The Cognitive and Mathematical Profiles of Children in Early Elementary School

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Abstract

The present study investigated the diverse cognitive profiles of children learning mathematics in early elementary school. Unlike other types of learning difficulties, mathematics impairments are not characterized by a single underlying cognitive deficit, instead multiple general and numeracy-specific cognitive skills have been proposed to underlie mathematics ability. Combining theory- and data-driven approaches, the study investigated cognitive mathematics profiles. Participants for this study were 97 children tracked from senior kindergarten to grade two, as part of the Count Me In Study. Using numeracy, working memory, receptive language, and phonological awareness factors, a two-step cluster analysis revealed a three-cluster solution. The groups were characterized as (1) above average overall, (2) average overall with weak visuospatial working memory, (3) poor overall with strong visuospatial working memory. Cluster 1 demonstrated strengths in mathematics and reading, compared to clusters 2 and 3. Developmental trends and potential interventions are discussed.

Introduction

What makes some children better at math than others? At the far end of the ability spectrum, there is *specific learning disability – mathematics,* characterized by an individual having significantly lower math performance than their general performance predicts (Mash & Wolfe, 2013). Mathematics disability is characterized by core deficits, enumerating sets, comparing quantities, and other features (Butterworth & Reigosa, 2008). The reading comparison of mathematics disability, *specific learning disability – reading,* is connected to a core deficit in phonological processing. Interventions for reading disability can target this core deficit and improve reading ability (Mash & Wolfe, 2013). There is no agreed upon core deficit in mathematics disability. Instead, several underlying factors have been investigated, suggesting the existence of math disability subtypes (Szucs et al., 2013) and distinct pathways to mathematical success (Lefevre et al., 2010; Sowinski et al., 2015). Theoretical approaches describe mathematics ability with domain-general and domain-specific explanations. Domain-general explanations involve individuals' skill in more general cognitive structures (e.g., visuospatial working memory, working memory). Domain-specific explanations emphasize underlying numeracy abilities (e.g., subitizing and magnitude representation; Butterworth & Reigosa, 2008).

These theoretical frameworks have led to the suggestion of mathematics difficulty subtypes (e.g., Hassinger-Das et al. 2014; Jordan, 2007; McCloskey et al., 1985; Temple, 1997) and the investigation of subtypes through data-driven approaches (Archibald et al., 2013; Bartelet et al., 2014). The present study combined these approaches to explore the cognitive profiles of elementary school children, tracked longitudinally from senior kindergarten (SK) to Grade 2, learning mathematics.

Domain-specific explanations of mathematics difficulty address specific impairments in numeracy abilities proposed to underlie mathematics ability, including subitizing and estimation, and neuroabnormalities in numeracy-dominated brain areas (Davis et al., 2009; Landerl, 2013). In subitizing tasks, individuals enumerate sets of dots as quickly as possible without counting. Typically, children can subitize (enumerate without counting) three or four dots. Children with mathematics impairments typically show greater increases in response time (RT) as the size of the set increases. Children with typical mathematics skill usually display similar RTs for sets of 1-3 dots (Landerl, 2013). Performance on subitizing tasks has been proposed as a key discriminator of math ability (Penner-Wilger et al., 2007). Among children with poor mathematics skill, subitizing slopes are much steeper (Landerl, 2013).

In contrast, domain-general explanations involve processes not specific to mathematics (e.g., executive control, language systems, the visuospatial system, Butterworth & Reigosa, 2008; Szucs, et al., 2013). Examining children with "pure developmental dyscalculia," Szucs et al. (2013) contrasted five theories of developmental dyscalculia (magnitude representation, working memory, inhibition, attention and spatial processing). Using a variety of math-specific and general cognitive measures, the researchers supported deficits in working memory, inhibition, attention, and spatial processing, but did not find support for deficits in magnitude representation – which has been the dominate domain-specific explanation of mathematics difficulty (De Smedt & Gilmore, 2011; Piazza et al., 2010; Rouselle & Noel, 2007). Neuroimaging data supports Szucs et al.'s (2013) assertion (Davis et al., 2009). Using functional magnetic resonance imaging (fMRI), Davis et al. (2009) illustrated neural activation differences in spatial working memory areas, not in magnitude representation areas, among children with mathematics difficulties, compared to matched children. Additionally, Davis et al. (2009) suggests children with mathematics learning difficulties use developmentally immature strategies to solve mathematics problems, compared to their non-impaired peers (as a result of their spatial memory deficits) leading to slower RTs in arithmetic fluency tasks.

