of a single test from each of the Fleishman categories described above. The tests were Helicopter Shoot (control precision), Mashburn Task (multilimb coordination), Wheel avoidance-hard

version (rate control), and Direction Control (response orientation). Except for abbreviated instructions, the 5 replications for each test were identical to the earlier time 1 and time 2 administrations. Tests alternated (i.e. were evenly spaced throughout the testing session) with the order of alternation a random factor across participants.

General intellectual ability

General ability was measured by the efficiency of four general cognitive processes, working memory, induction, fact learning, and skill learning. Each process was measured by a spatial, verbal, and quantitative test. All participants received the same items (though not in the same order) with at least one practice problem and/or demonstration of all the types of problems they would encounter. Participants had a limited but liberal amount of time (determined in pilot studies) to respond to each question. Feedback was given after every problem, with at least a 1000 ms inter-trial interval (for simpler tasks) and at most a minute (for study of feedback on complex tasks). Blocks of items were always stimulus-balanced and randomly ordered, with total-correct feedback and rest at block end. All participants used the mouse for responding.

Working memory.

Spatial working memory involved remembering what stick figures drawn on a 3 x 3 grid of nine dots went with what variables x, y, and z. Figures were made up of from 2 to 5 dots. An encoding phase assigned figures to variables (10 seconds a piece). Encoding involved computation as two sets of line segments (on two grids) were combined using a plus or minus operator. Sometimes variables were functions of other variables (e.g. y might equal z minus some displayed set of segments). A recall phase followed that had participants draw the values of x, y, and z (in that order) on a grid using mouse clicks. Participants did 9 sets (27 recalls).

Quantitative working memory involved recalling the last 3 numbers (between 1 and 9) on a sequentially presented list (3 seconds an item, items overwriting last item). If numbers were white, values were recalled as presented; if numbers were red, the value recalled was 10 minus the number. Mixed as well as same color lists were presented. Participants did 2 sets of 8 lists of from 3 to 6 items.

Verbal working memory involved the construction of a list of animal and furniture terms from a set of isolated instructions that are sequentially presented for 5 seconds (a variant on Baddeley, 1968). For instance-- "the dog comes after the bird" / "the lamp is not before the rug" / "animals do not come after furniture" -- would generate a unique four-term series (bird, dog, rug, lamp) which the participant would pick from a list of 8 alternatives. Participants did 24 problems.

Induction.

The verbal and spatial induction tests were odd-man out paradigms. Participants viewed three rows of three figures (words) each. Participants had to click on the row that did not follow an unspecified rule followed by the other two rows. The majority rule changed every trial.

Participants did 10 spatial problems and 20 verbal problems. The quantitative induction test presented the participant with a 3 x 3 array of 8 numbers and one blank cell. Participants had to determine the rule that generated the numbers and provide the missing cell value. Participants did 20 problems.

Fact-learning.

The quantitative test had participants study an array of 12 random numbers between 1 and 100 for one minute, after which a recognition test of 26 (old/new) numbers was given. Participants repeated this on another array. The spatial tests had participants study lists of 4 figural paired-associates presented sequentially and in isolation of each other for 8 seconds each. Stimulus and response terms were similar to those in the spatial working memory test. After study, cued-recall of the list was given in random order. Participants did 3 lists. The verbal test had participants learn 8 unique S-R associations, where the stimulus terms were drawn from a set of occupations (e.g. plumber) and responses from a set of furniture items (e.g. lamp, table). Participants did 8 blocks of 32 S-R verifications with a menu (top screen) showing the complete list of unique associations above each pair verified (bottom screen). Accuracy on the ninth and tenth block, which had no menu, was the test score.

Skill learning.

The verbal test was a variation on Thurstone's letter-reduction task (Thurstone and Thurstone, 1941). Instead of letters, words referring to past (past, before, yesterday), present (present, now, today), or future (future, later, tomorrow) were used. The participant provided the correct tense to two-word strings according to Thurstone's same rule (i.e. same tense yield the same tense--e.g. "before past" = click on past button) and different rule (i.e. different tenses yield the excluded tense -- e.g. "now yesterday" = click on future button). Participants did 3 blocks of 24 problems.

The quantitative task taught participants to classify numbers between 1 and 20 (ten excluded) into big/positive (where big means greater than 10), small/positive, negative/odd, or negative/even. Big/positive and negative/odd numbers required a left-button response; whereas other classes required a right button. Participants did 12 blocks of 32 problems.

The spatial task presented 4 sequential dots in a 2 x 2 grid of cells, where cell 1 and 2 is left and right members of row 1 and cell 3 and 4 are the same for row 2. Dots remained on screen .5 seconds and occurred with pacing beeps. The dots could "draw" either a c-pattern (e.g. 1-2-4-3, 3-1-2-4), an x pattern (e.g. 1-4-3-2, 2-3-1-4), or a z pattern (e.g. 1-3-2-4, 1-2-3-4). Either the 2nd or 3rd dot of each trial was not presented, though its accompanying beep was. The participant had to select which pattern the 3 visible and 1 invisible dots made with a response deadline of 2 seconds, after which the trial was incorrect. Participants did 4 blocks of 24.

Specific information-processing battery

Temporal Processing.

Temporal processing was measured in 3 different paradigms, with two tests in each. Participant wristwatches had been removed at the start of the session.

In an "arrival-time" paradigm, participants viewed a cyan-line grow from the left to right across the screen. The line stopped part way, and participants pressed a mouse button when they thought the line had reached the right side. A five percent tolerance window on either side of the target arrival time defined a correct response, with trials terminating at response or at the end of the window. Three conditions of speed (arrivals at 5, 7.5, and 10 seconds) and two stopping distances (a quarter and midway across the screen) were factorially combined and given in random order. Participants did 6 practice and 18 randomly ordered test trials with right/wrong plus closeness-to-target feedback after every trial. The other test in this paradigm was isomorphic in all respects but used a digital clock that stopped (blanked out) either at 25 or 50 and whose arrival time at 100 had to be estimated.

A "who-wins" paradigm used either a pair of lines or a pair of digital clocks. One object would start at a given rate some lead-time before the other started at a different rate. Both objects would disappear at the same point along their travel. Participants had until the race was won to move a mouse cursor over to the winner and click. Objects could disappear either a quarter or midway through travel. The race could either end close (e.g. a clock-count difference of 5 to 2), medium (11 to 8), or distant (21 to 18). And finally, base speed of the first object could be fast, medium, or slow (arrival times of 5, 7.5, or 10 seconds). These factors were combined factorially. Participants did six representative problems and 54 test trials with randomly ordered conditions. Feedback occurred after every trial.

Pure time estimation tasks used either a clock or a horse icon. Participants pressed a mouse button when either clock or horse had run the requisite time, i.e. 5, 10, 15, or 20 seconds. Error tolerance was the same as in the arrival-time tests. Time-to-wait was indicated at the beginning of each trial. For instance, the timing interval started when a "0..10" appeared above a horse at the left side of the screen. Right/wrong feedback and a digital display of the time waited was given after every trial. Participants did 6 practice trials and 24 randomly ordered test trials.

The 6 temporal processing (hereafter TP) scores were reduced to 3 composites, one for each temporal-processing paradigm (e.g. estimate arrival).

Processing speed.

Two visual search tasks (hereafter, VS tasks) and two inspection-time tasks (hereafter IT tasks) were given at two replications in the first and second halves of the battery. A single replication is described (time 2 differing only in abbreviated instructions and the lack of practice problems). Most of these tasks derive from Chaiken (1994).

For VS, participants were presented a 3 x 3 array of 9 two-digit numbers from 1 to 20 (e.g. 01,02, ... 20) written in a small font (i.e., .4 x .2 cm). One array member was yellow and the rest were white. If any white array-member repeated the yellow one, the participant responded "target present" by pressing the L-key with the right index finger; if not, the participant responded "target absent" by pressing the D key with the left index finger. In the compressed-condition, separation was 1 cm (between number centers); in the spread-out condition separation was 9.5 cm. Participants did 4 sets of 14 (balanced) trials for each condition. Conditions were blocked with order balanced across participants. Accuracy set, feedback, and scoring were as in Fitts. Hence, two of the processing speed markers were a compressed and spread-out visual search score.

A quantitative version of IT required the participant to identify whether 3, 4, or 5 red dots had been presented before a dynamic backward mask of erasure dots. After 24 consecutive correct responses to unmasked stimuli, participants did 135 stimulus-balanced and randomly ordered trials at 171, 214, and 257 msec viewing times. Rest and feedback were every 27 trials. A "verbal" version of IT required participants to identify which trigram of Xs and Os occurred (i.e. XOO, XXO, OXX, OOX) before a backward mask of alternating Xs and Os (i.e. XOXOXOX). Practice on unmasked stimuli, was given and participants did 144 stimulus-balanced and randomly ordered trials at 72, 114, and 157 msec viewing times. Rest and feedback were every 24 trials. A composite IT score was derived by averaging the (z-scored) accuracy from each task and was used as the third marker of processing speed (hereafter, PS).

Results

Descriptive Statistics on Tests.

All the data that might be of interest for this study cannot be published here but is made available through archives (Chaiken, Kyllonen, and Tirre, 1999a, 1999b). For instance, univariate statistics for individual psychomotor tests, general cognitive, and specific-information processing tests are given in the archives (Table W1 through W3, respectively, where the W prefix indicates a website table).

All psychomotor tests but arc-pursuit showed a practice effect from time-1 to time-2 sessions (t_s ranging from 1.4 to 18.0, median $t = 7.4$). All tests but lane-tracking showed reasonable time1/time2 plots and reliability (r_s ranging from .63 to .92, median $r = .74$). Lane tracking could be repaired using a rank transformation (raising its time1/time2 reliability from .21 to .71).

Viability of Fleishman's Taxonomy

Our first analyses evaluated Fleishman's scheme for explaining correlations among psychomotor test scores (Table W4). Figure 1 displays the three types of models we considered. We assessed whether Fleishman's hypothesized abilities (e.g. control precision) improved fit beyond a baseline model with only a general psychomotor ability (hereafter, g_p). We made this

assessment in two contexts: 1) a nesting of Fleishman's factors inside g_p , and 2) correlated Fleishman factors. The concept of nesting was introduced before as means of identifying unique factors (e.g. control precision) controlling for broader factors (e.g. g_p). A commonly employed alternative to nesting is the "correlated factors model," where there is not a general factor, each test loads only on one factor, and all factors freely correlate. In this model, the uniqueness of a particular factor is represented by its less than perfect correlation to other factors.

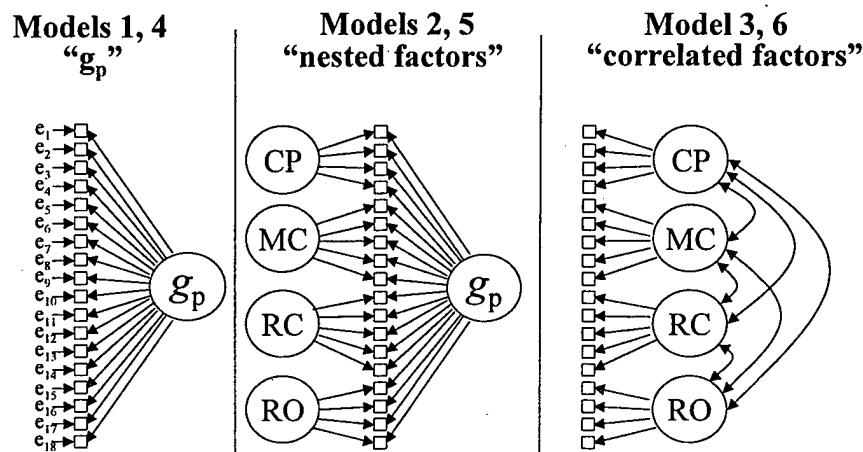


Figure 1. Models assessing Fleishman's taxonomy for the psychomotor test-score data (i.e. covariances for 4 control-precision [factor CP], 5 multi-limb coordination [MC], 5 rate-control [RC], and 4 response-orientation [RO] tests). Score error terms were present in all models but are shown only in baseline, g_p models to reduce clutter. Models 1,2, and 3 are for Time 1 data. Models 4, 5, and 6 are for Time 2 data.

