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Mathematics Ability and Related Skills in Preschoolers Born Very Preterm




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ARTICLE



# Mathematics ability and related skills in preschoolers born very preterm

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**ABSTRACT**

Children born very preterm (VPT) are at risk for academic, behavioral, and/or emotional problems. Mathematics is a particular weakness and better understanding of the relationship between preterm birth and early mathematics ability is needed, particularly as early as possible to aid in early intervention. Preschoolers born VPT ($n$ = 58) and those born full term (FT; $n$ = 29) were administered a large battery of measures within 6 months of beginning kindergarten. A multiple-mediation model was utilized to characterize the difference in skills underlying mathematics ability between groups. Children born VPT performed significantly worse than FT-born children on a measure of mathematics ability as well as full-scale IQ, verbal skills, visual–motor integration, phonological awareness, phonological working memory, motor skills, and executive functioning. Mathematics was significantly correlated with verbal skills, visual–motor integration, phonological processing, and motor skills across both groups. When entered into the mediation model, verbal skills, visual–motor integration, and phonological awareness were significant mediators of the group differences. This analysis provides insights into the pre-academic skills that are weak in preschoolers born VPT and their relationship to mathematics. It is important to identify children who will have difficulties as early as possible, particularly for VPT children who are at higher risk for academic difficulties. Therefore, this model may be used in evaluating VPT children for emerging difficulties as well as an indicator that if other weaknesses are found, an assessment of mathematics should be conducted.

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Very preterm birth; mathematics; preschool; test of early mathematics ability; academic skills; child neuropsychology



In the United States, about 1 in 10 babies are born preterm and rates continue to increase each year. Preterm birth, gestational age (GA) of less than 37 weeks, has been correlated with an increased risk of serious health issues. Due to advances in medical care, neonatal survival rates continue to improve (Martin, Hamilton, & Osterman, 2016) and more severe forms of birth defects (e.g., cerebral palsy or periventricular leukomalacia grade IV) occur less frequently. Yet, even children without severe brain damage are more likely to have developmental, behavioral, and/or learning problems as they grow (Anderson, 2014).

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Children born very preterm (VPT; GA less than 33 weeks) are at increased risk for academic difficulties, and even children without low IQs are more likely than their full-term (FT)-born peers to have specific learning disabilities or underachievement in reading, spelling, and/or mathematics (Aarnoudse-Moens, Weisglas-Kuperus, van Goudoever, & Oosterlaan, 2009; Litt, Taylor, Klein, & Hack, 2005). Previous studies with independent samples have shown mathematics to be a particular weakness (Akshoomoff et al., 2017; Taylor, Espy, & Anderson, 2009; Taylor, Klein, Drotar, Schluchter, & Hack, 2006). Preschool is an important period in a child's development and early identification of academic weaknesses and targeted intervention are essential to improving outcomes. This is particularly relevant for children born VPT who are at increased risk of having difficulties.

A few studies have examined mathematics skills in preschoolers and young school-age children born VPT. One study found that VPT-born children as early as preschool age performed significantly worse than their term-born peers on school-based measures of mathematics (Aarnoudse-Moens, Oosterlaan, Duivenvoorden, van Goudoever, & Weisglas-Kuperus, 2011) and another study found prominent lags across multiple measures of mathematics at age 6 (Pritchard et al., 2009). Academic weaknesses, particularly in mathematics, were found in kindergarten among children born extremely preterm (Taylor et al., 2011). Scores on the Test of Early Mathematics Ability – Third Edition (TEMA-3) (Ginsburg & Baroody, 2003) were highly correlated with neonatal risk factors (i.e., preterm birth and/or low birth weight) in a large, longitudinal cohort that was tested as they were entering kindergarten as part of a prospective study of the effects of early health indicators on development (Kull & Coley, 2015).

