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# Evidence of validity in a new method for measurement of dexterity in children and adolescents

**Brigitte Vollmer**[1], **Linda Holmström**[1], **Lea Forsman**[1], **Lena Krumlinde-Sundholm**[1], **Francisco J Valero-Cuevas**[2], **Hans Forssberg**[1], and **Fredrik Ullén**[1]

[1] Neuropaediatric Research Unit, Department of Women's and Children's Health, Karolinska Institutet, and Stockholm Brain Institute, Stockholm, Sweden

[2] Department of Biomedical Engineering and Division of Biokinesiology & Physical Therapy, University of Southern California, Los Angeles, CA, USA

## Abstract

**Aim—**Impaired performance in manipulative tasks is common in neurodevelopmental disorders. Thus accurate assessment of an individual's ability to coordinate fingertip forces is important for planning treatment. We evaluated a recently developed assessment tool (the Strength–Dexterity Test), which is based on manipulation of unstable objects, in a paediatric population.

**Method—**A Rasch model was used to examine the validity and reliability of the Strength–Dexterity Test in a sample of 56 typically developing children and adolescents (30 males, 26 females; age range 4y 10mo–17y 3mo; mean age 9y 8mo, SD 3y 8mo). In addition, we examined how performance on this test relates to the widely used Box and Blocks Test for assessment of gross manual dexterity and finger strength measured with a pinch meter.

**Results—**The constructs measured with the 78-item Strength–Dexterity Test include dexterity and strength, and form a unique unidimensional latent trait, named fingertip force coordination, that improves with age. The test has internal scale validity when applied to a typical paediatric population. Positive correlations (significant at $p<0.001$) were found among all three tests.

**Interpretation—**We provide preliminary evidence of construct validity in the Strength–Dexterity Test. Our findings suggest that this test has the potential to be developed into a promising tool for assessing dexterity in children.

**What this paper adds**

- This study provides preliminary evidence in a paediatric sample for construct validity for a new test that measures fingertip force coordination when manipulating unstable objects.
- The study indicates that the Strength–Dexterity Test is a promising tool for assessing dexterity in children.

Most everyday activities require the manipulation of objects with the fingertips, an ability that is often referred to as dexterity. Various factors influence performance in manipulative tasks, such as independence of finger movements, speed, strength, and eye–hand

Correspondence to Dr Brigitte Vollmer at Neuropaediatric Research Unit, Department of Women's and Children's Health, Karolinska Institutet, Astrid Lindgren Children's Hospital, Q2:O7, 17176 Stockholm, Sweden. brigitte.vollmer@ki.se.

coordination (for review see Carroll[1]). In addition, precise control of the fingertip forces employed to the object is critical to object manipulation.[2,3]

Impaired fine motor skills are common in neurodevelopmental disorders. Therefore, accurate assessment of an individual's ability to control the fingertip forces would be clinically useful for planning and evaluation of treatment. Currently, no such tests are available. For example, the Box and Blocks test[4] and tests that involve moving pegs (e.g. Nine Hole Peg Test) reflect multiple aspects of motor control, such as preshaping the hand, grasping, moving and releasing the object, and moving the arm and/or hand. In the 'precision grip–lift task', developed by Johansson et al. (for review see Johansson and Cole[5]), the fingertip forces employed to the contact surfaces are measured. However, in this paradigm, the object is *stable* and the person uses an automatised grip–lift synergy that provides grasp stability by a strong temporal coupling of grip and lift forces.[6]

Recently, a new method (the Strength–Dexterity Test)[7] to assess an individual's ability to control the direction of the fingertip force vectors in the manipulation of *unstable* objects has been developed. This ability to control precisely the direction and strength of fingertip forces is crucial for many everyday activities (e.g. getting dressed or eating). The Strength–Dexterity Test task consists of compressing a spring (see Fig. 1) without buckling it, which requires control of the direction and strength of fingertip forces, based on sensory–motor feedback. This test has been used in adults and has also been assessed for repeatability.[7] The motivation for studying a paediatric population originates from the need to develop tools that are sensitive to small but nevertheless relevant changes in dexterity in typical and atypical development.

Our first aim was to analyse the internal scale validity of the Strength–Dexterity Test in a typical paediatric population by employing a Rasch measurement model. Second, we wanted to investigate how the Strength–Dexterity Test relates to tests for pinch strength and manual dexterity. Third, we examined how performance varies with age and whether there are any sex differences.

## Method

### Participants

We examined a sample of 56 typically developing children (30 males, 26 females) aged 4 years 10 months to 17 years 3 months (mean age 9y 8mo, SD 3y 8mo); two of the 56 participants were left-handed. The participants were recruited from local nurseries and schools and had no history of neurological or neurodevelopmental problems. Testing was performed either at home, at school, or at the nursery.

Ethical approval for the study was granted by the Regional Ethics Committee of Stockholm, Sweden. Written informed consent was obtained from the parents of the participants under 16 years of age, with assent from the children themselves. For those over 16 years, written consent was obtained from the participants only.

### Method

First, the Box and Blocks Test of Manual Dexterity[4] was administered. Then, maximal strength for 'opposition pinch' (using both the index and middle fingers) was measured (model PG-60 pinch gauge; B&L Engineering, Tustin, CA, USA). Next, the Strength–Dexterity Test was presented; this test consists of compressing a variety of springs (with three-fingered pinch using both the index and the middle fingers; see Fig. 1) to their solid length (i.e. the coils touching) without buckling. The springs are characterized by two indices: the strength index (which specifies the force required to compress the spring and is indicated by spring specification labelled 1–13) and the dexterity index (which specifies the degree of mechanical instability, i.e. the tendency of the spring to buckle, and is indicated by spring specification labelled A–H). Both indices are a function of the geometry of the spring and the physical properties of the material used, and are adjusted independently for the different springs. The original Strength–Dexterity Test kit consists of 82 compression springs. In our study, only subsets of springs with strength requirements below and slightly exceeding the participant's maximal pinch force were used. Therefore, the number of springs presented varied between participants, with a mean of 73 springs used (range 53–82). Springs were presented in random order and the participants were asked to compress each spring with the dominant hand. A binary score was used to record a success (at least one of the three allowed trials per spring results in complete compression; score 1) or failure (none of the three allowed trials per spring results in complete compression; score 0). Only compression of a spring to its solid length was scored as success. The correct finger posture required a slight flexion at all joints to prevent hyperextension, while the fourth and fifth digits were curled out of the way (Fig. 1). Instructions and demonstration of the correct finger posture were given, and the participants were allowed sufficient time to familiarise themselves with the task. The participants were reminded to keep their elbow and forearm in a stable position on the table, and to maintain opposition pinch. Breaks were provided to prevent fatigue and maintain concentration. On average, the test procedure for each participant lasted approximately 15 minutes.