Table 1 (Models 1 through 6) summarizes our single-session findings. While model fits were not high (Bentler [1993] recommends a BBNF statistic of .90 or above), model fits with and without Fleishman factors can still be compared. Models adding the Fleishman factors to g_p in a nested-factor representation fit marginally better than models with only g_p (e.g. Model 2 vs. Model 1, $\chi^2(18) = 45, p < .01$). However, models in which Fleishman factors correlate freely (i.e. Models 3 and 6) fit no better than more restricted models in which all factors correlate perfectly (i.e. the six correlations fixed at unity; session 1: $\chi^2(6) = 10.2, p < .20$; session 2: $\chi^2(6) = 5.7, p < .50$). As only the nested factor models showed any improvement from the addition of Fleishman factors, we assessed these improvements for interpretability as we describe next.

Table 1.

Model goodness-of-fit statistics for psychomotor test-score models in Figure 1.

Model	df	χ^2	BBNF	RMSEA
<u>Time 1 Data Only</u>				
Null (Independence)	171	1563	-----	.248
1. General psychomotor factor (g_p)	135	264	.882	.085
2. Nested Fleishman factors	117	219	.893	.082
3. Correlated Fleishman factors	129	254	.881	.086
<u>Time 2 Data Only</u>				
Null (Independence)	171	1594	-----	.251
4. General psychomotor factor (g_p)	135	276	.874	.089
5. Nested Fleishman factors	117	240	.874	.090
6. Correlated Fleishman factors	129	271	.868	.091
<u>Time 1 and 2 Data Together</u>				
Null (Independence)	666	5329	-----	.230
7. General psychomotor factor (g_p)	576	1522	.765	.112
8. g_p + learning	558	1392	.787	.107

Notes. $N = 133$ for all analyses. BBNF is the Bentler-Bonett Non-normed Fit index (described in Bentler, 1993). RMSEA is the Root Mean Square Error of Approximation (Browne and Cudeck, 1993).

Inspection of the significant path loadings in Models 2 and 5 suggested interpretability problems. In session 1, only 6 (of the 18) tests had significant loadings on the expected factor, and these loadings were widely dispersed over the 4 factors. In session 2, only 7 tests had significant loadings, and these were again widely dispersed. Only four of the 10 tests that loaded the expected factor were the same from session 1 to session 2. EQS also provides a Lagrange multiplier (LM) test, which suggests ways to improve model fit by allowing tests to load on other factors than their expected one. The LM test suggested 9 additional loadings of tests on the wrong factors for session 1 (e.g., a multilimb coordination test loading on the rate control factor) and suggested 5 additional loadings of tests on the wrong factors for session 2. There was no overlap in the LM test modifications suggested for session 1 and 2 data.

From these analyses, we conclude Fleishman's taxonomy does not describe these data. As no alternative taxonomy for multiple psychomotor abilities emerged, we also conclude that the general psychomotor factor model is the best description of our test battery.

Learning Effects

Most psychomotor tasks showed learning effects: Participants improved with practice (Table W1). A question is what psychological factor is responsible for that improvement. It could be that a general psychomotor ability factor is what produces learning, that is, individuals with high psychomotor ability learn faster. Or it could be that there is a psychomotor learning factor separate from general psychomotor ability.

A way to test for the existence of a psychomotor learning factor is to analyze session 1 and session 2 psychomotor scores in the same structural analysis. We can then evaluate the idea that session 2 tests have reliable ability variance that is unique from general psychomotor ability. Model 7 is a single-factor model, in which all 36 scores (18 tests by 2 sessions) load on g_p , and Model 8 adds an additional nested learning factor on which only the Session 2 scores are allowed to load. In these models, Session 1 and 2 errors for a particular test were allowed to correlate.

Table 1 shows that the addition of the learning factor (Model 8) resulted in a modest increase in the goodness of fit ($\chi^2(18) = 130, p < .01$). Loadings on the learning factor were well behaved. Fifteen of the 18 loadings on the learning factor were significant (i.e., $z > 2$), and no loadings were in the wrong direction. Hence, a learning factor independent of g_p was observed.

To further understand the nature of this learning factor, we correlated magnitude of the learning-factor loading with practice effect size (available from Table W1). We expected that tests with greater practice effects would have higher loadings on the learning factor. Surprisingly, we found that loading and practice effect were significantly negatively correlated ($r[15] = -.55, p < .05$). That is, tests with greater practice effects tended to have smaller loadings on the learning factor.

We then speculated that the learning factor might represent a change in the abilities necessary to do the test (cf., Ackerman, 1988; Fleishman & Hempel, 1954). If so, we might expect a smaller Session 1-Session 2 correlation for tests with large loadings on the learning factor. The trend was in the right direction ($r[15] = -.27, p > .05$), but the relationship was not significant. We conclude, then, that there is some factor responsible for the difference in performance between Session 1 and Session 2 testing. We tentatively refer to this factor as the psychomotor learning factor, but the psychological mechanism for it is not apparent from these analyses.

Regression of Psychomotor on Cognitive Factors

A means for determining the nature of the psychomotor factors is to regress those on cognitive factors. To perform this regression analysis, we first conducted a preliminary analysis of the cognitive variables alone. Next, because it is problematic to conduct structural equation analyses with large numbers of variables and a relatively small N , we reduced the number of variables analyzed by forming composites for the cognitive and psychomotor tests. We then conducted the regression analysis using the composite variables. Each of these steps is described in turn.

Analysis of the Cognitive Variables Alone

The questions addressed by this preliminary analysis were how many, and how best to identify, the cognitive factors from the cognitive test score correlations (Table W5). The analysis tested a "correlated-factors" model positing six factors (Working Memory, Induction, Fact Learning, Skill Learning, Temporal Processing, and Processing Speed), where each factor was

uniquely associated with three tests, as specified in the study design (see Method). The model fit the data reasonably well ($\chi^2(120) = 210$; NNFI = .888; CFI = .912; RMSEA=.074).

However, we did find that the first four factors (Working Memory, Induction, Fact Learning, Skill Learning) correlated very highly with one another (mean correlation was .93). These four factors were not as highly correlated with Temporal Processing or Processing Speed (mean correlation was .53). Because of the extremely high correlations among the first four factors, we decided the distinctions between them were not crucial for the subsequent regression analysis.

Forming Composites for Conducting the Regression Analysis

There are too many variables ($k = 54$) for the sample size ($N \approx 145$) to produce stable results in the latent structure regression analyses (i.e., the analyses that includes both the cognitive and the psychomotor variables). That motivates reducing the number of variables. Forming composites is a way to reduce the number of variables. The issue then is which variables to add together in composites. The a priori design proposed variable-to-factor mappings (e.g., 3 tests mapped to the working memory factor, five different tests mapped to the multilimb coordination factor). Because none of our analyses, reported above, revealed alternative variable-to-factor mappings superior to the a priori mappings, we decided to form composites based on the study design.

First we formed composites of each of the highly intercorrelated cognitive factors, resulting in a Working Memory, Induction, Fact Learning, and Skill Learning composite. We did not form composites out of the temporal processing and processing speed variables, however, because they were somewhat independent of the other cognitive factors. Thus, we could estimate relationships between the psychomotor factors and three cognitive factors: general ability, temporal processing, and processing speed.

We then formed composites of each of the four Fleishman factors (Control Precision, Multilimb Coordination, Rate Control, and Response Orientation), one for Session 1 and a separate composite for Session 2 (totaling 8 psychomotor composites).¹ Our analyses showed evidence for a learning factor, which is why we did not collapse across sessions. Our analyses did not show evidence for the separation of the Fleishman factors, however. Therefore, in the regression analyses, we used the eight Fleishman composites as indicators of a single general psychomotor ability factor, and the four Session-2 composites as indicators of a psychomotor learning factor.

¹ For both cognitive and psychomotor composites, we reflected component scores, where needed, so that larger scores indicated better performance. Then we formed the composites by averaging the available z scores of the components, thus allowing us to ignore (randomly determined) missing component scores for some subjects and composites.

Psychomotor-on-Cognitive Regression Analysis

Figure 2 shows the initial latent-variable model for psychomotor and cognitive composite correlations (reported in Table W6). We will refer to this model as the “standard” model. This model regresses two psychomotor factors (general psychomotor ability and the psychomotor learning factor) on three cognitive factors (general cognitive ability, temporal processing, and processing speed).² Note that this is a nested-factor model (Gustaffson & Balke, 1993) on both the “predictor” (cognitive) and “criterion” (psychomotor) side of the regression. That is, the factors nested in general ability (cognitive or psychomotor) are independent of general ability. Note also that the two nested factors on the cognitive side were constrained to be uncorrelated. The standard model fit the data well (see Table 2).

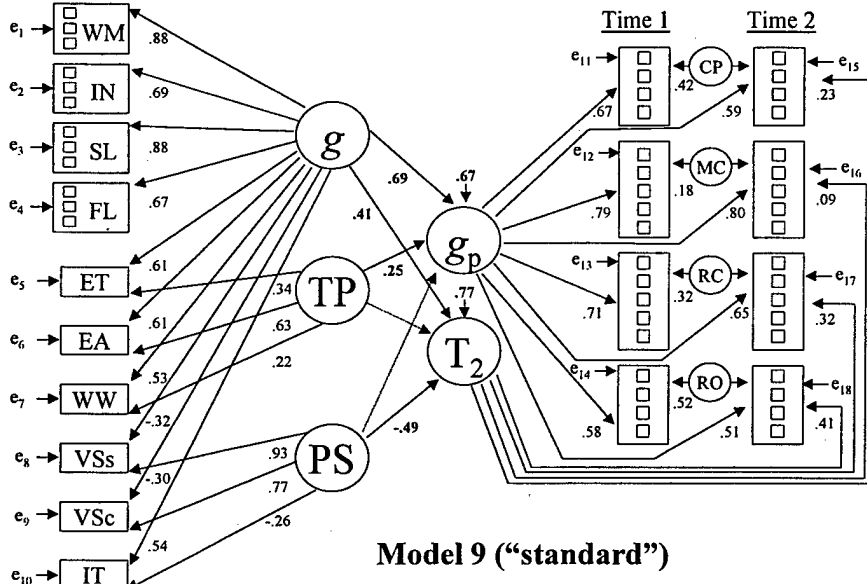


Figure 2. Nested factor model regressing psychomotor (g_p , T_2) on cognitive (g , TP , PS) factors. If the PS factor and tests are excluded from the analysis, the TP path to g_p is .32, and g to g_p path is .67. WM = working memory; IN = induction; SL = skill learning; FL = fact learning; ET = Estimating time; EA = Estimating Arrival; WW = Who wins?; VSs = Visual Search, spread out; VSc = Visual Search, compressed; IT = Inspection Time; g = general cognitive; TP = temporal processing; PS = processing speed; g_p = general psychomotor; T_2 = Session 2 (psychomotor learning factor); CP = control precision; MC = multilimb coordination; RC = rate control; RO = response orientation. The two factor paths from each of CP, MC, RC, and RO were nearly identical and are represented in the figure as a single (averaged) loading.