Data-driven approaches have used cluster analysis to investigate the cognitive profiles of children with mathematics difficulties. Bartelet et al. (2014) used a variety of math-specific and general cognitive measures and identified six profiles of mathematics difficulty: (1) weak mental number line (poor number line task performance), (2) weak approximate number system (poor non-symbolic performance), (3) spatial difficulties (poor spatial working memory), (4) access deficit (poor symbolic knowledge and counting skills), (5) no numerical cognitive deficit (strong verbal working memory skills without concurrent deficits in numeracy measures), (6) garden variety (many numeracy and general cognitive deficits). These profiles are similar to many of the subtypes suggested by theory-driven research. Archibald, et al. (2013) investigated the cognitive profiles of children with language, reading, and math learning difficulties using a large epidemiological sample. Children were given a battery of standardized tests measuring language, reading fluency, phonological awareness, general intelligence, working memory, and arithmetic ability. Archibald et al., (2013)'s profiles were characterized by: (1) below average across most measures, (2) below average sentence recall (3) below average reading efficacy, (4) below average math and reading, (5) below average math fluency, (6) and above average overall. The math impairment group displayed high performances in general intelligence, despite arithmetic weaknesses. Since Archibald et al. (2013) did not include wider range of general (e.g., processing speed, nonverbal reasoning) and math-specific (e.g., subitizing, estimation) variables, these numeracy and cognitive skills within these profiles cannot be evaluated. However, Archibald et al. (2013) identified comorbidity between reading and mathematics difficulty, and the absence of comorbidity between mathematics difficulty and specific language impairments, suggesting the possible contribution of low reading skill to mathematics difficulty.

Investigating children of all math performance levels, LeFevre et al. (2010) tested a model of associations between early cognitive precursors, numeracy skill, and math outcomes. This model identifies three pathways that precede math ability: quantitative (numeracy), linguistic (receptive vocabulary and phonological awareness), and spatial attention (visuospatial working memory). These pathways contribute independently to numeracy skills during the early years of formal education and are differently related to performance on many math outcome measures. Each of the pathways were related to performance on numeration and calculation ability, as well as symbolic number line estimation, but the spatial pathway was not involved in magnitude comparison. Least surprisingly, the linguistic pathway was the only pathway to account for variability in word reading, but more surprisingly, it was the only pathway to be involved in all mathematics outcomes. This research indicates the diversity present in math performance and suggests that an individual may compensate for weaknesses in one area of performance with strengths in other pathways. This research also highlights the importance of considering the role of linguistic skill in math performance, as indicated by the relation of the linguistic pathway to each of the math outcomes.

Recently, Sowinski et al. (2015) revised the Pathways Model (LeFevre et al., 2010) by considering more quantitative measures. In the refined model, only the quantitative and linguistic pathways, and not the working memory pathway, accounted for unique variance in calculation and number knowledge, suggesting the contribution of pathways depends on the cognitive task.

Mathematics ability cannot be explained by a singular factor. Rather, independent pathways to mathematics success exist along with distinct profiles of mathematics ability characterized by a range of deficits in numeracy and general cognitive abilities. Building from previous theoretical and data-driven approaches, the present study investigates the cognitive profiles of children by following clusters of children longitudinally from SK to grade two and evaluating their performance on mathematics, reading and general cognitive measures. It is proposed that cognitive profiles will be formed based on SK subitizing, language skills, and visuospatial working memory and that these profiles will have distinct math and reading outcomes in Grades 1 and 2, based on the models tested by Lefevre et al., (2010), additionally, profiles are not expected to differ on processing speed or phonological working memory (e.g., Bartelet et al., 2014).