In order to better understand the nature of mathematics difficulties in children who were born VPT, it is imperative to examine the large set of skills that have been shown are related to success in mathematics in typical development (Geary & Moore, 2016). In FT-born, typically developing children, mathematics has been shown to depend on a variety of skills including verbal and visual working memory, visual–spatial skills, fine motor skills, attention, inhibitory control, processing speed, visual–motor integration, visual memory, and phonological awareness (Barnes & Raghubar, 2014; De Smedt, Taylor, Archibald, & Ansari, 2010; Geary, 2004, 2011; Mayes, Calhoun, Bixler, & Zimmerman, 2009; Szucs, Devine, Soltesz, Nobes, & Gabriel, 2014). Mathematics and reading have shown to be strongly correlated in school-age children (Ashkenazi, Rubinsten, & De Smedt, 2017). This relationship may in part reflect the involvement of common skills such as phonological processing, verbal comprehension, and working memory (Jordan, Wylie, & Mulhern, 2010; Szucs et al., 2014; Willcutt et al., 2013). The relationship between verbal skills (i.e., phonological awareness and verbal comprehension) and mathematics specifically is likely due to the language system being used for representing and manipulating information, such as articulating number words (Geary, 2004). In addition, fine motor skills and attention in kindergarten have been shown to predict later achievement in mathematics (Grissmer, Grimm, Aiyer, Murrah, & Steele, 2010).

The relationship between many of the same cognitive skills and mathematics has been examined across several studies in school-age children born VPT. In early elementary school-age children born extremely preterm, general intelligence, reading skills, and visuospatial skills were shown to predict scores on the Wechsler Individual

Achievement Test in mathematics (Simms et al., 2013). Studies have shown that VPT-born children are often weaker than their FT-born peers in vocabulary and language functioning (van Noort-van der Spek, Franken, & Weisglas-Kuperus, 2012). Johnson, Wolke, Hennessy, and Marlow (2011) found that letter knowledge and performance on a phoneme deletion task at 6 years of age predicted mathematics scores for extremely preterm-born 11-year-old children. Motor and visual-motor integration skills are also weaknesses in children born VPT (Mayes et al., 2009; Zhang, Mahoney, & Pinto-Martin, 2013). Motor skills were found to be related to mathematics achievement in a group of 6-year-old children born extremely preterm (Marlow, Hennessy, Bracewell, Wolke, & Group, 2007) and in a group of 8-year-old children born VPT (Wocadlo & Rieger, 2008), even in the absence of cerebral palsy. Mathematics underperformance in VPT-born children has been related to visuospatial processing and working memory (Simms et al., 2015). Executive functions have been shown to be affected in VPT-born school-aged children (Bayless & Stevenson, 2007) and are also related to children's success in school (Cameron et al., 2012).

Specifically, in preschoolers born FT, many of these same skills are related to mathematics. Preschool mathematics performance has been shown to be related to visuospatial abilities (Verdine, Golinkoff, Hirsh-Pasek, & Newcombe, 2017), visual working memory (Toll, Kroesbergen, & Van Luit, 2016), phonological awareness (Krajewski & Schneider, 2009), and reading comprehension (Grimm, 2008). Executive function also plays a prominent role in preschoolers' mathematics ability and predicts their mathematics achievement (Clark et al., 2014; Purpura, Schmitt, & Ganley, 2017). Working memory and behavioral self-regulation have been shown to be related to visual-motor integration in early school-aged children, which in turn also predicts later performance on measures of mathematics, word reading, and receptive vocabulary (Becker, Miao, Duncan, & McClelland, 2014; Mayes et al., 2009). One study demonstrated that teacher-rated executive function, using the Behavior Rating of Executive Functioning – Preschool version (BRIEF-P), predicted mathematics achievement above and beyond reading and general intelligence (Clark, Pritchard, & Woodward, 2010). Though previous studies have examined the relationship between mathematics and other skills in preschoolers, there are few studies that investigate these same relationships in preschoolers who were born VPT.

The purpose of this study was to examine mathematics skills in preschoolers born VPT and a cohort of term-born peers. We were also interested in assessing the skills that are known to contribute to development of mathematics skills and to explore if and how these skills predict weakness in early mathematics in children born VPT. To accomplish this goal, we utilized a multiple mediation model, a method that has previously been shown to be useful when investigating the relationship between mathematics and other skills in children with a disorder that affects mathematics (Raghubar et al., 2015). This model included measures previously shown to be related to mathematics in preschoolers and school-age children, as well as those shown to be weaker in children who were born VPT. The multiple mediation technique allows for evaluation of the skills measured by each instrument as a model of the differences in mathematics performance between VPT and FT-born children. A multiple mediation model also allows for the establishment of a profile of skill weaknesses related to mathematics in children born VPT. This profile allows for higher sensitivity in detecting children who

may have difficulties. As evidenced by the wide range of measures and skills that have been included in previous studies, it is clear that there are multiple domains that contribute to mathematics. By including multiple related domains in one model, we are able to form a more complete picture of the skills that contribute to weaknesses in mathematics ability seen in children born VPT. In addition, we are in the unique position to help create criteria that might identify VPT-born children who will not perform as well as their peers in school.