## Statistical analysis

We applied a Rasch model analysis for dichotomous data (using WINSTEPS 3.65.0 software; www.winsteps.com) to examine whether the test items (i.e. the different springs) measured one single latent trait, which we named coordination of fingertip forces. An analysis was performed on the full set of raw data to examine internal scale validity and reliability of the Strength–Dexterity Test. The aims were to evaluate whether the items (1) defined a unidimensional construct, (2) were appropriately spread along the continuum of increasing difficulty, (3) were appropriately targeted to the sample of typically developing children and adolescents, and (4) were sensitive to detect differences among person ability measures. Reliability was evaluated in terms of whether the items could separate individuals into distinct levels of ability; the separation ratio was transformed into a strata index describing the number of significantly different levels of measures.[8] Dimensionality was further examined by a principal components analysis of the standardised residuals. Regression analyses were then used to investigate whether the Strength–Dexterity Test shared variance with pinch strength and performance on the Box and Blocks Test, and to characterize developmental curves of performance on the three tests. Finally, sex differences in performance were analysed using one-way analysis of variance (ANOVA) for both the whole data set and as a function of age. Levene's test of homogeneity of variances was used to test whether the two sex groups were homoscedatic. For the Strength–Dexterity Test, this was not the case, thus sex differences were also investigated using the non-parametric Mann–Whitney *U* test. An alpha value of 0.05 was used throughout as threshold for statistical significance; for all analyses, two-tailed tests were used.

## Rasch analysis

A central assumption of the Rasch model is that the probability of a particular participant passing a particular test item is determined by two parameters: the ability level of the participant and the difficulty level of the item.[9] Both parameters are measures on the same interval scale, which represents the latent trait a test is assumed to measure.

In a Rasch analysis raw scores are transformed into interval measures by a log odds transformation of the probability of a correct response, using the unit logits for calibrating items and measuring individuals. Test items are then listed in an ordered way, and participants are ordered according to their abilities with respect to the measured trait. A higher measure indicates a more difficult item or better ability. The difficulty of each item is shown by the item calibrations; the higher the measure, the more difficult the item. Goodness-of-fit statistics are used to evaluate the degree of fit between the actual patterns of responses and the Rasch assumptions. Acceptable goodness-of-fit statistics for the participants give evidence of person response validity, and goodness-of-fit statistics for the items give evidence of whether the items meet the requirements of unidimensionality. Infit statistics indicate unexpected scores close to the item's estimated difficulty or the participant's estimated ability. Outfit statistics give information on unexpected responses far from those expected (i.e. are sensitive to outliers). Mean square values are a ratio of the observed and the predicted residual variance and have an expected value of 1, with a higher value indicating that the observed scores have greater variation than predicted, and a lower value indicating that observed scores have less variation than expected. A test is by convention considered to have acceptable unidimensionality when at least 95% of the items fit the Rasch measurement model.[9,10] For this study, the infit mean square residual value of 1.4 or less, with an associated $z$-value of not more than 2.0, was used for acceptable goodness-of-fit.[10,11] In an additional principal components analysis on the Rasch residuals, we used Linacre's guidelines for principal components analysis supporting good unidimensionality if the measures explain more than 60% of the variance and no more than 5% of the first contrast (WINSTEPS software manual, www.winsteps.com).

Reliability can be inferred from the standard error of the estimated calibrations given for each measure of items and participants. The person separation index defines the statistically distinct number of ability strata for the scale and indicates the precision of the measure and its sensitivity to detect differences among person ability measures. A separation value should be greater than 2 to separate difficulty levels of items or ability levels of individuals. Discernible strata are calculated with the formula $(4G+1)/3$, where $G$ is the separation ratio scale index obtained in the Rasch analysis, comparing the ‘true’ spread of the measures with their measurement error.[8]

## Results

### Rasch analysis

A Rasch analysis was performed on the full set of raw data obtained from the original 82-spring set. Subsequently, four items that were not mastered by any of the participants were removed. A second Rasch analysis was then performed on the remaining set of 78 items (Table I). Twenty items (see bottom of Table I) were found to have no calibration value (i.e. these items were manageable for every participant and thus did not contribute to the ability measures of a participant). These items were, nevertheless, kept in the set because the intended future target group for the Strength–Dexterity Test includes people with impaired hand function, for whom these easier items may be relevant. Table I shows the item calibration values and goodness-of-fit statistics for the 78-item Strength–Dexterity Test performed on the data obtained from the 56 typically developing children. The item calibration ranged from −7.64 to 8.56 logits (with a mean value as default set to 0). All items except two (<3%) demonstrated good fit to the Rasch model at the individual item level, which indicates a valid unidimensional scale. The items were well distributed along the full calibration range and were appropriately targeted for the sample, with exception of the 20 items at the lower end of the scale. The person ability measures range was −5.15 to 8.16 logit (mean 0.31). The standard error ranged from 0.50 to 0.66 for measures lower than 5.39 logit and increased up to a maximum of 0.84 for higher measures. All participants except two (3.5%) demonstrated accurate fit to the model assertions. Dimensionality was further supported by the principal component analysis, which demonstrated that the variance explained by measures was 71%, and that the unexplained variance explained by the first contrast was 3.6%. The separation value (5.02) and the reliability (0.96) indicate that the distribution of individuals could be separated into statistically distinct strata, which in our case produced seven strata.