² Not shown, but present in all regression models reported, is a direct path between a gender variable and each cognitive and psychomotor variable. Hence the effects of gender are controlled for before regression coefficients are estimated.

Table 2.

Model Goodness-of-fit statistics for regression of psychomotor on cognitive factors.

Model	df	χ^2	BBNF	RMSEA
Null (Independence)	171	2421	-----	.302
9. Standard Model	115	179	.958	.062
<u>Varying the Identity of the Cognitive Factors</u>				
10. Correlated cognitive factors model	118	204	.945	.072
11. 1-strand	114	157	.971	.052
12. 2-strands	113	143	.980	.044
13. Correlated TP, PS (nested in g)	114	167	.965	.057
<u>Varying the Identity of the Psychomotor Factors</u>				
14. Non-nested Time1-Time2	118	208	.942	.073
15. Reverse Nesting	115	204	.941	.073
<u>One vs. Two Pass Estimates of Regression Coefficients</u>				
16. Two-pass model*	181	186	.998	.016

Note. $N = 145$ for all analyses. This N is larger than the one in Table 1 because making composites of scores allowed us to recover missing data (see footnote 1). BBNF and RMSEA are defined in Table 1.

*Model 18 fit statistics are not comparable to one-pass statistics given the fixing of parameters from prior model fits.

Figure 2 also shows the estimated coefficients for the standard model. The factor loadings look reasonable and are consistent with previous analyses. For the psychomotor scores there is a strong general factor, and a weaker psychomotor learning factor (loadings for the latter are significant with minimum $z > 2.2$, $p < .05$). For the cognitive scores, there is also a strong general factor and weaker nested factors (loadings for the latter significant with minimum $z > 2.3$, $p < .05$).

The key results from the regression analysis are that the significant predictors of general psychomotor ability are general cognitive ability ($r = .69$, $z = 8.3$, $p < .01$) and temporal processing ability ($r = .25$, $z = 2.7$, $p < .01$). The key predictors of the learning factor are processing speed ($r = -.49$, $z = -4.4$, $p < .01$), and general cognitive ability ($r = .41$, $z = 2.6$, $p < .01$).

Although this initial model fit the data well, it is important to consider alternative models. In particular, it is important to observe how parameters describing the relationships between cognitive and psychomotor factors vary. If the estimates stay consistent under different models, we can be more confident in the qualitative conclusions.

There are several plausible alternatives to the standard. We can sort these into three categories: alternative ways to (a) identify the cognitive factors, (b) identify the psychomotor factors, and (c) estimate the psychomotor-on-cognitive regression coefficients.

Varying the Identity of the Cognitive Factors

Our first alternative to the standard model was the "correlated factors model" as applied to the cognitive factors (Model 10). The main effect of correlating the cognitive factors was to reduce to non-significance psychomotor ability's dependence on the "general cognitive factor" (now identified by the 4 general cognitive composites, e.g. induction, and the paths to PS and TP factors). However, psychomotor ability depended more on TP in this model ($r = .51$), and TP and general cognitive ability correlated highly ($r = .80$). Hence, while no direct relation between "g" and psychomotor ability appeared, the model suggested a large indirect relation through TP. As Model 10 fit worse than the standard (see Table 2), we looked at models closer to the standard.

Another way to redefine the cognitive factors is to repair the standard model, based on diagnostic statistics, such as the LM test for adding post-hoc paths. The LM test indicated an improved model fit would result from allowing one of the TP tests (Estimating Arrival) to load additionally on the PS factor (Model 11). We will refer to this model as the "1-strand" repair model. Similarly a "2-strand" model, that includes Model 11's repair and allows one of the PS tests (Inspection Time) to load TP, further improved fit (Model 12). We also speculated that these two repairs might alternatively be achieved by allowing the TP and PS factors to correlate with one another, while keeping both these factors nested in g (Model 13). The resulting fit statistics for these repair models are shown in Table 2.

All the repairs increase goodness of fit relative to the standard. They also qualitatively alter the regression coefficients only for the g_p on TP path, which is significant in Models 11 and 12 ($r = .26$ and $r = .35$, respectively), but not in Model 13 ($r = .08$). Therefore, a key issue is the magnitude of the relationship between g_p and TP. Is the relationship between the two factors more likely higher, as in the standard model, and the strand models, or lower, as in the correlated TP-PS model?

By goodness of fit considerations a model with a significant path from TP to g_p is favored (i.e. the equally parsimonious Model 11 fits better than Model 13). This provides some evidence for a "higher" estimation of TP's relationship to g_p . As another approach to this question, we also created a simpler version of the standard model that excludes the PS tests and the PS factor, but includes all other variables and factors. In this "No-PS" model, the g_p on g regression coefficient was .67, about the same as the other models. But, the g_p on TP regression was .32 ($z = 3.5$), which is more like the standard and multiple-strand models. Hence, from several perspectives, one can argue that the g_p -TP path is significant, in the .25 to .35 range.

Varying the Identity of the Psychomotor Factors

In the standard model, we implemented "temporal" nesting of the psychomotor factors (Session 2, hereafter referred to as T_2 , which was nested in g_p). We could only devise two reasonable alternatives to this scheme. For one, we replaced the psychomotor nesting with correlated psychomotor factors. This model has a Session 1 factor (hereafter, T_1) with direct paths to the Session 1 psychomotor composites and a T_2 factor with direct paths only to the Session 2 composites. Rather than having a g_p in this model, T_1 has a causal path to T_2 . We call this the "non-nested Time1 - Time2" psychomotor model (Model 14). Another model has a g_p

factor as in the standard model, but replaces the nested T_2 factor with an analogous nested T_1 factor. We call this the "reverse nesting" psychomotor model (Model 15).

Neither of these models fit as well as the standard model (see Table 2). Additionally, neither model had radically different regression coefficients from the standard model with respect to TP or g paths. The PS - T_2 path was greatly reduced in Model 14 but still significant ($r = -.11$; $z = -3.1$) while the PS - T_1 path was not. Model 15 had qualitatively different PS paths from earlier models due to the change in focus from the unique aspects of the Session 2 psychomotor scores to the unique aspects of Session 1 scores.

One vs. Two-Pass Estimates of Regression Coefficients

An alternative to the one-pass estimation procedure we have employed to this point is to estimate parts of the overall model separately. For example, in this study, our major concern is with the links between the predictor variables (g, TP, PS) and the criterion variables (g_p and T_2). It is possible to estimate the predictor side coefficients (factor loadings) in one run, estimate the criterion side coefficients in a separate run, then fix the estimates from the separate runs, in a third run to estimate the linking regression coefficients. There might be theoretical reasons for doing this. The identification of a factor is influenced by all outward links from that factor. This includes both indicator variables (the tests that define the factor), and criterion variables (the tests and factors that factor predicts). But, one might not want to have the factor's identity determined by the variables that factor predicts.

Results from the two-pass analysis were, in most ways, highly similar to the standard model (e.g. .70 and .29 for g_p regressed on g and TP, respectively; -.48 for T_2 on PS). The one exception was the g on T_2 path which was much weaker ($r = .19$, $z=1.8$). We therefore conclude that the relationship between g and T_2 is more tentative than are the other relationships we found.

The Changing Nature of Psychomotor Ability with Practice

In our final set of analyses, we explored the predictors of extended psychomotor performance. Recall that four psychomotor tests, one from each category were given 5 additional test replications (for a total of 7). Each replication lasted roughly 8-10 minutes, depending on the task. Table 3 shows descriptive statistics over replications. Note that performance improves for all tasks.

Table 3.

Descriptive statistics on psychomotor tasks given extended practice.

Replication	CP2		ML2		RC2		RO3	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1	31.4	30.1	6.3	3.5	56.4	9.9	1827	716
2	49.1	31.7	9.3	3.8	62.2	11.7	1631	631
3	65.6	31.9	10.9	3.9	68.6	11.9	1226	487
4	71.3	30.1	12.2	4.2	73.0	12.4	1146	310
5	71.9	27.9	12.8	4.6	75.1	12.0	1113	251
6	81.8	23.5	13.1	5.0	74.9	12.8	1087	227
7	79.4	24.2	13.7	4.8	75.2	12.8	1038	185

Note.

Tests given extended practice were helicopter-shoot (CP2, measured by overall percent shot down), Mashburn (ML2, measured by average number completed in fixed time), 2-wheel avoidance (RC2, measured by average number correct less the number incorrect in fixed time), and direction control (RO3, measure by msec latency).

A tractable way to model these data is the following. For each of the seven psychomotor sessions regress the general psychomotor factor for that session on the three cognitive factors (g, temporal processing, and processing speed). That is, we performed seven separate latent-variable regressions (See Figure 3), one for the correlations of each replication (Table W7). Goodness of fit and regression coefficients from these analyses are given in Table 4.

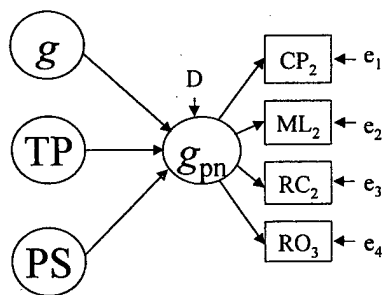


Figure 3. Psychomotor-on-cognitive factor regression models; coefficients estimated separately for each of seven occasions.

Table 4.

Regression coefficients and some fit statistics for extended practice models (general psychomotor ability, g_p , predicted at seven practice levels).

Replication	g	TP	PS	e	n	BBNF
g_{p1}	.71*	.25*	.10	.65	136	.880
g_{p2}	.77*	.12	.14	.62	142	.916
g_{p3}	.67*	.16	.18*	.71	142	.941
g_{p4}	.63*	.20*	.24*	.71	142	.931
g_{p5}	.67*	.19*	.32*	.64	142	.930
g_{p6}	.67*	.16	.38*	.62	142	.910
g_{p7}	.65*	.19*	.41*	.61	138	.913

Note.

Model $df = 68$. Column n gives pair-wise n for each analysis.

* $p < .05$ level, one-tailed.

The key finding from this analysis is that the role of processing speed in affecting psychomotor ability increased with practice. The role of the other cognitive factors, g , and temporal processing, remained relatively constant.

Discussion

Confirmatory factor analyses of psychomotor scores yielded evidence for a strong general psychomotor ability (g_p), and a weaker psychomotor learning factor emerging on practiced psychomotor tests (T_2). The finding of the small dimensionality of the psychomotor abilities space was somewhat contrary to expectations from the literature (Cronbach, 1970; Fleishman, 1954), where it has been suggested that there might be several psychomotor factors, such as control precision, multilimb coordination, rate control, and response orientation.

The Small Dimensionality of the Psychomotor Abilities Space

There are several ways our conclusion of a general psychomotor factor could be challenged. First, one could argue that the general factor observed was a method artifact, due to common computerized administration and manipulanda. However, computerized administration is increasingly common with many important real-world tasks, and hence the method variance might be valid measurement variance. Also, we found cognitive factors, which did not employ psychomotor manipulanda, correlated highly with the psychomotor factor.