## Method

### *Participants*

The data in this study were collected as part on an ongoing, longitudinal investigation of neurocognitive development of children born VPT as they begin formal schooling. VPT born ($n$ = 58) as well as FT-born ($n$ = 29) participants were recruited into the study within 6 months of starting kindergarten, which typically requires the child to be 5 years of age by September of the year they will begin school. The full longitudinal study will include a large battery of measures as well as neuroimaging to be completed at two additional timepoints between school years (i.e., after kindergarten and after first grade). It is expected that data collection will be complete in the fall of 2018. Children born FT were recruited via the University of California, San Diego (UCSD) Center for Human Development (CHD) database of parents who consented, through an internet contact form or flyers and representatives at community events, to be contacted regarding studies conducted by the CHD. Children in the VPT group (born 24–32 weeks GA) were recruited primarily from the UCSD High-Risk Infant Follow-up Clinic. Children with a history of severe brain injury (e.g., Grade 3–4 intraventricular hemorrhage, cystic periventricular leukomalacia, moderate–severe ventricular dilation), evidence of significant disability (e.g., moderate–severe cerebral palsy, bilateral blindness, bilateral deafness), chromosomal or genetic abnormalities likely to affect development, or any neurological disorder not related to preterm birth (e.g., closed head injury) were excluded from the study. FT children were included if they were born at 38 or more weeks GA and had no history of neurological, psychiatric, or developmental disorders. All participants in the study were required to be primarily English speaking and without a known history of in utero maternal substance abuse. All children were screened for significant hearing and vision difficulties. Children with a known history of significant anxiety that might interfere with study tasks, or metallic implants that are contraindicated for magnetic resonance imaging (MRI), were also excluded from the study. Additionally, all children were screened using the Wechsler Preschool and Primary Scale of Intelligence – Fourth Edition (WPPSI-IV), and children with a Verbal Comprehension Index (VCI) below 80 were excluded from the current study. The larger study aims to predict educational outcomes in children who are "healthy preterm," those with a relatively benign neonatal course who are more commonly deemed as performing within the expected range at infant/toddler follow-up. The VCI cutoff criterion was also intended as an additional way to exclude children who

would have difficulty understanding and completing the entire battery of test measures.

The sample includes 12 children who were born "extremely preterm" (24–27 weeks gestation). Previous studies have shown mixed results, with some showing a relationship between GA at birth and academic, cognitive, or behavioral outcomes while others do not show such a relationship (Aarnoudse-Moens et al., 2009; Bhutta, Cleves, Casey, Cradock, & Anand, 2002). In addition, some studies distinguish between children born VPT (28–32 weeks gestation) and children born extremely preterm (24–27 weeks gestation). In the current study, there is no significant correlation between GA and TEMA-3 ($r = -.133$; $p = .321$), full-scale IQ ($r = -.073$; $p = .585$), VCI ($r = -.106$; $p = .427$), VMI ($r = -.066$; $p = .622$), CTOPP-Elision ($r = .054$; $p = .688$), CTOPP-NWR ($r = .110$; $p = .409$), or BRIEF GEC ($r = -.154$; $p = .249$). Therefore, the 12 children born extremely preterm were included in the VPT group.

The Human Research Protections Programs and Institutional Review Board at the UCSD approved all procedures, and each participant's legal guardian gave informed consent. The ongoing study will track these children each year for a total of 3 years. Data continue to be collected, as this is a longitudinal study in progress, the current data represent only children who completed the first year of study visits and had valid data for all of the measures of interest.