Methods

Participants

Participants were 97 children (51 male, M = 71.7 months, SD = 3.98 months, range = 18 months) tracked longitudinally over three years from SK to Grade Two. Participants were drawn from the Count Me In project, a large longitudinal study, and were recruited from seven schools in three Canadian cities. Parental consent was attained for all children who participated in the study.

Materials

Screening Variables (Senior Kindergarten)

Subitizing. Children's ability to enumerate sets without counting was measured using a subitizing task. In this task, 1-6 dots are displayed on a computer screen. Three trials were presented for each dot array, for a total of 18 trials. The dots for each trial were displayed in pseudo-random arrangements. Subitizing slopes were computed using the median RTs for 1-3 dots and the best fitting regression line was calculated for each child. This RT slope was used as the measure of subitizing. A higher slope suggests the child is counting the three dot display while a lower slope suggests that the child is subitizing the dot display.

Visuospatial Working Memory. A computerized variant of the Corsi Block task was used to measure of visual-spatial working memory. In this task, children viewed a frog jumping in sequence from one lily pad to another and included nine lily pads dispersed on the laptop screen (DeStefano & LeFevre, 2003; α_c = .699, N = 191). Children completed one practice trial and 12 experimental trials, with the length of the span ranging from 2 to 7. The task was stopped when the child made two consecutive errors. Children's maximum span was used as the measure of visuospatial working memory.

Phonological Awareness. Phonological awareness was measured using the Elision subtest of the Comprehensive Test of Phonological Processing (CTOPP; Wagner, Torgesen, Rashotte, 1999). Children heard a word and were asked to say the word again, but omit a sound (e.g., brat without the / r /). Children's Elision grade standardized scores from SK (*M* = 10, *SD* = 3) were used as the measure of phonological awareness.

Receptive Language. The Peabody Picture Vocabulary Test – Revised – Form B (PPVT; Dunn & Dunn, 1997) was used to measure receptive language. Children were shown a set of four pictures and chose the picture that corresponded with a verbally presented vocabulary word. The words increased in relative difficulty as the test progressed. The task was terminated after the child made six errors in eight consecutive questions. Due to the high performance level of the children participating in Count Me In, the starting set for the PPVT was raised to one set higher than suggested by Dunn and Dunn (1997). PPVT SK scores, standardized by grade (*M* = 100, *SD* = 15), were used as the measure of receptive language.

Evaluation Variables (Grades 1 & 2)

Mathematics Achievement (KeyMath Numeration). The Numeration subtest of the KeyMath Test-Revised (Connolly, 2000) covers concepts including quantity, order, and place value. Raw Numeration scores from Grade 1 and 2 were used as measures of mathematical achievement.

Mathematics Achievement (Woodcock-Johnson Calculation). The Calculation subtest of the Woodcock-Johnson Tests of Achievement (WJ-Math; Woodcock & Johnson, 1989) covers mathematical problems that increase in difficulty from basic addition (i.e., 1 + 1) to matrix algebra. The test was stopped once the child made six sequential errors or believed that they could not answer any more questions. Children's Grade 1 and 2 raw scores were used as measures of mathematical achievement.

Arithmetic Fluency. Children's arithmetic fluency was measured in a single digit addition task. Children were instructed to sum single digit addends as quickly as possible without making many errors. Children's Grade 1 and 2 median RT were used as measures of arithmetic fluency.

Reading Skill. The Word Identification subtest of the Woodcock Reading Mastery Test – Revised/ Normative Update, Form G (WJ-Reading; Woodcock, 1998) was used to assess reading skill. Children were shown a set of words (e.g., cat) and were asked to read each word. The words increased in relative difficulty as the test progressed. The test was terminated when the child made six consecutive errors, including errors of pronunciation. Children's Grade 1 Word Identification Scores (*M* = 100, *SD* = 15) were used as the measure of reading skill. Reading measures were not collected in Grade 2.

Nonverbal Reasoning. The analogy subtest of the Cognitive Intelligence Test (CIT; Gardner, 1990) was used to assess children's nonverbal reasoning. Children were presented with a pattern of blocks with one missing block. Children were asked to select the correct response from a set of possible solutions arranged across the bottom of the page. The task was stopped after six consecutive errors. Using the KR-20, the total reliability of the CIT was determined to be .90. Children's standardized Grade 2 scores were used as the measure of nonverbal reasoning. Non-verbal reasoning measures were not collected in Grade 1.