### Correlational structure of the Strength–Dexterity Test and other measures

Pinch strength measured with the pinch meter ranged from 17.8 to 129.0N (mean 48.3N; SD 19.9N). Box and Blocks Test scores for 55 participants (one male did not complete this test) ranged from 32 to 76 (mean 52.2, SD 10.6). Correlations between the tests are summarised in Table II and Figure 3a and b. Positive correlations were found between all tests. Of particular interest was whether performance on the Box and Blocks Test (Fig. 3a) and pinch strength (Fig. 3b) accounted for independent variance in the Strength–Dexterity Test. Thus, a regression analysis of Strength–Dexterity Test scores on pinch strength and scores from the Box and Blocks Test was performed. The multiple $R^2$ was 0.72, with significant relations with both pinch strength ($t_{52}$=5.63; $p$<0.001; beta 0.51 SE 0.09) and the Box and Blocks Test ($t_{52}$=4.78; $p$<0.001; beta 0.44 SE 0.09). Unique contributions (i.e. squared semi-partial correlation coefficients) of pinch strength and the Box and Blocks Test to Strength–Dexterity Test variance were 16.9% and 12.1% respectively. Shared pinch strength and Box and Blocks Test variance accounted for the largest fraction (43.2%) of Strength–Dexterity Test variance. These relations are illustrated in a Venn diagram (Fig. 4).

### Strength–Dexterity Test performance as function of age

Performance on all tests improved with age (Table II). Strength–Dexterity Test measures at different ages are shown in Figure 5. We were particularly interested in whether Strength–Dexterity Test scores improved when controlling for pinch strength. A regression of the Strength–Dexterity Test on age and pinch strength was therefore performed. The multiple $R^2$ of this correlation was 0.80, with significant relations with both pinch strength ($t_{53}$=3.99; $p$<0.002) and age ($t_{53}$=7.26; $p$<0.001). Improvement in performance with age was thus also seen in the non-pinch strength-related variance of the Strength–Dexterity Test, which presumably reflects dexterity. A second regression model was tested in which Strength–Dexterity Test scores were regressed simultaneously on age, pinch strength, and Box and Blocks Test scores. Significant relationships with age ($t_{51}$=4.63; $p$<0.001) and pinch strength ($t_{51}$=3.81; $p$<0.003) remained, whereas the relationship with the Box and Blocks Test ($t_{51}$=1.35; $p$=0.183) was non-significant.

### Sex differences

Overall effects of sex on Strength–Dexterity Test performance were investigated using one-way ANOVA. No significant sex difference in mean scores was found on the Strength–Dexterity Test ($F_{1,54}$=0.91; $p$=0.343; see Fig. 5), the Box and Blocks Test ($F_{1,53}$=0.022; $p$=0.881), or pinch strength ($F_{1,54}$=0.78; $p$=0.382). Levene's test for homogeneity of variances showed homogeneous variances in males and females for Box and Blocks ($F_{1,54}$=1.95; $p$=0.168) and pinch strength ($F_{1,54}$=2.62; $p$=0.111), whereas the variances for the Strength–Dexterity Test were not homogeneous in the two sex groups ($F_{1,54}$=4.96; $p$=0.030). However, a Mann–Whitney $U$ test did not reveal a sex difference for the Strength–Dexterity Test ($U$=346; $p$=0.470). To investigate whether there were sex differences in developmental curves on the Strength–Dexterity Test, a general linear model, with the Strength–Dexterity Test as the dependent variable, sex as the categorical predictor, and age as the continuous predictor, was utilized. This revealed a significant effect of age ($F_{1,52}$=166.4; $p$<0.001) and sex ($F_{1,52}$=5.67; $p$=0.021) and a significant sex–age interaction ($F_{1,52}$=9.64; $p$=0.003), that is, the improvement in Strength–Dexterity Test performance with age demonstrated a steeper slope in male children. The corresponding model for pinch strength revealed a significant age effect ($F_{1,52}$=48.5; $p$<0.001) but no effects of sex

($F_{1,52}$=0.35; $p$=0.557) or sex–age interaction ($F_{1,52}$=0.97; $p$=0.330). Similarly, for the Box and Blocks Test, there was a strong effect of age ($F_{1,52}$=80.0; $p$<0.001), but only weak evidence for an effect of sex ($F_{1,52}$=2.9; $p$=0.092) or sex–age interaction ($F_{1,52}$=3.4; $p$=0.070).

## Discussion

We have, in a paediatric population, explored a new method for assessment of dexterity based on manipulation of unstable objects. The Rasch analysis confirmed the internal scale validity and that the Strength–Dexterity Test measures one single latent trait, named fingertip force coordination. The Strength–Dexterity Test was able to separate the participants into different levels of ability, which indicates its potential to be a useful tool for descriptive as well as evaluative purposes. Test items were appropriately spread along the continuum of increasing difficulty and were found to provide an adequate challenge to a sample of typically developing children and adolescents. In addition to examining a sample of typically developing children, we explored a small sample of children with cerebral palsy (CP), in whom varying degrees of hand impairment were seen (data not presented). This exploratory analysis demonstrated that the children with CP were widely distributed on the person ability scale. This indicates that the Strength–Dexterity Test is sensitive to hand motor impairment and suggests that it has the potential to be developed to a clinically useful tool for assessing dexterity in children with atypical development. However, this needs to be investigated further in a much larger sample of children with hand motor impairment.

Large positive correlations were found between performances on pinch strength, the Box and Blocks Test, and the Strength–Dexterity Test. As it is well established that both speed of performance[4,12,13] and grip strength[14–16] improve with age, this was not a surprising finding in the present study considering the large age range of our sample. Further work that includes administering the Strength–Dexterity Test in the context of larger test batteries and in more homogeneous age samples are required to determine the factor structure of the Strength–Dexterity Test in more detail. Nevertheless, our results provide preliminary evidence that there is a unique and unidimensional latent trait measured in the Strength–Dexterity Test. A small proportion of this non-strength-related variance was shared with the Box and Blocks Test, whereas the rest (see Fig. 4) was unique to the Strength–Dexterity Test and is likely to reflect individual differences in dynamic control of fingertip force vectors. Figure 4 also illustrates that each of the three tools we used assesses a distinctly different feature of hand function beyond the commonalities they share. It should be noted, however, that, as performances on all tests were positively correlated, estimates of the relative importance of the Box and Blocks Test and pinch strength as predictors of the Strength–Dexterity Test may have low reliability.