Second, one might challenge the diversity of the tasks we employed. In fact, there was a diversity of tasks. We used continuous tracking tasks, discrete response tasks, multi-limb and single limb tasks, and measured accuracy, latency, and error distance. One could argue that the diversity of tasks and measures exceeded that of the typical study.

Why do studies such as Fleishman (1954) find multiple factors, and give little emphasis to a general one? One possibility is that Fleishman's analyses ruled out a general factor, or more specifically, were biased against measuring a general factor. For instance, Fleishman (1954) presented a table (his Table 3, p. 446) displaying results from the unrotated solution, including first factor loadings, which ranged from .11 to .67, averaging around .43. These can be interpreted as general factor loadings. However, he did not interpret them that way because the method of the day was to ignore that information in favor of a reparameterization of the solution (in factor analysis terminology, rotation to simple structure). This technique was designed to identify "more interpretable" multiple factors (Thurstone, 1935).

More recently, factor analysts have suggested hierarchical decompositions of correlation matrices (Carroll, 1993; Gustafsson & Balke, 1993; Schmid & Leiman, 1957). We reanalyzed Fleishman's (1954) correlation matrix to determine whether a g_p factor was supported by his data. We used Fleishman's exploratory factor analysis results (after rotation) to suggest factors that could be nested within (i.e. orthogonal to) a psychomotor g (see Table W8). The resulting model fit adequately (Bentler-Bonnet nonnormed fit index=.918). We found, even with the (significant) Fleishman factors included, that a psychomotor g was still necessary. All but one of Fleishman's 40 tests had significant loadings on the general factor.

Hence, even for the diverse apparatus tests present in Fleishman, 1954, (e.g. complex coordination, tapping, and manual dexterity tests), a general psychomotor ability can be observed similar to what we found. Not surprisingly, the g_p loadings we found for Fleishman's tests were highly similar to the unrotated loadings for the first factor that Fleishman reported.

The role of g (or working memory) in psychomotor ability

Our finding that general cognitive ability is a major component of general psychomotor ability, while consistent with recent work (Ree and Carretta, 1994), is nevertheless important and noteworthy. Beyond the lack of support for this idea in the literature, there is a stereotype of psychomotor and cognitive abilities being distinct, but contrary to stereotype we found that there is considerable overlap: Cognitively able individuals tend to do well on psychomotor tasks. Recall here our definition of psychomotor tasks, which is that they emphasize perceptual and motor responses. Our definition did not give particular advantage to factors such as strength, stamina, steadiness, dexterity, and others identified by Fleishman (1964). Perhaps it is these aspects of psychomotor behavior that give rise to the stereotypes of a distinction between cognitive and psychomotor ability.

How can we be sure that we measured cognitive ability appropriately? We believe that the variety of tests we employed is balanced with respect to the processes and materials found to best reflect g , for two reasons. First, Carroll (1993), whose abilities taxonomy is widely viewed as an optimal representation of the domain, found that induction, spatial visualization, quantitative reasoning, and verbal ability factors were the most valid indicators of g (his Table 15.5, p. 597). Consistent with this result, we used induction as a test composite category and constructed test composites from spatial, quantitative and verbal materials. Second, there is an argument that the particulars of how one measures g are not that important, provided that there is

some diversity in the selection of cognitive measures. This is because when g is extracted from batteries employing diverse ability measures, the g s are highly correlated (e.g. Kyllonen, 1993; Thorndike, 1987). For this reason, the relationship between g and psychomotor ability will replicate when g is derived from test batteries other than ours.

Given the relationship between g and psychomotor ability is strong, why is it strong? A way to understand this is that g can be interpreted largely as a working memory capacity factor (Kyllonen & Christal, 1990; Kyllonen, 1993). Thus, working-memory may be what limits psychomotor performance. Working memory may impact on psychomotor ability in two ways, via complexity and via novelty. With respect to complexity, some of our psychomotor tasks required the participant to simultaneously apply two-different rules for action as when two limbs were needed to control a screen object (e.g. multi-limb coordination tasks). Such tasks implicate working memory, and, in fact, the tasks with the highest loading on g_p were these types of task. With respect to novelty, models of skill-acquisition predict relatively unpracticed tasks to be resource sensitive (e.g. Ackerman, 1988, Fitts, 1964).

The role of time estimation in psychomotor ability

An important finding was that time estimation is related to psychomotor ability. This supports Keele et. al.'s (1985) speculation that motor processing and temporal processing are related (see also, Fleury, et. al., 1992). However, we found the relationship controlling for general cognitive ability, whereas Keele et. al. did not control for g . This is important because it is well known that there is a correlation between performance on any two cognitive tasks. What we are claiming here is that beyond this general cognitive correlation (what Spearman, 1904, referred to as "positive manifold"), there is a special relationship between timing and psychomotor ability.

Why is there a relationship between temporal and psychomotor abilities? A way to address this is to think about the direction of causality between temporal and psychomotor abilities. Our modeling implied temporal ability determining psychomotor ability, but can directionality run in the opposite direction? For instance, an explanation for the relationship could be that most timing tests (e.g. time estimation) rely on a mental counting process which in turn depends on the articulatory loop (Baddeley, 1976). Use of the articulatory loop presumably is a psychomotor process.

However, there are empirical arguments for the causality running from TP to motor processing. Tirre and Raouf (1998) have found temporal processing tasks load with "dynamic-visual processing" tasks, for which an articulation strategy would not help. Therefore, timing ability has perceptual linkages and perception might be considered antecedent to motor response. We have also observed that simple time-interval waiting tasks using short target intervals not easily represented through articulation (e.g., 667 ms) also load a TP factor with some of the tasks employed in this study (Chaiken, 1997).

Unique aspects of psychomotor ability

While psychomotor ability can be predicted by the general cognitive factor, and by temporal processing, there is still substantial unexplained residual variance in the general psychomotor ability factor. Specifically, a significant disturbance for the g_p variance, $r = .67$, $z = 5.9$, in Model 9, indicates that psychomotor tests would still identify a factor after controlling for cognitive factors. One possibility is that we did not include, in our study, important cognitive factors that would have predicted that residual variance. Another possibility is that psychomotor ability can be thought of as basic. The practical implication of the latter possibility is that selection technologies for jobs with psychomotor components will always show a "profit" (i.e. incremental prediction) from inclusion of psychomotor tests having significant loadings on g_p .

The changing nature of psychomotor skill with practice

Participants improved on all the psychomotor tasks as a result of practice. A question is whether the nature of psychomotor ability changed as a result of practice. We can address that by examining the predictors of psychomotor task performance over time. In both the analysis of the time 2 factor, and in the analysis of extended practice, we found that the regression weight on processing speed increased with practice. No substantial changes were observed with respect to the other cognitive factors.

Why should processing speed be increasingly related with practiced psychomotor ability? It could be that initially, most of the processing activity on the psychomotor tasks is concerned with figuring out optimal strategies, a high working-memory demanding activity. With practice, participants continue to tax working memory, which explains the continued high correlations with the general factor. But as learning occurs, in addition to the working-memory bottleneck, an additional performance limitation emerges, and that is the speed with which learned elements can be executed.

Ackerman (1988) has demonstrated similar correlation patterns, and has provided a similar explanation. The difference between our findings and his is that we did not see much of a drop in the relation with the general cognitive factor over time. It could be that our tasks were not well enough practiced to observe the drop, or it could be that there is something different about the nature of our tasks compared to his.

Future Research

In summary, we found that psychomotor ability can be characterized as a fairly unitary factor, and that much of the variance in that factor can be accounted for by general cognitive ability, or working memory capacity, and time estimation ability. With practice, psychomotor task performance improves, and becomes increasingly constrained by processing speed. Further research will be concerned with the role of these factors in complex real-world criterion tasks, such as learning to fly an airplane, operating uninhabited aerial vehicles, playing sports, operating heavy machinery, and the like.

References

- Ackerman, P. L. (1988). Determinants of individual differences during skill acquisition: cognitive abilities and information processing. Journal of Experimental Psychology: General, *117*, 288-318.
- Adams J. A. (1987). Historical review and appraisal of research on the learning, retention, and transfer of human motor skills. Psychological Bulletin, *101*, 41-74.
- Baddeley, A. D. (1968). A three minute reasoning test based on grammatical transformation. Psychonomic Science, *10*, 341-342.
- Baddeley, A. D. (1976). The Psychology of Memory. New York: Basic Books.
- Bentler, P. M. (1993). EQS: structural equations program manual. Los Angeles, CA: BMDP Statistical Software.
- Browne, M., & Cudeck, R. (1993). Alternative ways of assessing model fit. In K. A. Bollen & J. S. Long (Eds), Testing structural equation models (pgs. 136-162). Thousand Oaks, CA: Sage Publications Inc.
- Carroll, J. B. (1993) Human Cognitive Abilities: A Survey of Factor-Analytic Studies. New York: Cambridge University Press.
- Carretta, T. R., & Ree, M. J. (1994). Pilot-candidate selection method: sources of validity. International Journal of Aviation Psychology, *4*, 103-117.
- Chaiken, S. R. (1997, October). Psychometric probes of psychomotor working memory (does psychomotor workload = cognitive workload?). Poster session presented at The Future of Learning and Individual Differences Conference, University of Minnesota, Minneapolis.
- Chaiken, S. R. (1994). The inspection time not studied: processing speed ability unrelated to psychometric intelligence. Intelligence, *19*, 295-316.
- Chaiken, S. R., Kyllonen, P. C., & Tirre, W. C. (1999a). Archival Tables For: "Organization and Components of Psychomotor Ability" [Online]. Available: ' http://www.williams.af.mil/html/research_archive.htm ' [May,1999].
- Chaiken, S. R., Kyllonen, P. C., & Tirre, W. C. (1999b). Archival Tables For: "Organization and Components of Psychomotor Ability" (AFRL-HE-BR-TR-1999-0146). Brooks AFB, TX.
- Cronbach, L. J. (1970). Essentials of psychological testing. New York, Harper and Row.
- Fitts, P. M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. Journal of Experimental Psychology, *47*, 381-391.
- Fitts, P. M. (1964). Perceptual-motor skill learning. In A. W. Melton (Ed.), Categories of human learning (pg. 243-285).
- Fleishman, E. A. (1954). Dimensional analysis of psychomotor abilities. Journal of Experimental Psychology, *48*, 437-454.

Fleishman, E. A. (1964). The structure and measurement of physical fitness. Englewood Cliffs, NJ: Prentice-Hall.

Fleishman, E. A., & Hempel, W. E., (1954). Changes in factor structure of a complex psychomotor test as a function of practice. Psychometrika, *19*, 239-252.

Fleury M., Bard C., Gagnon M., & Teasdale N. (1992). Coincidence-anticipation timing: the perceptual-motor interface. In Proteau L. & Elliot D. (Eds.) Vision and Motor Control (pg. 67-103). Amsterdam: North-Holland.

Gustafsson, J. E. & Balke, G. (1993). General and specific abilities as predictors of school achievement. Multivariate Behavioral Research, *28*, 407-434.

Hick, W. E. (1952). On the rate of gain of information. Quarterly Journal of Experimental Psychology, *4*, 11-26.