## Cognitive and behavioral measures

All children were administered a large, standardized battery of measures intended to characterize their cognitive, behavioral, and academic skills. Children were assessed in a series of four testing sessions, about 2 h each, to minimize possible fatigue. All measures and sessions were completed in a standardized order with exceptions only in rare cases, related to equipment or staff availability. Sessions were scheduled at the family's convenience, with a target of completion of all sessions within 6 weeks. During the assessment, the parent or guardian completed a set of standardized questionnaires regarding the child's current skills and behavior, the child's health history, and demographic information. In the current analysis, a subset of these measures was selected based on previous studies of mathematics.

### TEMA-3

The TEMA-3 is an individually administered, single measure with items capturing formal and informal mathematics. It is designed to measure mathematics ability in children 3–8:11 years of age (Ginsburg & Baroody, 2003). The measure produces a score, the Math Ability Score, which is a standard score, calculated as the sum of all items correctly answered corrected for age.

### WPPSI-IV

The WPPSI-IV is a broad measure of cognitive abilities used in children and includes indices of verbal comprehension, visual spatial abilities, fluid reasoning, working memory, and processing speed (Wechsler, 2012). The primary measure of interest for the current study was the VCI. This index was selected to account for verbal skills typically learned from a child's environment and school, measured by verbal concept formation

and verbal reasoning. Children who are born preterm may have weaknesses in verbal abilities (van Noort-van der Spek et al., 2012), though weaknesses in mathematics have been shown to persist even when controlling for verbal abilities (Taylor et al., 2009). This specific index was chosen to capture children's verbal reasoning skills.

### *Beery-Buktenica Developmental Test of Visual-Motor Integration (VMI)*

The VMI is a pencil and paper task that requires participants to copy line drawings of geometric figures of increasing complexity. This task measures visual-motor integration which requires visual–spatial perception, visual and motor coordination, and fine motor skills (Beery, Buktenica, & Beery, 2004).

### *BRIEF-P*

The BRIEF-P is a questionnaire designed to measure executive function behaviors in children 2–5 years of age (Gioia, Isquith, & Guy, 2002). This measure was given to the child's primary guardian, who was most often the mother. The overall composite, the Global Executive Composite (GEC), was used in this analysis. The score reflects the number of problem behaviors endorsed and therefore, a higher score indicates more concerns.

### *Cambridge Neuropsychological Test Automated Battery – Spatial working memory*

The Cambridge Neuropsychological Test Automated Battery (CANTAB) is a computerized battery of tasks designed to measure a variety of cognitive functions. The spatial working memory (SWM) task requires the participant to search and find a series of blue "tokens" hidden in boxes by pressing the boxes on the screen. There is only one token hidden at a time and tokens are never hidden in the same box twice. Therefore, the child must remember where they previously found a token and not return to the same box, as there will never be a token there. The number of boxes increases with each trial to a total of eight boxes. The measure of interest, the "between-errors" score, represents the total number of times a child returned to a box where they had already found a token within a trial. This task is intended to measure spatial aspects of working memory, an aspect of executive function.

### *Comprehensive Test of Phonological Processing – Second Edition*

The Comprehensive Test of Phonological Processing – Second Edition (CTOPP-2) measures reading-related phonological processing abilities and includes nine subtests designed to measure phonological awareness, phonological working memory, and rapid naming (Wagner, Torgesen, Rashotte, & Pearson, 2013). For this study, two subtests, Elision and Nonword Repetition, were included in the analysis. These two measures were selected because they have been used previously to account for specific, basic verbal skills when investigating mathematics (De Smedt et al., 2010).

### *Elision*

This subtest measures the phonological skills of the individual by asking them to say a word and then say the same word, dropping a designated sound from the word. The dropped sound is either a syllable or single word. This task is designed to measure phonological awareness.

### Nonword repetition

This subtest requires listening to recorded pronounceable nonwords and repeats them back to the examiner. The purpose of this test is to measure phonological working memory.

### Movement Assessment Battery for Children – Second Edition

The Movement Assessment Battery for Children – Second Edition (MABC-2) is a measure of children's movement skills and measures manual dexterity, balance, and visual–motor coordination through a series of motor tasks (Henderson, Sugden, & Barnett, 2007). This measure includes a total score that summarizes the child's scores across the domains of motor functioning, which was the primary measure used in this analysis.