Phonological Working Memory. Children completed a reverse digit-span task as a measure of working memory. Children were asked to recall a series of spoken digits presented by an on-screen dog character. Children repeated the numbers in the reverse order to which they were presented (14 trials; Orsini et al., 1987). Children must hold and manipulate the numbers, rather than simply storing the numbers in this task. Digit lengths started at two and increased in length until the child was inaccurate for both trials of a certain length. Participants' Grade 1 maximum reverse span was used as the measure of phonological working memory. Phonological working memory measures were not collected in Grade 2.

Processing Speed. Children completed a simple choice reaction time task as a measure of processing speed. Children were presented with one of two types of stimuli (X or O). Children then had to press the appropriate key as quickly as possible without making an error. Children completed 24 trials in one minute. Children's mean RT from SK to Grade 2 was used as the measure of processing speed.

Procedure

In May of each year (Kindergarten – Grade 2), children were tested by trained research assistants. Computer tasks and pencil-and-paper tasks were given in two separate sessions lasting between 15 and 30 minutes, with sessions extended as necessary. The order of tasks was consistent each year. In the first session, children completed the subitizing, arithmetic fluency, Corsi, processing speed, and digit span measures. During the second session, children completed the CIT, KeyMath, WJ-Math, PPVT, CTOPP, and WJ-Reading measures. Each year, children were engaged in approximately one hour of testing time.

Results

Cluster Analysis

Four screening variables (subitizing, visuospatial working memory, phonological awareness, and receptive language) were entered into a two-step cluster analysis, with the log-likelihood as the distancing measure and Schwarz's Bayesian Criterion (BIC) as the clustering criterion. The two-type cluster analysis revealed a three-factor solution with an average silhouette statistic of 0.4. Descriptive statistics for the clusters are reported in Table 1. The clusters were characterized by (1) above average overall, (2) average overall with weak visuospatial working memory, (3) poor overall with strong visuospatial working memory. More specifically, cluster one displayed average subitizing (approximately at median), very strong visuospatial working memory (cluster mean at 75th percentile of sample), very strong phonological awareness (cluster mean at 75th percentile of sample), and strong receptive language. Cluster two showed very weak visuospatial working memory (cluster mean at 25th percentile of sample), average phonological awareness (cluster mean at sample median), slightly below average receptive language, and average subitizing. Cluster three was characterized by very strong visuospatial working memory (cluster mean at 75th percentile of sample), very weak phonological processing (cluster mean below the 25th percentile of sample), very weak receptive language (cluster mean below the 25th percentile of sample), and slightly below average subitizing.

Analysis of Mathematical Outcomes

To assess the longitudinal mathematical outcomes of the different clusters, a 2(Grade: one, two) x 3(cluster membership: one, two, three) mixed factorial ANOVA was performed with KeyMath, WJ-Math, addition fluency as dependent variables.

For KeyMath Numeration, there was a main effect of grade; children correctly answered more questions in grade two (M = 13.9, SD = .33) than they did in grade one (M = 10.8, SD = .32), $F(1,85) = 99.25$, $p < .001$, $\eta^2 = .54$, power = 1.0. Additionally, there was a main effect of cluster membership, $F(2,85) = 9.09$, $p < .001$, $\eta^2 = .18$, power = .97. Using Tukey's HSD, post-hoc analyses revealed that children in cluster one performed better on the KeyMath (M = 13.9, SD = .38) than children in cluster 2 (M = 12.2, SD = .43, $t(74) = 2.38$, $p = .008$) or those in cluster 3 (M = 11.1, SD = .65, $t(56) = 3.24$, $p = .001$.