No significant overall effect of sex on performance in either of the tests was found. This could be a consequence of limited power with the current sample size. However, across the investigated age range for all three tests, a steeper slope was seen in males. Surprisingly, we found a significant sex–age interaction for the Strength–Dexterity Test but not for pinch strength. This might indicate that sex differences in dexterity develop with age.

Functional magnetic resonance imaging (fMRI) studies on manipulation of stable objects have found that the precision grip is controlled by a bilateral frontoparietal–cerebellar network.[17] Within this network, activity in several areas is modulated by the magnitude of the forces produced, indicating that these areas are involved in the control of the precise fingertip force level.[18,19] In manipulation of stable objects, stability (i.e. coordination between the grip force and the lift force) is provided by an automatized grip–lift synergy,[6] whereas, in manipulation of unstable objects, the direction of the fingertip force vectors (which are probably controlled by circuits receiving constant somatosensory and visual feedback) becomes critical. Little is known about the neural correlates underlying the precise control of the fingertip forces in manipulation of unstable objects. Milner et al.,[20,21] using fMRI, explored neural mechanisms of the manipulation of objects with simple and complex dynamics. They found evidence for strong activation in the ipsilateral cerebellum and for selective activation of areas, including the contralateral secondary somatosensory cortex and the ipsilateral inferior parietal lobule, when objects with complex dynamics were manipulated. Recent fMRI studies using paradigms that include items from the Strength–Dexterity Test indicate that there are areas in the basal ganglia and within the bilateral frontoparietal–cerebellar network that modulate their activity when visual and friction conditions are altered or when the dexterity demand is increased[22] (Vollmer, unpublished data). We propose that the Strength–Dexterity Test also has the potential to become a tool for systematic investigation of neural correlates of dexterity in both typical and atypical populations.

## Conclusion

Our study confirms aspects of validity and reliability of a new method that assesses dexterity in a population of typically developing children. We suggest that the Strength–Dexterity Test, after further development, will be a useful tool for the assessment of dexterity in children and for investigation of neural correlates of dexterity.

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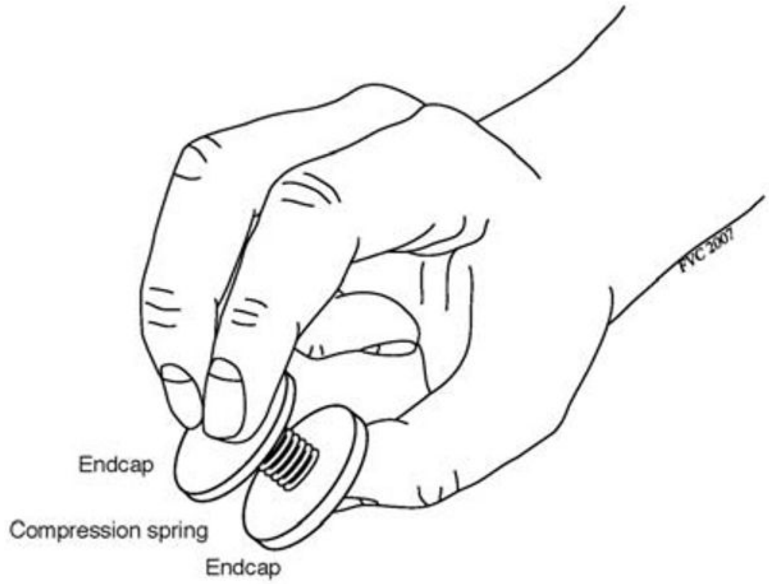