## Statistical analyses

Statistical analyses were completed in SPSS 23 (SPSS, 2014). Standard scores on the TEMA-3 were inspected for outliers using boxplots. No child's scores were considered outliers, and therefore all 87 children were included in the final analysis. Alpha for all analyses was set at $p \leq .05$. Demographic information was analyzed using chi-square (sex, race) and analysis of variance (ANOVA; age, socioeconomic status [SES]). SES was calculated as a combination of parent-reported household income and years of maternal education (or primary caregiver in cases where the biological mother was not the primary caregiver) stratified into levels, each level re-coded as an ordinal value and then summed to make a single score. Maternal education was coded as 1 = high school graduate or less, 2 = 1–3 years of college, 3 = college graduate, and 4 = professional degree. Income was coded as 1 = $0–49,999, 2 = $50,000–99,999, 3 = $100,000–199,999, and 4 = $200,000 and above. This resulted in a value from 1 to 8 for each child (see Table 1 for means and percentage of sample in each bin). Group comparisons were

**Table 1.** Participant characteristics.

| Variable | VPT | FT | *p*-Value |
|---|---|---|---|
| Total subjects (*n*) | 58 | 29 | |
| Sex: M/F (% female) | 35/23 (39.7) | 15/14 (48.3) | .819 |
| Age: mean (*SD*) | 5.21 (.41) | 5.29 (.31) | .420 |
| GA at birth: mean (min–max) | 29.51 (24–32) | 39.96 (38–41) | <.001 |
| Birth weight (g): mean (*SD*) | 1320.40 (428.85) | 3452.10 (504.23) | <.001 |
| SES composite: mean (min–max) | 5.12 (2–8) | 5.38 (2–7) | .501 |
| Maternal education | Portion of whole sample | | |
| High school or less | 12.1% | 10.3% | |
| 1–3 years college | 34.5% | 20.7% | |
| College graduate | 34.5% | 34.5% | |
| Professional (MA, MS, MD, PhD, etc.) | 19.0% | 34.5% | |
| Family annual income | | | |
| $0–49,999 | 15.5% | 3.8% | |
| $50,000–99,999 | 32.8% | 50.0% | |
| $100,000–199,999 | 34.5% | 46.2% | |
| $200,000 and above | 17.2% | 0% | |

VPT: Very preterm born; FT: full-term born; M/F: male/female; *SD*: standard deviation; GA: gestational age at birth in weeks; min–max: minimum to maximum; g: grams.

made between groups on each of the measures using ANOVA. In order to investigate the relationship among variables, whole-sample Pearson correlations were conducted.

The final approach used in this study was data-driven multiple mediation model using the process extension for SPSS (Hayes, 2013). We applied this model to investigate the cognitive factors that contribute to group differences in mathematics ability and provide additional information above and beyond traditional regression models by simultaneously modeling the direct and indirect factors explaining variance in mathematics between groups. A nonparametric bootstrapping procedure, designed to balance statistical power and Type-I error, was applied for assessing indirect effects (Preacher & Hayes, 2008). For the current analysis, boot-strapped samples were set to 5000. The traditional four-step requirements initially laid out in Baron and Kenny (1986) were used to determine if mediation had occurred. These requirements are (1) the independent variable ($X$) must be a significant predictor of the dependent variable ($Y$), this is termed the total effect, or $c$ path. (2) The independent variable must be significantly correlated to the mediator variables ($M$), this is the $a$ path. (3) Mediator variables are significant predictors of the dependent variable while the independent variable is in the model, the $b$ path. (4) When the mediators are included, the independent variable no longer significantly predicts the dependent variable, the direct effect or $c'$ path. The indirect effect is the reduction between $c$ and $c'$ caused by inclusion of the mediators. Given these steps, any variables not significantly correlated with TEMA-3 scores will not be included in the mediation model.

## Results

### Group characteristics

Participant characteristics are listed in Table 1. There were no significant differences between groups for sex ($\chi^2$ [df = 1] = .052; $p$ = .819), race ($\chi^2$ [df = 4] = 4.840; $p$ = .304), age ($F$ [1,85] = .658, $p$ = .420), or SES ($F$ [1,85] = .455; $p$ = .502). As expected, the groups were significantly different for GA at birth ($F$ [1,85] = 543.02; $p$ < .001) and weight at birth ($F$ [1,85] = 389.21; $p$ < .001).