Table 1: Descriptive statistics for clusters

Cluster	1	2	3
N (male)	45 (25)	35 (18)	17 (8)
Age (SD)	71.6 (3.88)	71.8 (3.91)	72.0 (4.56)
Subitizing Slope	162	194	290
VSWM (SD)	4.2 (.61)	2.6 (.49)	3.94 (.83)
PA (SD)	12.5 (2.36)	10.4 (1.77)	8.0 (1.23)
RL (SD)	114.7 (2.36)	111.0 (8.6)	97.9 (9.9)
Descriptor	Above average overall	Average, weak VSWM	Below average, strong VSWM

For Woodcock-Johnson Calculation, there was a main effect of grade; children correctly answered more questions in grade two (M = 11.7, SD = .30) than they did in grade one (M = 8.0, SD = .28), $F(1,85) = 128.09$, $p < .001$, $\eta^2 = .60$, power = 1.0. There was also a main effect of cluster membership, $F(2,85) = 13.63$, $p < .001$, $\eta^2 = .24$, power = 1.0. Tukey's HSD post-hoc test revealed that children in cluster 1 correctly solved more questions (M = 11.4, SD = .31) than those in cluster 2 (M = 9.1, SD = .36, $t(74) = 3.21$, $p < .001$) or those in cluster 3 (M = 9.1, SD = 54., $t(56) = 2.92$, $p = .002$).

For addition fluency, a main effect of grade was observed. When in grade two, children were faster to solve small addition problems (M = 2347 ms , SD = 75.6 ms) than when in grade one (M = 4138 ms , SD = 182.4 ms), $F(1,85) = 125.96$, $p < .001$, $\eta^2 = .60$, power = 1.0. Additionally, there was a main effect of cluster membership, $F(2,85) = 8.73$, $p < .001$, $\eta^2 = .17$, power = .97. Tukey's HSD post-hoc test revealed children in cluster one were faster (M = 2646 ms , SD = 148.6 ms) than children in cluster two (M = 3364 ms, SD = 170.2 ms, $t(74) = 3.21$, $p < .001$) or those in cluster three, (M = 3719.3, SD = 257.4, $t(56) = 3.25$, $p < .001$). Third, a quantitative interaction between cluster membership and grade was observed, $F(2,85) = 7.50$, $p = .001$, $\eta^2 = .15$, power = .94. As illustrated in Figure 1, although slower in grade one than their cluster 2 peers, children in cluster 3 reached the same level of addition fluency in grade 2 as there their cluster 2 peers. However, children in clusters 2 and 3 did not reach the addition fluency levels of their cluster 1 peers in grade two.

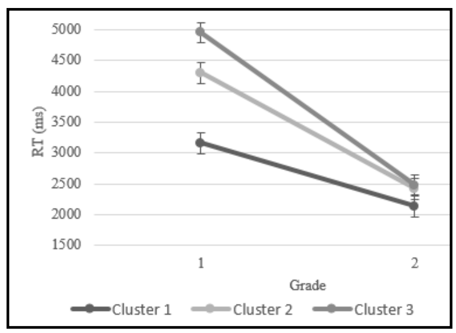

Figure 1: Interaction between cluster and grade for addition fluency.

Analysis of Reading Outcomes

To assess the reading outcomes of the different clusters, a one-way between subjects ANOVA was performed with Grade 1 standardized Woodcock-Johnson Word Identification scores as the dependent variable. Reading scores were not available for Grade 2. There was a main effect of cluster membership, $F(2,86) = 7.90$, $p = .001$. Using Tukey's HSD, post-hoc analyses revealed that children in cluster one had stronger reading skills (M = 124.2, SD = 12.02) than cluster two (M = 117.6, SD = 12.01, $t(74) = 1.67$, $p = .048$) or cluster three (M = 110.4, SD = 12.70, $t(56) = 3.25$, $p = .001$).

Analysis of General Cognitive Outcomes

To determine if the clusters differ on more general cognitive outcomes, two separate one-way between subjects ANOVAs were conducted with nonverbal reasoning and phonological working memory as dependent variables. Additionally, a 3(grade: SK, one, two) x 3(cluster membership: one, two, three) mixed factorial ANOVA was used to assess potential differences in processing speed.

The clusters were found to differ in their nonverbal reasoning ability, $F(2,94) = 4.62$, $p = .012$. In post-hoc analysis, Tukey's HSD revealed that children in cluster one had stronger nonverbal reasoning skills ($M = 106.8$, $SD = 12.52$) than cluster two ($M = 97.9$, $SD = 14.24$, $t(80) = 1.99$, $p = .013$), but not stronger than cluster three ($M = 99.4$, $SD = 14.77$, $t(62) = 1.67$, *ns*). The clusters were not found to differ in their phonological working memory, $F(75) = .45$, *ns*.