Imhoff, D. L., & Levine, J. M. (1980). Perceptual-motor and cognitive performance task battery for pilot selection. (AFHRL-TR-80-27). Brooks AFB, TX: Air Force Human Resources Laboratory, Manpower and Personnel Division.

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

Keele, S. W., Pokorny, R. A., Corcos, D. M., & Ivry R. (1985). Do perception and motor production share common timing mechanisms: a correlational analysis. Acta Psychologica, *60*, 173-191.

Kyllonen, P. C. (1991). Principles for creating a computerized test battery. Intelligence, *15*, 1-15.

Kyllonen, P. C. (1993). Aptitude testing inspired by information processing: A test of the four-sources model. Journal of General Psychology, *120*, 375-405.

Kyllonen, P. C., & Christal, R. E. (1990). Reasoning ability is (little more than) working-memory capacity?! Intelligence, *14*, 389-434.

Levine, L. L., Spector, P. E., Menon, S., Narayanan, L., & Cannon-Bowers, J. (1996). Validity generalization for cognitive, psychomotor, and perceptual tests for craft jobs in the utility industry. Human Performance, *9*, 1-22.

Lyon, D. R., & Waag, W. L. (1995). Time course of visual extrapolation accuracy. Acta Psychologica, *89*, 239-260.

Melton, A. W., ed. (1947). Army Air Force Aviation Psychology Research Reports: Apparatus tests (Report No. 4). Washington, DC: U.S. Government Printing Office.

Mashburn, N. C. (1934). The complex coordinator as a performance test in the selection of military flying personnel. Journal of Aviation Medicine, *5*, 155-164.

Proteau L. (1992). On the Specificity of learning and the role of visual information for movement control. In Proteau L. & Elliot D. (Eds.) Vision and Motor Control (pg. 67-103). Amsterdam: North-Holland.

Ree, M. J., & Carretta, T. R. (1994). The correlation of general cognitive ability and psychomotor tracking tests. International Journal of Selection and Assessment, 2, 209-216.

Schmid, J. & Leiman, J. (1957). The development of hierarchical factor solutions. Psychometrika, 22, 53-61.

Seashore, S. (1931). The aptitude hypothesis in motor skills. Journal of Experimental Psychology, 14, 555-561.

Seashore, R. H. (1930). Individual differences in motor skills. Journal of General Psychology, 3, 38-65.

Seashore, R. H. (1939). Work methods: An often neglected factor underlying individual differences. Psychological Review, 46, 123-141.

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

Thorndike, R.L. (1987). Stability of factor loadings. Personality and Individual Differences, 8, 585-586.

Thurstone, L.L. (1935). The vectors of mind. Chicago: University of Chicago Press.

Thurstone, L. L., & Thurstone, T. G. (1941). Factorial studies of intelligence. Psychometric Monographs, 2.

Tirre, W. C. & Raouf, K. K. (1998). Structural models of cognitive and perceptual-motor abilities. Personality and Individual Differences, 24, 603-614.

Authors Note

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APPENDIX: WEBSITE CONTENTS OF

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ARCHIVAL TABLES FOR:

"ORGANIZATION AND COMPONENTS OF PSYCHOMOTOR ABILITY"

BY

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These tables supplement an article accepted (contingent on revision) at "Cognitive Psychology."

NOTE: Copying from the clipboard can concatenate lines and affect readability. We suggest saving this archive locally to a .txt file (e.g. File menu: "Save as..."). Then edit the saved file as appropriate. Changing to courier font and decreasing page margins may also be required.

Table W1. Psychomotor Test Scores for First (T1) and Second (T2) Administrations.

Factor / Test Name	Measure	M		SD		N		d	r1,2 loading
		T1	T2	T1	T2	T1, T2, T1, 2	T1, 2		
Control Precision (CP)									
1 Rotary Pursuit	Distance	79	72	31	34	153, 143, 138		- .39	.75
2 Helicopters	% Correct	31	49	30	32	143, 146, 130		1.04	.75
3 Fitts Task	RT	.82	.73	.20	.15	147, 143, 133		-.67	.63
4 Grids Task	RT	1.94	1.81	.26	.25	122, 143, 109		-.92	.74
Multilimb Coordination (MC)									
1 Center the Ball	Distance	26	24	4	5	152, 147, 140		-.81	.79
2 Mashburn	N Completed	6	9	4	4	146, 146, 133		1.57	.82
3 2-hand Tracking	Distance	70	55	28	31	140, 143, 126		-1.29	.85
4 Star Draw	RT	52	44	22	21	139, 143, 125		-1.02	.85
5 Pop the Balloons	N Completed	6	7	3	3	154, 145, 141		1.08	.75
Rate Control (RC)									
1 Arc Pursuit	Distance	15	15	6	7	144, 145, 129		- .12	.67
2 2-wheel Avoidance	N Completed	56	62	10	12	122, 144, 113		1.12	.73
3 1-wheel Avoidance	% Correct	85	90	17	12	139, 144, 126		.46	.64
4 Circle Pursuit	Distance	33	26	18	15	158, 144, 143		-.60	.80
5 Lane Tracking	Distance*	17	23	12	28	151, 144, 142		---	.71
Response Orientation (RO)									
1 Sounds & Lights	RT	.77	.75	.14	.13	138, 143, 123		.20	.67
2 Red-Green Orient'n	RT	18.4	14.7	9.9	6.7	154, 142, 137		.71	.83
3 Direction Control	RT	1.8	1.6	.7	.6	138, 147, 126		.46	.63
4 Hicks Task	RT	.26	.26	.04	.03	145, 128, 128		.20	.92

Note. Distance is mean x-pixel distance. RT is mean time per problem in s; N Completed is number completed in a fixed time. SD is standard deviation. Effect size is Mean (T2) - Mean (T1) / SD (T1-T2). T1,2 is the N common to both test administrations. Effect size (d) and reliability (r1,2) are based on common N (T1,2). Means and Standard Deviations are based on session N. Loading is test loading on the learning factor for Model 8.

*Lane-tracking r (T1, T2) is for the rank-transformed Distance measure. All other statistics from this row are from the raw Distance measure. r (T1, T2) for raw Distance was .21, due to the presence of an outlier.

Table W2.

Percentage Correct on Cognitive Tasks.

	M	SD	N
Working Memory, Quantitative	75.2	29.4	142
Working Memory, Spatial	41.8	29.5	145
Working Memory, Verbal	54.9	26.1	141
Fact Learning, Quantitative	79.6	11.1	147
Fact Learning, Spatial	35.3	25.9	144
Fact Learning, Verbal	91.3	9.5	150
Induction, Quantitative	78.5	20.9	144
Induction, Spatial	76.6	19.1	143
Induction, Verbal	60.9	19.2	144
Skill Learning, Quantitative	86.4	15.6	147
Skill Learning, Spatial	53.4	16.4	142
Skill Learning, Verbal	73.3	24.4	145

Table W3.

Specific information-processing test scores.

	M	SD	N
Temporal Processing			
Estimating Arrival, Lines (% within tolerance)	23	15	143
Estimating Arrival, Clocks (% within tolerance)	38	20	142
Estimating Time, Lines (% within tolerance)	54	29	143
Estimating Time, Clocks (% within tolerance)	54	28	142
Who Wins? 2 Lines (% correct)	71	12	143
Who Wins? 2 Clocks (% correct)	64	9	142
Processing Speed			
Inspection Time, Verbal, time 1 (% correct)	64	21	143
Inspection Time, Verbal, time 2 (% correct)	68	24	142
Inspection Time, Quantitative, time 1 (% correct)	80	17	143
Inspection Time, Quantitative, time 2 (% correct)	79	17	142
Visual Search, Compressed 1 (response time)	1615	260	141
Visual Search, Compressed 2 (response time)	1527	245	142
Visual Search, Spread-out 1 (response time)	2627	401	142
Visual Search, Spread-out 2 (response time)	2505	362	141

Note.

Percent within tolerance means within 5% of the target estimation (plus or minus).

Note: The following correlational tables (W4 - W7) are embedded in EQS command files. These files (i.e. text between /TITLE and /end) fit example models from the paper.

Table W4.

Cognitive and psychomotor scores used in models reported in Table 1 (published paper): pairwise-deleted correlation matrix and standard deviations.

/TITLE

Fleishman analyses for individual psychomotor scores

! Words after exclamation marks are comments.

! Model 8 from the published paper is what is run here. However,

! the correlation matrix and sd vector allows you to run Models 1 - 7

! provided the equations and variance sections are respecified appropriately.

/SPECIFICATIONS

```

VARIABLES=47; CASES=133; !average pairwise with cog 134
METHODS=ML;
MATRIX=correlation;
fields=12;
/LABELS
V1=CP11; V2=CP21; V3=CP31; V4=CP41; V5=ML11;
V6=ML21; V7=ML3A1; V8=ML3B1; V9=ML41; V10=RC11;
V11=RC2A1; V12=RC2B1; V13=RC31; V14=RC41; V15=RO11;
V16=RO21; V17=RO31; V18=RO41; V19=CP12; V20=CP22;
V21=CP32; V22=CP42; V23=ML12; V24=ML22; V25=ML3A2;
V26=ML3B2; V27=ML42; V28=RC12; V29=RC2A2; V30=RC2B2;
V31=RC32; V32=RC42; V33=RO12; V34=RO22; V35=RO32;
V36=RO42; V37=g-WM; V38=g-IN; V39=g-SL; V40=g-FL;
V41=PS-IT; V42=PS-VSC; V43=PS-VSS; V44=TP-EA; V45=TP-ET;
V46=TP-WW; V47=MALE;
! factor labels
f1 = gp; f6=time2; !time2=psychomotor learning factor
/technical
iterations =30;
/print
fit=all;
/equations
v1 = *V47 + *F1 + e1;
v2 = *V47 + *F1 + e2;
v3 = *V47 + *F1 + e3;
v4 = *V47 + *F1 + e4;
v5 = *V47 + *F1 + e5;
v6 = *V47 + *F1 + e6;
v7 = *V47 + *F1 + e7;
v8 = *V47 + *F1 + e8;
v9 = *V47 + *F1 + e9;
v10 = *V47 + *F1 + e10;
v11 = *V47 + *F1 + e11;
v12 = *V47 + *F1 + e12;
v13 = *V47 + *F1 + e13;
v14 = *V47 + *F1 + e14;
v15 = *V47 + *F1 + e15;
v16 = *V47 + *F1 + e16;
v17 = *V47 + *F1 + e17;
v18 = *V47 + *F1 + e18;
v19 = *V47 + *F1 + *f6 + e19;
v20 = *V47 + *F1 + *f6 + e20;
v21 = *V47 + *F1 + *f6 + e21;
v22 = *V47 + *F1 + *f6 + e22;
v23 = *V47 + *F1 + *f6 + e23;
v24 = *V47 + *F1 + *f6 + e24;
v25 = *V47 + *F1 + *f6 + e25;
v26 = *V47 + *F1 + *f6 + e26;
v27 = *V47 + *F1 + *f6 + e27;
v28 = *V47 + *F1 + *f6 + e28;
v29 = *V47 + *F1 + *f6 + e29;
v30 = *V47 + *F1 + *f6 + e30;
v31 = *V47 + *F1 + *f6 + e31;
v32 = *V47 + *F1 + *f6 + e32;
v33 = *V47 + *F1 + *f6 + e33;
v34 = *V47 + *F1 + *f6 + e34;
v35 = *V47 + *F1 + *f6 + e35;
v36 = *V47 + *F1 + *f6 + e36;
/variances
f1=1; f6=1;
e1 =*;