**Figure 1.**
Compression spring and correct finger positions for task performance.

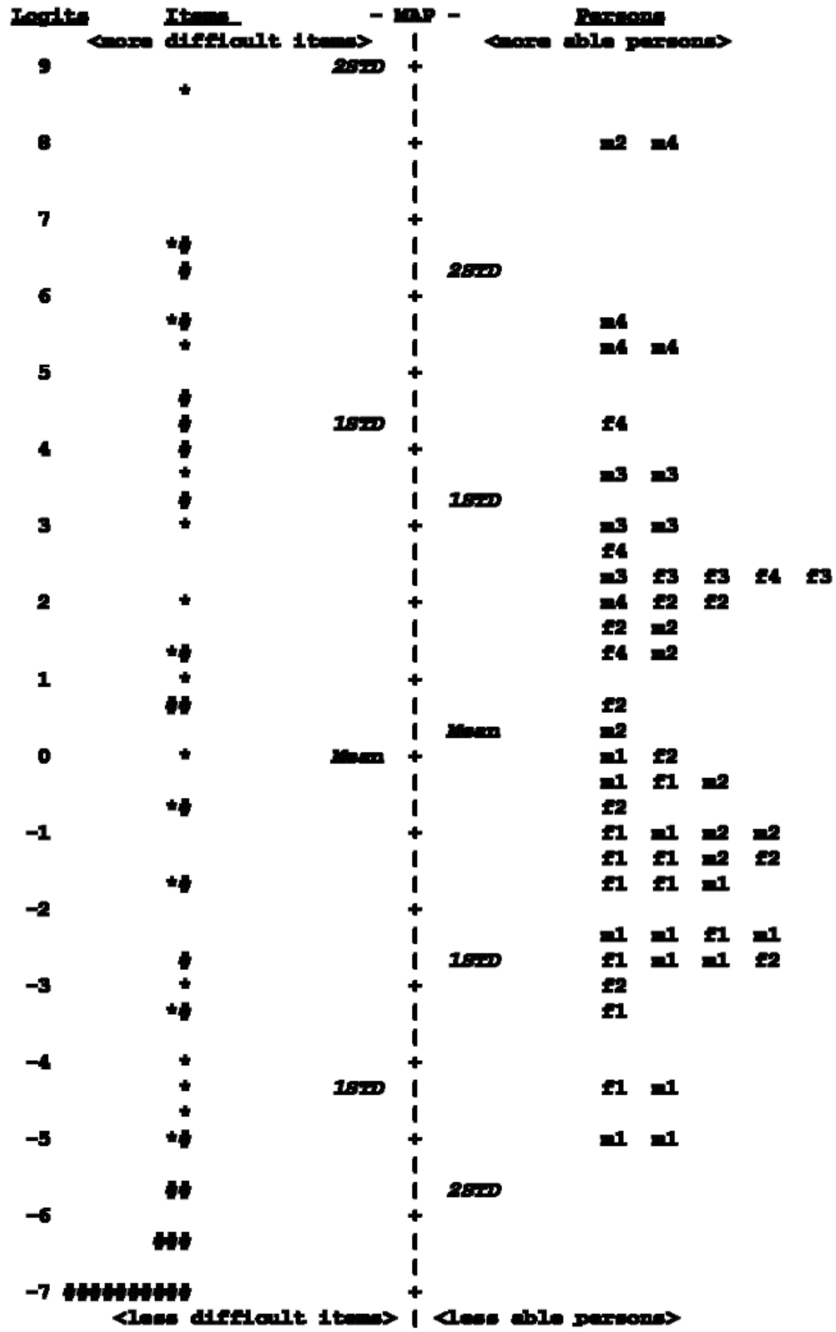


**Figure 2.**

Map of item calibrations and person measures including 78 items and 56 typically developing children/adolescents. Each '#' represents two items and each '*' represents one item. Items at the higher end of the scale are more difficult than items at the lower end, and individuals at the higher end of the scale are more able than those at the lower end. The numbers indicate age categories; group 1=59–83 months (*n*=21), group 2=84–119 months (*n*=15), group 3=120–155 months (*n*=10), and group 4=156–208 months (*n*=10). 2STD, marker indicating measures two standard deviations away from the mean measure; m, male; 1STD, marker indicating measures one standard deviation away from the mean measure; f, female.

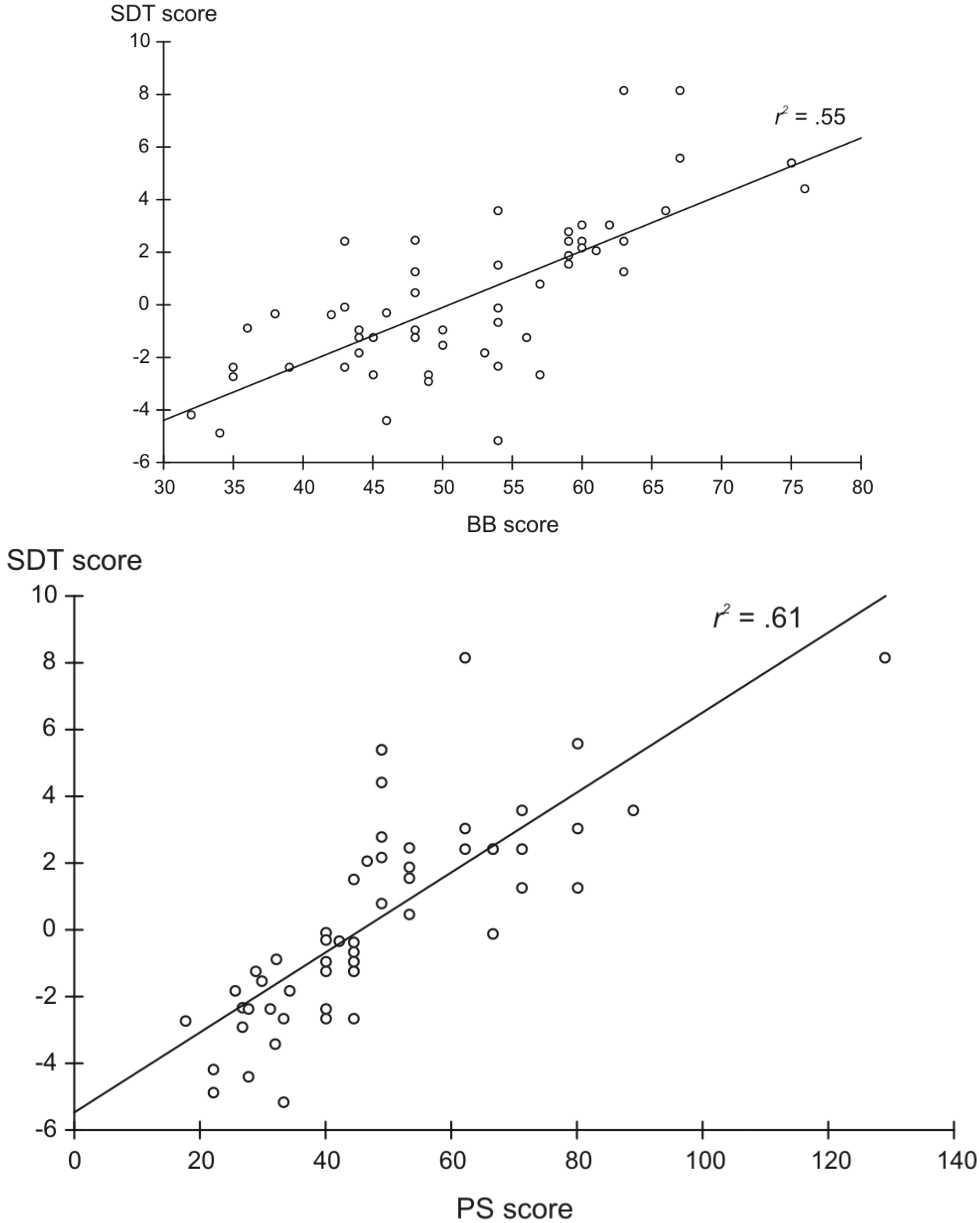


**Figure 3.**

Scatter plots and regression lines of Strength–Dexterity Test participant ability measures (SDT score) versus Box and Blocks scores (BB score) (a), and pinch strength scores (PS score) (b). Both correlations were significant ($p$<0.001).