In the mixed design factorial ANOVA, a main effect of grade was observed for processing speed, $F(2,85) = 26.20$, $p < .001$, $\eta^2 = .24$, power = 1.0. Tests of within-subjects contrasts revealed a linear trend, indicating that children's processing speed decreased as they moved into older grades, $F(1,84) = 56.45$, $p < .001$, $\eta^2 = .40$, power = 1.0. There was no main effect of cluster membership, indicating that processing speed did not differ by cluster, $F(2,84) = 1.12$, *ns*, $\eta^2 = .03$, power = .24. Nor was there an observed interaction, $F(4,83) = .79$, *ns*, $\eta^2 = .02$, power = .25.

Discussion

The present study investigated cognitive profiles of children in kindergarten, formed using cluster analysis based on subitizing, visuospatial working memory, phonological awareness and receptive language, and the associated learning outcomes for the different cluster groups in Grade 1 and 2. The clusters were characterized as (1) above average overall, (2) average overall with weak visuospatial working memory, and (3) poor overall with strong visuospatial working memory. Across a variety of outcome measures, children in cluster one outperformed their peers, longitudinally in both Grade 1 and 2. These children displayed strong math scores (arithmetic ability, arithmetic fluency, numeration and calculation skills), and stronger reading skills than their peers in clusters two and three. Encouragingly, these children represented the largest portion of the sample (47%). However, over half the sample, underperformed in comparison to cluster one. Children in these clusters present with distinct cognitive profiles with unique strengths and weakness. Successful interventions may draw on the strengths of these children, to compensate for their weaknesses and to improve their achievement outcomes.

Longitudinal trends for arithmetic ability and fluency indicate that children in cluster one maintained their advantage over the next two years. In the present study, children in clusters two and three did not compensate for their early performance deficits as formal education continued. In arithmetic fluency, children in cluster three, who were slower to accurately complete addition problems in grade one than their peers, reached the performance level of their cluster two peers by grade two. Despite these rapid performance increases, neither children in cluster two nor in cluster three reached the performance level of children in cluster one. In this study and in other work (Aunola et al., 2004), we see evidence that children who start school with poor numeracy skills do not catch up to their peers as formal education progresses. Therefore, there is a need for early identification of at-risk children and interventions targeted to children's pattern of strengths and weaknesses to increase performance outcomes.

Children in cluster two showed weakness in their visuospatial working memory, but average phonological processing, receptive language, and subitizing. Leferve et al. (2010)'s Pathways Model would suggest that the strengths in the linguistic and quantitative pathways can be targeted to maximize the success of these students. Conversely, children in cluster three, who displayed weaknesses in in phonological awareness and receptive language, but strong visuospatial working memory systems might benefit from interventions targeted to utilize their visuospatial competence. Interventions targeted toward children's strength may offer greater likelihoods of success (Gary et al., 2012).

It is possible that the differences in cognitive profiles observed in the present study and in previous work (e.g. Archibald et al., 2013, Bartelet et al., 2014) are due to underlying differences in processing speed or general working memory capacity. However, no differences in processing speed or phonological working memory were seen between the clusters, suggesting it is visuospatial working memory, specifically, and subitizing abilities that underlie math ability, rather than broader processes involving pure speed or general working memory resources.

Some researchers suggest that differences in mathematical ability stem from core differences in magnitude comparison (De Smedt & Gilmore, 2011, Piazza et al., 2010; Rouselle & Noel, 2007), others suggest differences in visuospatial working memory better account for differences in math ability (Davis et al., 2009; Szucs et al., 2013). Unfortunately, our study did not include a magnitude comparison task during SK, however our study does indicate the importance of the visuospatial system, along with quantitative and linguistic skills in math performance.

The results of the current study suggest (1) early identification measures to determine which students are at risk for math difficulties and (2) cluster-based interventions that target children's strengths as a means to improve their math outcomes. Our lab is currently designing such interventions.

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