```

```

e2  =*;
e3  =*;
e4  =*;
e5  =*;
e6  =*;
e7  =*;
e8  =*;
e9  =*;
e10 =*;
e11 =*;
e12 =*;
e13 =*;
e14 =*;
e15 =*;
e16 =*;
e17 =*;
e18 =*;
e19 =*;
e20 =*;
e21 =*;
e22 =*;
e23 =*;
e24 =*;
e25 =*;
e26 =*;
e27 =*;
e28 =*;
e29 =*;
e30 =*;
e31 =*;
e32 =*;
e33 =*;
e34 =*;
e35 =*;
e36 =*;
/covariances
e1 ,e19 =*;
e2 ,e20 =*;
e3 ,e21 =*;
e4 ,e22 =*;
e5 ,e23 =*;
e6 ,e24 =*;
e7 ,e25 =*;
e8 ,e26 =*;
e9 ,e27 =*;
e10,e28 =*;
e11,e29 =*;
e12,e30 =*;
e13,e31 =*;
e14,e32 =*;
e15,e33 =*;
e16,e34 =*;
e17,e35 =*;
e18,e36 =*;
/matrix
1.000
-.595 1.000
.269 -.343 1.000
.404 -.444 .346 1.000
.567 -.678 .328 .308 1.000
-.459 .486 -.297 -.402 -.563 1.000

```

.638	-.547	.395	.464	.575	-.486	1.000						
.567	-.594	.388	.421	.583	-.487	.590	1.000					
-.589	.660	-.344	-.482	-.608	.472	-.568	-.702	1.000				
.633	-.645	.315	.434	.582	-.505	.642	.713	-.670	1.000			
-.384	.500	-.250	-.409	-.464	.360	-.571	-.366	.451	-.436	1.000		
-.572	.437	-.169	-.267	-.425	.453	-.426	-.481	.538	-.523	.408	1.000	
.690	-.626	.351	.408	.599	-.545	.642	.688	-.684	.763	-.437	-.644	
.610	-.572	.226	.411	.586	-.428	.627	.554	-.615	.676	-.451	-.452	
.284	-.187	.331	.193	.255	-.257	.316	.391	-.273	.320	-.214	-.068	
.457	-.433	.403	.274	.492	-.543	.481	.520	-.499	.562	-.359	-.500	
.341	-.456	.296	.395	.446	-.432	.402	.619	-.491	.474	-.283	-.338	
.297	-.397	.185	.327	.319	-.356	.305	.200	-.317	.337	-.303	-.185	
.749	-.377	.306	.324	.494	-.369	.647	.379	-.462	.459	-.405	-.328	
-.575	.748	-.313	-.471	-.580	.532	-.507	-.663	.668	-.736	.434	.521	
.256	-.335	.630	.354	.373	-.293	.233	.386	-.330	.278	-.249	-.287	
.358	-.339	.376	.737	.301	-.310	.359	.384	-.383	.425	-.259	-.245	
.618	-.649	.306	.420	.789	-.551	.654	.612	-.612	.564	-.547	-.409	
-.519	.433	-.391	-.545	-.544	.818	-.481	-.555	.540	-.519	.340	.518	
.671	-.471	.376	.385	.585	-.513	.852	.596	-.584	.613	-.563	-.456	
.547	-.568	.393	.465	.505	-.496	.540	.846	-.663	.642	-.388	-.465	
-.587	.626	-.340	-.411	-.598	.398	-.561	-.710	.749	-.672	.321	.429	
.650	-.492	.233	.255	.495	-.395	.577	.525	-.497	.666	-.376	-.390	
-.489	.538	-.247	-.455	-.532	.390	-.533	-.477	.594	-.531	.728	.424	
-.657	.420	-.250	-.354	-.506	.458	-.470	-.472	.533	-.576	.260	.637	
.613	-.521	.296	.458	.487	-.431	.573	.583	-.642	.714	-.408	-.474	
.543	-.457	.210	.337	.556	-.335	.511	.381	-.481	.510	-.387	-.338	
.280	-.198	.301	.274	.272	-.255	.298	.222	-.218	.274	-.287	-.152	
.500	-.425	.373	.271	.473	-.453	.434	.525	-.498	.482	-.332	-.400	
.502	-.430	.291	.340	.467	-.519	.473	.614	-.461	.486	-.228	-.382	
.413	-.415	.223	.395	.414	-.367	.387	.249	-.359	.407	-.372	-.206	
-.335	.318	-.206	-.241	-.419	.535	-.489	-.331	.328	-.275	.170	.254	
-.285	.304	-.133	-.185	-.439	.467	-.292	-.325	.376	-.301	.131	.235	
-.395	.364	-.207	-.275	-.475	.494	-.550	-.405	.348	-.298	.270	.332	
-.141	.132	-.129	-.204	-.197	.345	-.255	-.183	.191	-.108	.028	.043	
-.412	.269	-.187	-.331	-.271	.290	-.403	-.303	.438	-.348	.246	.280	
.229	-.290	.295	.253	.245	-.160	.164	.337	-.243	.155	-.095	-.063	
.194	-.238	.273	.305	.224	-.061	.232	.226	-.171	.125	-.209	-.057	
-.381	.363	-.321	-.337	-.402	.428	-.545	-.328	.369	-.297	.392	.300	
-.380	.382	-.205	-.284	-.402	.349	-.517	-.331	.304	-.301	.326	.251	
-.395	.292	-.126	-.180	-.402	.378	-.428	-.374	.361	-.303	.174	.352	
-.335	.556	-.314	-.318	-.467	.338	-.320	-.484	.425	-.496	.319	.380	
1.000												
.665	1.000											
.308	.287	1.000										
.676	.540	.313	1.000									
.493	.435	.053	.430	1.000								
.352	.274	.386	.271	.231	1.000							
.520	.593	.351	.368	.290	.350	1.000						
-.740	-.631	-.284	-.493	-.395	-.361	-.475	1.000					
.368	.272	.184	.340	.314	.233	.283	-.400	1.000				
.326	.382	.345	.240	.306	.313	.367	-.394	.444	1.000			
.573	.687	.204	.512	.425	.235	.580	-.623	.330	.328	1.000		
-.650	-.518	-.304	-.550	-.522	-.344	-.455	.541	-.450	-.454	-.567	1.000	
.658	.661	.318	.520	.411	.277	.713	-.561	.264	.396	.637	-.528	
.709	.541	.373	.518	.507	.264	.474	-.682	.369	.409	.552	-.564	
-.717	-.615	-.447	-.556	-.454	-.388	-.494	.669	-.382	-.461	-.613	.534	
.588	.622	.371	.427	.346	.251	.635	-.606	.196	.359	.560	-.418	
-.570	-.564	-.244	-.408	-.339	-.346	-.372	.594	-.352	-.395	-.592	.428	
-.698	-.541	-.230	-.511	-.422	-.282	-.540	.526	-.379	-.322	-.466	.604	
.798	.611	.366	.540	.450	.420	.559	-.688	.286	.371	.529	-.572	
.474	.715	.217	.458	.359	.198	.621	-.511	.215	.401	.587	-.438	

.317	.305	.667	.328	.155	.285	.365	-.304	.293	.287	.244	-.385
.590	.487	.296	.826	.334	.232	.372	-.522	.337	.313	.508	-.460
.589	.466	.314	.487	.632	.233	.407	-.523	.283	.408	.487	-.620
.423	.374	.423	.356	.288	.923	.475	-.403	.340	.430	.333	-.418
-.427	-.546	-.243	-.547	-.345	-.188	-.357	.372	-.169	-.248	-.479	.513
-.368	-.491	-.193	-.360	-.292	-.219	-.208	.388	-.150	-.203	-.450	.473
-.471	-.592	-.232	-.528	-.264	-.175	-.444	.431	-.218	-.286	-.579	.475
-.079	-.300	-.139	-.204	-.189	-.059	-.219	.166	.020	-.201	-.312	.285
-.425	-.492	-.323	-.431	-.499	-.220	-.457	.392	-.259	-.228	-.420	.398
.226	.210	.223	.263	.272	.200	.226	-.277	.342	.255	.327	-.184
.142	.227	.257	.226	.193	.222	.310	-.213	.370	.309	.299	-.106
-.463	-.573	-.267	-.374	-.353	-.220	-.505	.441	-.291	-.297	-.556	.429
-.418	-.459	-.206	-.360	-.300	-.243	-.463	.386	-.220	-.290	-.484	.303
-.439	-.470	-.351	-.392	-.297	-.198	-.427	.379	-.106	-.151	-.421	.387
-.531	-.358	-.137	-.323	-.379	-.217	-.149	.519	-.298	-.248	-.309	.375
1.000											
.604	1.000										
-.567	-.687	1.000									
.623	.480	-.596	1.000								
-.525	-.476	.518	-.458	1.000							
-.537	-.598	.529	-.468	.385	1.000						
.619	.715	-.705	.627	-.527	-.699	1.000					
.565	.415	-.451	.592	-.400	-.445	.481	1.000				
.304	.302	-.354	.373	-.358	-.346	.370	.414	1.000			
.559	.525	-.550	.468	-.457	-.458	.530	.445	.347	1.000		
.552	.584	-.547	.552	-.405	-.452	.580	.428	.320	.509	1.000	
.396	.345	-.470	.429	-.446	-.382	.493	.334	.408	.369	.365	1.000
-.481	-.400	.382	-.426	.319	.395	-.393	-.448	-.236	-.486	-.476	-.250
-.378	-.380	.359	-.327	.269	.314	-.308	-.380	-.113	-.393	-.393	-.212
-.587	-.452	.380	-.470	.436	.434	-.463	-.487	-.240	-.505	-.476	-.261
-.229	-.180	.175	-.255	.100	.142	-.151	-.272	-.071	-.249	-.325	-.074
-.399	-.397	.446	-.454	.367	.491	-.429	-.432	-.448	-.386	-.453	-.319
.228	.270	-.294	.267	-.326	-.302	.225	.208	.333	.406	.267	.311
.240	.183	-.217	.296	-.314	-.289	.185	.281	.403	.322	.204	.373
-.556	-.419	.388	-.412	.412	.386	-.431	-.449	-.265	-.330	-.335	-.322
-.523	-.363	.368	-.412	.417	.357	-.373	-.442	-.343	-.378	-.350	-.344
-.393	-.360	.402	-.339	.249	.400	-.380	-.415	-.314	-.354	-.298	-.265
-.321	-.504	.422	-.232	.400	.396	-.492	-.206	-.165	-.339	-.379	-.233
1.000											
.624	1.000										
.795	.616	1.000									
.598	.515	.546	1.000								
.464	.331	.437	.351	1.000							
-.232	-.209	-.271	-.260	-.369	1.000						
-.223	-.155	-.290	-.246	-.411	.809	1.000					
.542	.428	.561	.325	.471	-.249	-.264	1.000				
.505	.380	.608	.313	.517	-.358	-.462	.618	1.000			
.462	.398	.470	.323	.458	-.110	-.120	.473	.432	1.000		
.094	.143	.154	-.153	.104	-.088	.055	.164	.157	.191	1.000	

/standard deviations

.314	.301	.196	.260	.376	.352	.275	.217	.277	.614	.992	.171
.181	.413	.143	.992	.716	.388	.338	.317	.151	.251	.446	.380
.309	.211	.268	.665	.117	.117	.150	.380	.134	.673	.631	.310
.846	.794	.829	.715	.886	.240	.359	.797	.896	.824	.475	

! DON'T EXCLUDE DECIMALS

/wtest

/lmttest

/end

Note. Psychomotor scores 1 through 18 (time 1 scores) and 19 through 36 (time 2 scores) correspond to the 18 tests given in Table W1. Cognitive composites

(variables 37 through 46) are the same as in Table W6. These are given to show that Model 9 results will replicate ($r=.68$, g on gp , $z=6.8$; $r = .26$, TP on gp , $z = 2.7$; $r = -.44$ PS on $T2$, $z = 3.6$; $BBNF = .767$) when psychomotor factors are derived from raw scores instead of composites (as in Table W6). In order to run a model on raw psychomotor scores, paired variables 8 and 26 were omitted to yield a matrix with a positive determinant. Average, minimum, maximum, and standard deviation of pairwise n : 134, 91, 158, and 10.2 respectively.