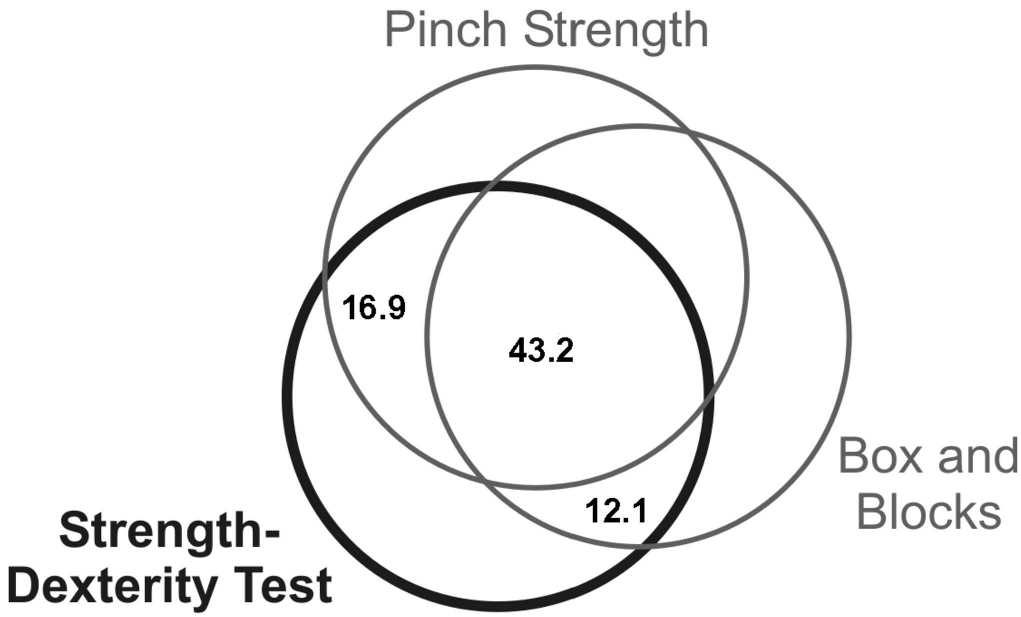


**Figure 4.**
Schematic Venn diagram illustrating the unique and shared contributions of the pinch strength and Box and Blocks Tests to variance in the Strength–Dexterity Test, as calculated from the 55 participants who completed all tests. Each circle represents the total variance of a test. Overlapping regions represent shared variances. The numbers in each sub-region indicate the percentage of the total Strength–Dexterity Test variance accounted for by that partition. The unique contribution of pinch strength was 16.9%, and 12.1% for the Box and Blocks Test. Shared variance between pinch strength and Box and Blocks test was 43.2%. The variance unique to the Strength–Dexterity Test was 27.8%.

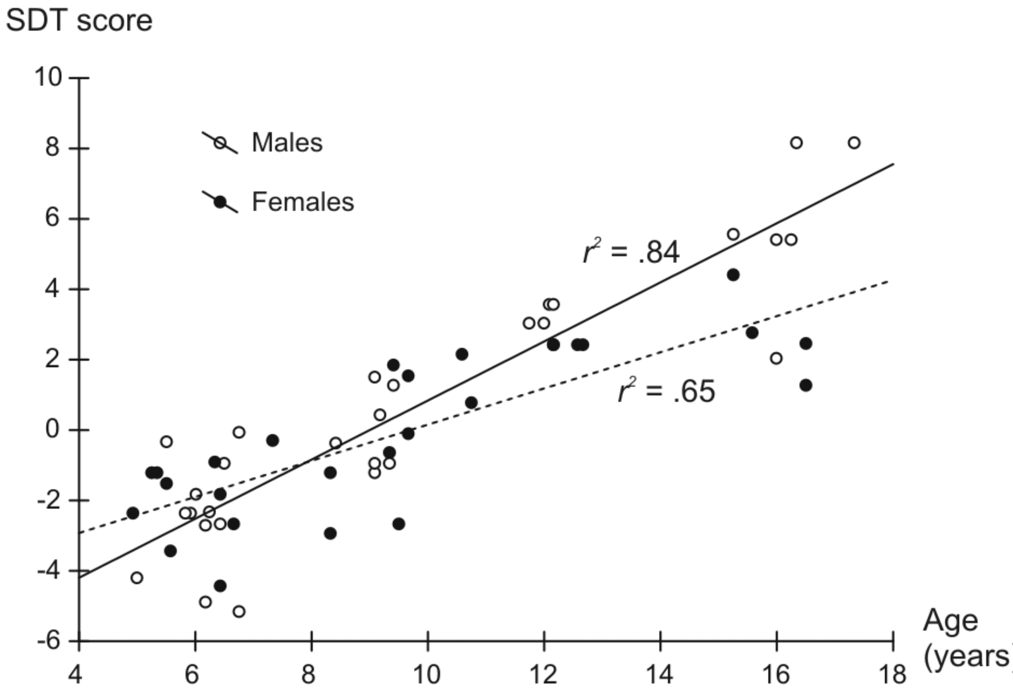


**Figure 5.**
Scatter plots and regression lines of Strength–Dexterity Test (SDT) participant ability measures versus age, plotted separately for males and females. There was no difference in mean performance of the Strength–Dexterity Test between males and females, but the increase in Strength–Dexterity Test performance with age demonstrated a significantly steeper slope in male children (see Results section).

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**Table I**

Strength–Dexterity test, measurement report, and fit indices for 78 items

| Measure | Standard error | Infit | | Outfit | | Item hierarchy |
|---|---|---|---|---|---|---|
| | | MnSq | *z*-score | MnSq | *z*-score | |
| 8.56 | 1.23 | 2.00 | 1.4 | 9.90 | 9.9 | H6 |
| 6.80 | 1.22 | 0.21 | −1.2 | 0.07 | −0.8 | B13 |
| 6.80 | 1.22 | 0.21 | −1.2 | 0.07 | −0.8 | C13 |
| 6.80 | 1.22 | 0.21 | −1.2 | 0.07 | −0.8 | D13 |
| 6.42 | 0.87 | 1.82 | 1.3 | 9.90 | 6.5 | H2 |
| 6.35 | 1.40 | 0.10 | −1.0 | 0.05 | −0.9 | F13 |
| 5.75 | 0.76 | 1.00 | 0.2 | 0.32 | 2.7 | H4 |
| 5.62 | 0.99 | 1.27 | 0.6 | 8.48 | 2.7 | B12 |
| 5.62 | 0.99 | 0.32 | −1.0 | 0.10 | −0.7 | C12 |
| 5.49 | 1.03 | 1.14 | 0.4 | 0.60 | 0.1 | E13 |
| 4.80 | 0.82 | 0.56 | −0.7 | 0.26 | −0.6 | F12 |
| 4.77 | 0.64 | 0.51 | −1.3 | 0.18 | −0.5 | E11 |
| 4.39 | 0.59 | 0.75 | −0.6 | 0.59 | 0.1 | C11 |
| 4.39 | 0.59 | 0.91 | −0.1 | 0.47 | −0.1 | F11 |
| 4.07 | 0.56 | 2.57 | 3.3 | 5.98 | 2.5 | H3 |
| 4.07 | 0.56 | 0.77 | −0.6 | 0.46 | −0.1 | F10 |
| 3.76 | 0.53 | 0.89 | −0.3 | 0.42 | −0.3 | D11 |
| 3.49 | 0.51 | 0.71 | −1.0 | 0.34 | −0.5 | B11 |
| 3.38 | 0.60 | 1.12 | 0.5 | 1.00 | 0.4 | D12 |
| 3.04 | 0.57 | 0.73 | −1.1 | 0.58 | 0.1 | E12 |
| 1.90 | 0.45 | 0.79 | −0.9 | 1.14 | 0.4 | G10 |
| 1.26 | 0.43 | 1.38 | 1.5 | 1.72 | 1.0 | G9 |
| 1.26 | 0.43 | 0.62 | −1.7 | 0.37 | −1.0 | B10 |
| 1.26 | 0.43 | 0.71 | −1.2 | 0.40 | −0.9 | D10 |
| 1.01 | 0.44 | 0.75 | −1.0 | 0.44 | −0.8 | E10 |
| 0.73 | 0.42 | 0.68 | −1.3 | 0. 35 | −0.9 | G6 |
| 0.71 | 0.42 | 0.39 | −3.1 | 0.23 | −1.5 | C10 |

| Measure | Standard error | Infit | | Outfit | | Item hierarchy |
|---|---|---|---|---|---|---|
| | | MnSq | *z*-score | MnSq | *z*-score | |
| 0.56 | 0.42 | 1.46 | 1.7 | 1.70 | 1.0 | H1 |
| 0.55 | 0.42 | 0.75 | −1.0 | 0.70 | −0.2 | B9 |
| −0.13 | 0.41 | 0.49 | −2.7 | 0.27 | −1.2 | D9 |
| −0.60 | 0.40 | 1.04 | 0.2 | 0.70 | −0.2 | G8 |
| −0.78 | 0.40 | 0.87 | −0.6 | 0.56 | −0.5 | E9 |
| −0.78 | 0.40 | 0.87 | −0.6 | 0.60 | −0.4 | F9 |
| −1.69 | 0.40 | 1.07 | 0.4 | 0.60 | −0.4 | G7 |
| −1.70 | 0.40 | 0.72 | −1.6 | 0.52 | −0.5 | D8 |
| −1.75 | 0.41 | 1.26 | 1.3 | 2.14 | 1.4 | C9 |
| −2.73 | 0.44 | 0.86 | −0.6 | 0.58 | −0.2 | E8 |
| −2.73 | 0.44 | 0.85 | −0.6 | 0.39 | −0.5 | F7 |
| −3.14 | 0.46 | 0.82 | −0.7 | 0.34 | −0.5 | B8 |
| −3.36 | 0.48 | 0.87 | −0.4 | 0.36 | −0.4 | A8 |
| −3.36 | 0.48 | 0.81 | −0.6 | 0.74 | 0.1 | C8 |
| −3.36 | 0.48 | 1.21 | 0.8 | 1.60 | 0.8 | G5 |
| −3.88 | 0.53 | 1.74 | 2.0 | 9.90 | 3.8 | F8 |
| −4.18 | 0.57 | 0.88 | −0.2 | 0.31 | −0.6 | A7 |
| −4.53 | 0.62 | 0.72 | −0.7 | 0.58 | −0.1 | B6 |
| −4.96 | 0.68 | 0.50 | −1.2 | 0.10 | −1.3 | D6 |
| −4.96 | 0.68 | 1.09 | 0.3 | 0.31 | −0.6 | F1 |
| −4.96 | 0.68 | 1.72 | 1.5 | 9.90 | 6.9 | G1 |
| −5.50 | 0.80 | 0.76 | −0.3 | 0.12 | −1.1 | C7 |
| −5.50 | 0.80 | 1.08 | 0.3 | 0.79 | 0.1 | D7 |
| −5.50 | 0.80 | 0.76 | −0.3 | 0.12 | −1.1 | E7 |
| −5.50 | 0.80 | 1.08 | 0.3 | 0.79 | 0.1 | F6 |
| −6.34 | 1.07 | 0.85 | 0.1 | 0.09 | −1.0 | B7 |
| −6.34 | 1.07 | 0.75 | 0.0 | 0.07 | −1.1 | C5 |
| −6.34 | 1.07 | 1.05 | 0.3 | 0.17 | −0.8 | C6 |
| −6.34 | 1.07 | 0.85 | 0.1 | 0.09 | −1.0 | E6 |
| −6.34 | 1.07 | 1.23 | 0.5 | 0.73 | 0.1 | F2 |

| Measure | Standard error | Infit | | Outfit | | Item hierarchy |
|---|---|---|---|---|---|---|
| | | MnSq | *z*-score | MnSq | *z*-score | |
| −6.34 | 1.07 | 0.85 | 0.1 | 0.09 | −1.0 | F5 |
| −7.64 | 1.86 | | | | | |
| Minimum estimated measure for items: | | | | | | A6, B4, B5, C3, C4, D1, D2, D3, D4, D5, E1, E2, E3, E4, E5, F3, F4, G2, G3, G4 |

Data from the 56 typically developed participants are included in this Rasch analysis. Items are ordered by decreasing difficulty. MnSq, mean square.