Table W5.

Cognitive tests: pairwise-deleted correlation matrix and standard deviations.

```

/TITLE
CAMPLUS raws
! Alternate version of Table W5.
! This run refers to the preliminary analysis of the cognitive variables.
/SPECIFICATIONS
  VARIABLES=18; CASES=139;
  METHODS=ML;
  MATRIX=correlation;
  fields=6;
/LABELS
V1=WMQ; V2=WMS3; V3=WMV1; V4=FLQ2; V5=FLS1;
V6=FLV3; V7=INQ3; V8=INS2; V9=INV1; V10=SLQ3;
V11=SLS1; V12=SLV2; V13=TP-EA; V14=TP-ET; V15=TP-WW;
V16=PS-VSC; V17=PS-VSS; V18=PS-IT;
! factor labels
f1=workmem; f2=factlrn; f3=induc; f4=skillrn; f5=timing; f6=prospeed;
/technical
iterations=190;
/print
  fit=all;
/equations
v1 = *f1      +   e1;
v2 = *f1      +   e2;
v3 = *f1      +   e3;
v4 = *f2      +   e4;
v5 = *f2      +   e5;
v6 = *f2      +   e6;
v7 = *f3      +   e7;
v8 = *f3      +   e8;
v9 = *f3      +   e9;
v10 = *f4     +  e10;
v11 = *f4     +  e11;
v12 = *f4     +  e12;
v13 = *f5     +  e13;
v14 = *f5     +  e14;
v15 = *f5     +  e15;
v16 = *f6     +  e16;
v17 = *f6     +  e17;
v18 = *f6     +  e18;
/variances
f1=1; f2=1; f3=1; f4=1; f5=1; f6=1;
  e1=*;
  e2=*;
  e3=*;
  e4=*;
  e5=*;
  e6=*;
  e7=*;

```

```

e8=*;
e9=*;
e10=*;
e11=*;
e12=*;
e13=*;
e14=*;
e15=*;
e16=*;
e17=*;
e18=*;
/covariances
f1,f2=*; f1,f3=*; f1,f4=*; f1,f5=*; f1,f6=*;
          f2,f3=*; f2,f4=*; f2,f5=*; f2,f6=*;
          f3,f4=*; f3,f5=*; f3,f6=*;
          f4,f5=*; f4,f6=*;
          f5,f6=*;

/matrix
1.000
.481 1.000
.491 .570 1.000
.186 .192 .316 1.000
.398 .558 .433 .188 1.000
.453 .393 .485 .201 .301 1.000
.316 .421 .306 .156 .237 .350
.405 .464 .446 .145 .395 .391
.248 .407 .408 .157 .316 .324
.573 .602 .584 .231 .385 .527
.413 .489 .436 .174 .426 .362
.519 .568 .563 .250 .337 .463
.466 .479 .400 .181 .248 .361
.413 .488 .339 .159 .271 .389
.354 .360 .409 .191 .323 .279
-.165 -.185 -.206 -.221 -.103 -.266
-.149 -.171 -.218 -.257 -.065 -.251
.309 .419 .406 .224 .335 .356
1.000
.430 1.000
.322 .359 1.000
.399 .527 .300 1.000
.319 .413 .339 .365 1.000
.358 .368 .315 .624 .389 1.000
.340 .405 .207 .462 .563 .374
.304 .279 .257 .510 .456 .516
.283 .409 .190 .336 .457 .390
-.153 -.220 -.155 -.142 -.290 -.179
-.061 -.159 -.142 -.166 -.268 -.235
.198 .381 .204 .365 .411 .300
1.000
.618 1.000
.473 .432 1.000
-.249 -.358 -.110 1.000
-.264 -.462 -.120 .809 1.000
.471 .517 .458 -.369 -.411 1.000
/standard deviations
29 29 26 11 26 9 21 19 19 16 16
24 80 90 82 24 36 89
/lmttest
/wttest
/end

```

Note.

Variable key: WMQ, WMS, WMV are working memory percent correct test scores for quantitative, spatial, and verbal respectively. FLQ, FLS, FLV, and INQ, INS, INV, and SLQ, SLS, SLV are the same types of scores for fact learning, induction, and skill learning, respectively. For other test scores see Figure 2 of the published paper. Average, minimum, maximum, and standard deviation of pairwise n: 139, 133, 147, 3.0 respectively.

Table W6.

Cognitive and psychomotor scores used in models reported in Table 2 (published paper): pairwise-deleted correlation matrix and standard deviations.

```
/TITLE
Psychomotor on cognitive regression
! Model 9, the standard model is what is run here.
! However, the correlation matrix and sd vector allows you to
! run Models 10 through 15 provided the equations section, variance,
! and covariance sections are respecified.
/SPECIFICATIONS
VARIABLES=19; CASES=145;
METHODS=ML;
  MATRIX=correlation;
  fields=12;
/LABELS
V1=CP-TIME1; V2=ML-TIME1; V3=RC-TIME1; V4=RO-TIME1; V5=CP-TIME2;
V6=ML-TIME2; V7=RC-TIME2; V8=RO-TIME2; V9=PS-IT; V10=PS-VSC;
V11=PS-VSS; V12=TP-EA; V13=TP-ET; V14=TP-WW; V15=g-SL;
V16=g-IN; V17=g-WM; V18=g-FL; V19=MALE;
! factor labels
f1 = gp;
! these next are like correlated errors among the same tests
f2=cp; f3=ml; f4=rc; f5=ro; f6=time2; ! time2= psychomotor learning factor.
! cognitive factors
f9=g; f8=ps; f7=tp;
/print
  fit=all;
/equations
v1 = *v19 + *f1 + *f2 + e1;
v2 = *v19 + *f1 + *f3 + e2;
v3 = *v19 + *f1 + *f4 + e3;
v4 = *v19 + *f1 + *f5 + e4;
v5 = *v19 + *f1 + *f2 + *F6 + e5;
v6 = *v19 + 1 f1 + *f3 + *F6 + e6;
v7 = *v19 + *f1 + *f4 + *F6 + e7;
v8 = *v19 + *f1 + *f5 + 1 F6 + e8;
v9 = *v19 + *f9 + *f8 + e9;
v10= *v19 + *f9 + *f8 + e10;
v11= *v19 + *f9 + *f8 + e11;
v12= *v19 + *f9 + *f7 + e12;
v13= *v19 + *f9 + *f7 + e13;
v14= *v19 + *f9 + *f7 + e14;
v15= *v19 + *f9 + e15;
v16= *v19 + *f9 + e16;
v17= *v19 + *f9 + e17;
v18= *v19 + *f9 + e18;
f1= *f9 + *f8 + *f7 + d1;
f6= *f9 + *f8 + *f7 + d6;
/variances
d1=100000*; d6=100000*;
f2=1; f3=1; f4=1; f5=1;
```



```

f7=1; f8=1; f9=1;
e1=*;
e2=*;
e3=*;
e4=*;
e5=*;
e6=*;
e7=*;
e8=*;
e9=*;
e10=*;
e11=*;
e12=*;
e13=*;
e14=*;
e15=*;
e16=*;
e17=*;
e18=*;
/covariances
! example only as command is commented out
! adding the line below allows you to run Model 13 in the paper.
! f7,f8=*;
/constraints
(v1,f2)=(v5,f2);
(v2,f3)=(v6,f3);
(v3,f4)=(v7,f4);
(v4,f5)=(v8,f5);
/matrix
1.000
.768 1.000
.727 .830 1.000
.558 .639 .619 1.000
.805 .669 .669 .562 1.000
.784 .919 .844 .657 .747 1.000
.728 .793 .869 .631 .734 .854 1.000
.610 .649 .635 .794 .646 .715 .751 1.000
.430 .437 .459 .468 .438 .505 .555 .542 1.000
-.362 -.288 -.203 -.293 -.367 -.316 -.340 -.442 -.369 1.000
-.351 -.225 -.177 -.276 -.420 -.255 -.351 -.458 -.411 .809 1.000
.490 .531 .496 .375 .493 .575 .530 .427 .471 -.249 -.264 1.000
.425 .479 .421 .352 .434 .501 .512 .480 .517 -.358 -.462 .618
.362 .495 .462 .403 .331 .483 .457 .411 .458 -.110 -.120 .473
.440 .574 .497 .377 .428 .598 .596 .494 .437 -.271 -.290 .561
.303 .498 .392 .375 .297 .494 .422 .390 .331 -.209 -.155 .428
.408 .540 .434 .429 .353 .538 .518 .485 .464 -.232 -.223 .542
.241 .293 .135 .176 .189 .282 .251 .271 .351 -.260 -.246 .325
.473 .493 .537 .369 .370 .474 .436 .329 .104 -.088 .055 .164
1.000
.432 1.000
.608 .470 1.000
.380 .398 .616 1.000
.505 .462 .795 .624 1.000
.313 .323 .546 .515 .598 1.000
.157 .191 .154 .143 .094 -.153 1.000
/standard deviations
.747 .827 .820 .690 .750 .816 .780 .729 .886 .240 .359 .797
.896 .824 .829 .794 .846 .715 .475
! DON'T EXCLUDE DECIMALS.
/wttest
/lmttest

```

/end

Note. See Figure 2 notes of the published paper for test score explanations. Average, minimum, maximum, and standard deviation of pairwise n: 145, 140, 161, 5.1 respectively.

Table W7.