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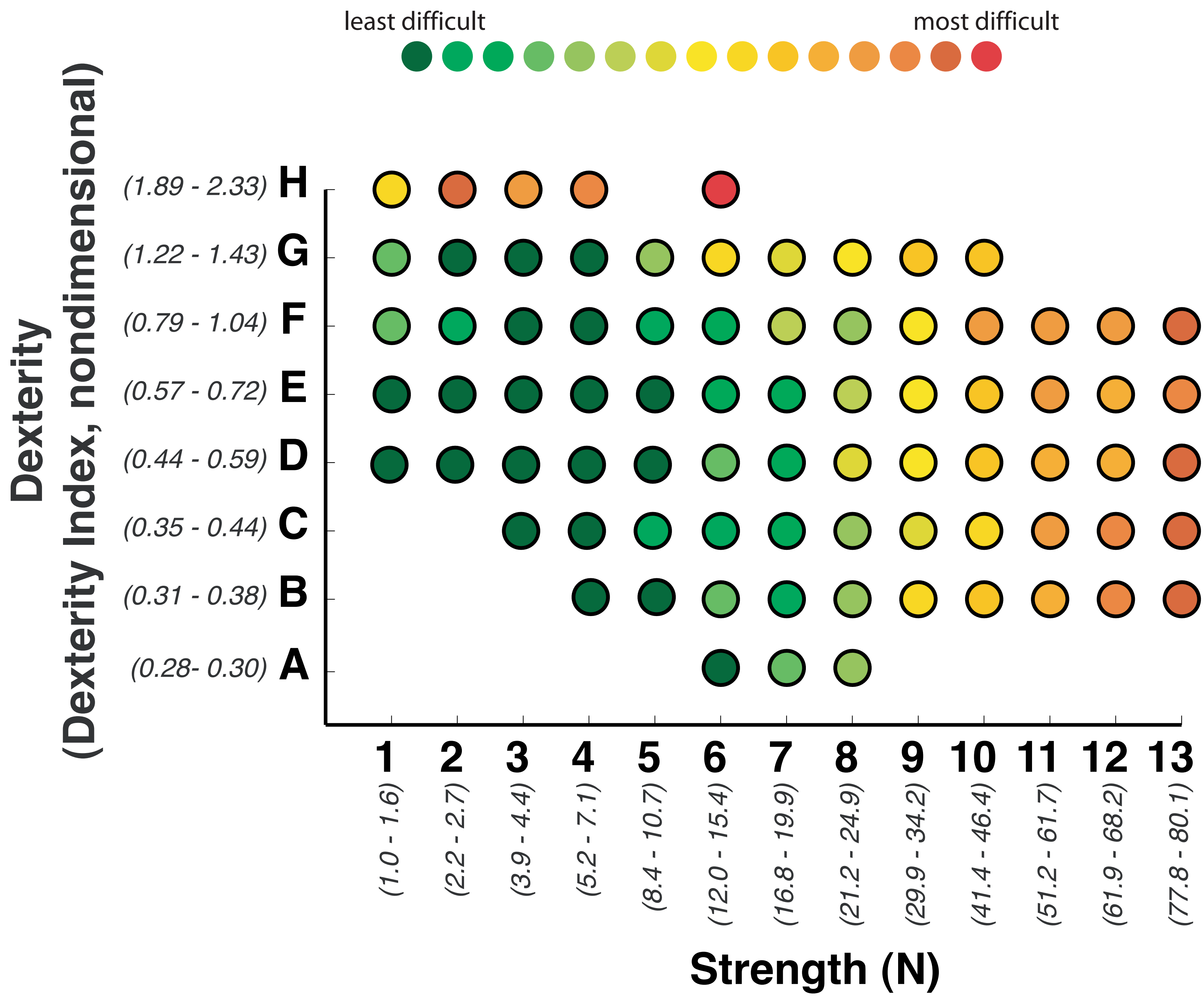
**Table II**

Zero-order correlations (Pearson's *r*) between test results and age

| | Pinch strength | Box and Blocks Test | Strength–Dexterity Test |
|---|---|---|---|
| Age | 0.70 (0.53–0.81) | 0.79 (0.66–0.87) | 0.86 (0.77–0.91) |
| Pinch strength | – | 0.60 (0.40–0.74) | 0.78 (0.65–0.86) |
| Box and Blocks | – | – | 0.74 (0.59–0.84) |

All correlations were significant at $p<0.001$. The correlations are based on all 56 typically developing participants, except for the Box and Blocks Test, which was completed by 55 participants. Confidence intervals (95%) for the *r* values are given in parenthesis.



least difficult
most difficult
Dexterity
(Dexterity Index, nondimensional)
(1.89 - 2.33) H
(1.22 - 1.43) G
(0.79 - 1.04) F
(0.57 - 0.72) E
(0.44 - 0.59) D
(0.35 - 0.44) C
(0.31 - 0.38) B
(0.28- 0.30) A
1 (1.0 - 1.6)
2 (2.2 - 2.7)
3 (3.9 - 4.4)
4 (5.2 - 7.1)
5 (8.4 - 10.7)
6 (12.0 - 15.4)
7 (16.8 - 19.9)
8 (21.2 - 24.9)
9 (29.9 - 34.2)
10 (41.4 - 46.4)
11 (51.2 - 61.7)
12 (61.9 - 68.2)
13 (77.8 - 80.1)
Strength (N)

Based on Table 1, we color-coded the springs in the SD-plane. As shown, the ordering by difficulty follows the expected trend that the more difficult springs lie at the periphery (i.e., higher dexterity and strength values). The most difficult spring is H6, followed by springs of both high strength and high dexterity. It is interesting to note that the Rasch analysis found highly unstable springs (e.g, H2) similarly difficult to highly stiff springs (e.g., B13), hence the interactions between strength and dexterity reported elsewhere in our results. In addition, the median difficult (in light ochre color) agrees well with the core zone bounded by G9 (indicated with dashed lines). We found this core region to be doable by all young adults tested in a prior study[7]. This suggests both that (i) the more able children we tested likely had already achieved the manual ability seen in mature young adults, and (ii) the range of sensitivity of the SD tests shows similar resolution for mature young adults (outside of the core) as it does for younger individuals. Importantly, there is a set of easiest springs (dark green) that are least informative for this TDC population and can likely be omitted without loss of information.