Cognitive and psychomotor scores used in models reported in Table 4 (published paper): pairwise-deleted correlation matrix and standard deviations.

```
/TITLE
  extended psychomotor practice
! time 1 is modeled here but the matrix and sds allows you to model all 7 times
! separately provided the equations section and variance sections are respecified.
/SPECIFICATIONS
VARIABLES=39;
CASES=136; ! changes depending on time need to look at Table 3 published paper
METHODS=ML;
MATRIX=correlation;
fields=12;
/LABELS
V1=CP21; V2=ML21; V3=RC2A1; V4=RO31; V5=CP22;
V6=ML22; V7=RC2A2; V8=RO32; V9=CP23; V10=ML23;
V11=RC2A3; V12=RO33; V13=CP24; V14=ML24; V15=RC2A4;
V16=RO34; V17=CP25; V18=ML25; V19=RC2A5; V20=RO35;
V21=CP26; V22=ML26; V23=RC2A6; V24=RO36; V25=CP27;
V26=ML27; V27=RC2A7; V28=RO37; V29=g-SL; V30=g-IN;
V31=g-WM; V32=g-FL; V33=TP-EA; V34=TP-ET; V35=TP-WW;
V36=PS-VSC; V37=PS-VSS; V38=PS-IT; V39=MALE;
! factor labels
f1 =gp;
f0 = g; f7=tp; f8=ps;
/print
  fit=all;
/equations
v1 = *v39 + *f1 + e1;
v2= *v39 + 1 f1 + e2;
v3= *v39 + *f1 + e3;
v4= *v39 + *f1 + e4;
!
v29 = *v39 + *f0 + e29;
v30 = *v39 + *f0 + e30;
v31 = *v39 + *f0 + e31;
v32 = *v39 + *f0 + e32;
!
v33 = *v39 + *f0 + *f7 + e33;
v34 = *v39 + *f0 + *f7 + e34;
v35 = *v39 + *f0 + *f7 + e35;
!
v36 = *v39 + *f0 + *f8 + e36;
v37 = *v39 + *f0 + *f8 + e37;
v38 = *v39 + *f0 + *f8 + e38;
!
f1= *f0 + *f8 + *f7 + d1;
/variances
f0=1; f7=1; f8=1;
d1=10000*;
e1=*;
```

```

e2=*;
e3=*;
e4=*;
!
e29=*;
e30=*;
e31=*;
e32=*;
e33=*;
e34=*;
e35=*;
e36=*;
e37=*;
e38=*;

```

```

/matrix

```

```

1.000
.486 1.000
.500 .360 1.000
-.456 -.432 -.283 1.000
.748 .532 .434 -.395 1.000
.433 .818 .340 -.522 .541 1.000
.538 .390 .728 -.339 .594 .428 1.000
-.430 -.519 -.228 .632 -.523 -.620 -.405 1.000
.684 .464 .391 -.480 .863 .553 .553 -.568 1.000
.418 .755 .382 -.527 .577 .897 .487 -.611 .606 1.000
.515 .422 .641 -.430 .629 .541 .816 -.480 .614 .586 1.000
-.376 -.390 -.307 .304 -.415 -.454 -.376 .754 -.461 -.467 -.402 1.000
.614 .421 .413 -.499 .800 .559 .498 -.547 .891 .598 .614 -.501
.350 .715 .365 -.474 .513 .819 .452 -.565 .538 .914 .519 -.479
.469 .321 .479 -.407 .582 .439 .696 -.430 .587 .524 .868 -.361
-.394 -.392 -.323 .501 -.427 -.530 -.438 .671 -.448 -.576 -.539 .927
.617 .410 .453 -.525 .799 .551 .512 -.557 .880 .590 .605 -.381
.368 .614 .410 -.426 .463 .752 .427 -.503 .448 .814 .502 -.506
.446 .277 .417 -.381 .485 .364 .627 -.358 .522 .421 .743 -.322
-.387 -.381 -.372 .510 -.436 -.561 -.463 .677 -.451 -.609 -.565 .850
.514 .379 .454 -.550 .710 .528 .413 -.520 .787 .589 .535 -.348
.339 .548 .419 -.304 .401 .656 .429 -.434 .365 .716 .433 -.458
.302 .260 .298 -.337 .374 .323 .482 -.329 .435 .398 .556 -.307
-.403 -.366 -.349 .494 -.429 -.547 -.456 .679 -.477 -.577 -.571 .819
.493 .395 .479 -.452 .722 .491 .476 -.498 .763 .542 .533 -.351
.295 .520 .420 -.299 .313 .604 .396 -.454 .286 .674 .360 -.441
.282 .238 .296 -.295 .381 .292 .490 -.293 .446 .414 .578 -.265
-.385 -.310 -.315 .448 -.339 -.418 -.390 .625 -.364 -.460 -.485 .830
.364 .494 .270 -.264 .431 .475 .436 -.476 .420 .470 .384 -.392
.304 .467 .131 -.292 .388 .473 .269 -.393 .370 .410 .286 -.345
.318 .535 .170 -.345 .372 .513 .319 -.476 .352 .468 .276 -.430
.132 .345 .028 -.189 .166 .285 .100 -.325 .215 .244 .129 -.294
.363 .428 .392 -.353 .441 .429 .412 -.335 .353 .482 .369 -.352
.382 .349 .326 -.300 .386 .303 .417 -.350 .314 .383 .360 -.334
.292 .378 .174 -.297 .379 .387 .249 -.298 .333 .401 .273 -.323
-.290 -.160 -.095 .272 -.277 -.184 -.326 .267 -.283 -.264 -.288 .309
-.238 -.061 -.209 .193 -.213 -.106 -.314 .204 -.177 -.194 -.240 .192
.269 .290 .246 -.499 .392 .398 .367 -.453 .383 .436 .448 -.365
.556 .338 .319 -.379 .519 .375 .400 -.379 .543 .350 .400 -.238
1.000
.533 1.000
.592 .473 1.000
-.482 -.565 -.453 1.000
.897 .542 .607 -.417 1.000
.431 .859 .487 -.509 .454 1.000

```

```

.508 .383 .862 -.435 .506 .470 1.000
-.474 -.601 -.486 .877 -.435 -.571 -.446 1.000
.813 .529 .548 -.390 .850 .472 .505 -.425 1.000
.318 .741 .395 -.444 .364 .875 .385 -.520 .343 1.000
.427 .402 .733 -.324 .431 .456 .841 -.343 .470 .350 1.000
-.502 -.577 -.492 .871 -.457 -.530 -.458 .943 -.461 -.458 -.373 1.000
.776 .520 .566 -.348 .865 .463 .488 -.385 .885 .374 .439 -.408
.261 .717 .344 -.422 .284 .844 .397 -.481 .302 .907 .445 -.427
.431 .394 .745 -.287 .446 .471 .804 -.319 .435 .406 .813 -.349
-.363 -.478 -.431 .843 -.288 -.458 -.426 .914 -.283 -.409 -.352 .933
.329 .450 .390 -.348 .404 .483 .359 -.395 .331 .443 .305 -.381
.323 .332 .295 -.259 .317 .325 .206 -.221 .265 .249 .160 -.275
.297 .436 .334 -.376 .333 .464 .309 -.407 .297 .427 .329 -.382
.133 .213 .159 -.126 .189 .295 .136 -.185 .182 .231 .093 -.158
.353 .472 .309 -.354 .375 .532 .265 -.351 .322 .497 .257 -.333
.306 .406 .314 -.376 .312 .451 .320 -.375 .265 .433 .224 -.377
.297 .402 .279 -.307 .293 .333 .234 -.251 .221 .306 .219 -.245
-.206 -.314 -.295 .345 -.148 -.371 -.331 .345 -.221 -.296 -.348 .394
-.105 -.286 -.294 .262 -.146 -.383 -.334 .294 -.184 -.323 -.308 .350
.390 .449 .467 -.395 .368 .500 .464 -.428 .433 .434 .406 -.447
.553 .293 .349 -.350 .512 .244 .380 -.292 .437 .225 .270 -.297
1.000
.320 1.000
.414 .441 1.000
-.225 -.428 -.311 1.000
.399 .395 .314 -.315 1.000
.291 .167 .262 -.160 .616 1.000
.344 .393 .285 -.328 .795 .624 1.000
.258 .177 .066 -.136 .546 .515 .598 1.000
.392 .424 .269 -.257 .561 .428 .542 .325 1.000
.295 .387 .325 -.336 .608 .380 .505 .313 .618 1.000
.288 .323 .256 -.226 .470 .398 .462 .323 .473 .432 1.000
-.184 -.341 -.306 .393 -.271 -.209 -.232 -.260 -.249 -.358 -.110 1.000
-.197 -.344 -.334 .354 -.290 -.155 -.223 -.246 -.264 -.462 -.120 .809
.396 .375 .398 -.355 .437 .331 .464 .351 .471 .517 .458 -.369
.417 .191 .284 -.245 .154 .143 .094 -.153 .164 .157 .191 -.088
1.000
-.411 1.000
.055 .104 1.000
/standard deviations
.301 .352 .992 .716 .317 .380 .117 .631 .319 .394 .119 .487
.301 .420 .124 .310 .279 .463 .119 .251 .235 .497 .128 .227
.242 .483 .128 .185 .829 .794 .846 .715 .797 .896 .824 .240
.359 .886 .475
! DON'T EXCLUDE DECIMALS.
/wttest
/lmttest
/end

```

Note. Tests CP2(n), ML2(n), RC2(n), RO3(n) are the corresponding tests from Table W1, where (n) denotes replication number. Scores 29 through 38 are cognitive composites described in Figure 2 of the published paper. Average, minimum, maximum, and standard deviation of pairwise n: 136, 101, 150, 9.1 respectively.

Table W8.
Standardized regression coefficients for a model of Fleishman (1954) data.

test	gp	1	2	3	4	5	6	7	8	e
1 Steadiness-precision	.24					.43			.20	.85
2 Steadiness-aiming	.24					.55			.17	.78
3 Track Tracing	.51					.56			.23	.61
4 Two-plate tapping	.63	.13		.15						.75
5 Key Tapping	.37									.93
6 Ten-target aiming-errors	.11			-.76						.64
7 Ten-target aiming-corrects	.53			.48						.70
8 Rotary aiming	.62	.11		.16						.76
9 Visual reaction time	.41						.67			.62
10 Auditory reaction time	.26						.67			.69
11 Minnesota rate of manipulation-piecing	.67		.15	.04						.73
12 Minnesota rate of manipulation-turning	.66		.23							.71
13 Purdue Pegboard-right hand	.49		.34							.80
14 Purdue Pegboard-left hand	.42		.47							.77
15 Purdue Pegboard-both hands	.50		.52							.69
16 Purdue Pegboard-assembly	.51		.43							.74
17 O'Conner finger dexterity	.53		.43							.73
18 Santa Anna dexterity	.50									.86
19 Hand precision aiming-errors	.32			-.27						.91
20 Hand precision aiming-corrects	.30							.30		.95
21 Discrimination RT	.46								.37	.75
22 Complex coordination	.45								.51	.73
23 Rudder control	.16								.50	.85
24 Rotary pursuit	.46								.29	.84
25 Dynamic balance	.15								.38	.91
26 Posture discrimination-vertical	.18									.98
27 Posture discrimination-angular	.10									.99
28 Punch board	.65									.76
29 Pin stick	.53									.85
30 Medium tapping	.65	.48								.59
31 Large tapping	.60	.68								.42
32 Aiming	.64	.15			.53					.53
33 Pursuit aiming I	.62	.17			.57					.51
34 Pursuit aiming II	.59	.17			.66					.43
35 Square marking	.43				.23			.17		.86
36 Tracing	.45									.90
37 Steadiness	.31					.24				.92
38 Printed version of #21	.45							.33		.83

39	Log book accuracy	.56		.59	.58
40	Marking accuracy	.55	.28	.36	.70

Note. Factor key: gp = general psychomotor ability; 1 = wrist-finger speed; 2 = finger dexterity; 3 = rate of arm movement; 4 = aiming; 5 = steadiness; 6 = reaction time; 7 = psychomotor speed; 8 = Psychomotor coordination (later called Control Precision). Fleishman factors not found: manual dexterity and spatial relations (factors 7 and 10 from Fleishman, 1954). Doublet and postural discrimination factors (factors 11 and 12) were represented as correlated error terms because scores loading these factors come from a common test.