### Correlational analysis

Correlational analyses are presented in Table 2. Significant correlations were found between the TEMA-3 and WPPSI-IV VCI ($r$ = .508, $p$ < .001), VMI ($r$ = .482, $p$ < .001), CTOPP-2 Elision ($r$ = .549, $p$ < .001), CTOPP-2 Nonword Repetition ($r$ = .302, $p$ = .006), and MABC-2 ($r$ = .296, $p$ = .007).

### Between-group differences

Group means are presented in Table 3. Group differences were found among many measures entered into the initial analysis. Children born VPT performed significantly worse on TEMA-3 ($F$ [1,85] = 8.00; $p$ = .006), WPPSI-IV full-scale IQ ($F$ [1,85] = 9.88; $p$ = .002), Fluid Reasoning Index ($F$ [1,85] = 17.18; $p$ < .001), and VCI ($F$ [1,85] = 5.46;

**Table 2.** Correlations among cognitive and behavioral measures.

| Measure | VCI | VMI | BRIEF-GEC | CANTAB SWM | CTOPP-Elision | CTOPP-nonword repetition | MABC-2 |
|---|---|---|---|---|---|---|---|
| TEMA-3 | .508 (<.001) | .482 (<.001) | −.136 (.223) | −.047 (.674) | .549 (<.001) | .302 (.006) | .296 (.007) |
| VCI | – | .422 (<.001) | −.202 (.069) | −.124 (.269) | .586 (<.001) | .269 (.014) | .137 (.221) |
| VMI | | – | −.195 (.080) | .012 (.915) | .332 (.002) | .178 (.110) | .328 (.003) |
| BRIEF-GEC | | | – | .037 (.744) | −.217 (.050) | −.079 (.480) | −.189 (.089) |
| CANTAB SWM | | | | – | −.057 (.610) | .035 (.755) | −.083 (.460) |
| CTOPP-Elision | | | | | – | .306 (.005) | .276 (.012) |
| CTOPP-nonword repetition | | | | | | – | .159 (.155) |

Values presented as *r* (*p*-value); TEMA-3: Test of Early Mathematics Ability – Third Edition; std. = standard score; WPPSI-IV: Wechsler Preschool and Primary Scale of Intelligence – Fourth Edition; VMI: Beery–Buktenica Developmental Test of Visual–Motor Integration; BRIEF GEC: Behavior Rating of Executive Function Global Executive Composite; CANTAB SWM: Cambridge Automated Neuropsychological Test Battery spatial working memory; CTOPP-2: Comprehensive Test of Phonological Processing – Second Edition; MABC-2: Movement Assessment Battery for Children – Second Edition.

**Table 3.** Summary of scores on cognitive and behavioral measures.

| | VPT | FT | |
|---|---|---|---|
| Measure | *M* (*SD*) | *M* (*SD*) | Group differences: *F* (*p*) |
| TEMA-3 std. | 96.93 (14.78) | 106.65 (14.05) | 8.00 (.006)** |
| WPPSI-IV | | | |
| FSIQ std. | 100.38 (13.17) | 109.31 (8.93) | 9.88 (.002)** |
| FRI std. | 97.95 (14.85) | 110.92 (8.62) | 17.18 (<.001)** |
| PSI std. | 102.24 (12.68) | 101.72 (12.67) | .03 (.864) |
| VCI std. | 102.38 (14.17) | 109.65 (10.62) | 5.46 (.022)* |
| VMI std. | 96.95 (9.83) | 102.85 (6.30) | 7.87 (.006)** |
| BRIEF GEC T-score | 51.60 (12.24) | 46.15 (6.92) | 4.49 (.037)* |
| CANTAB SWM | 68.64 (12.17) | 65.00 (8.98) | 1.86 (.177) |
| CTOPP-2 | | | |
| Elision scaled | 8.81 (2.74) | 10.27 (2.78) | 5.05 (.027)* |
| NWR scaled | 7.26 (2.85) | 9.27 (3.11) | 8.45 (.005)** |
| MABC-2 scaled | 6.31 (2.57) | 9.69 (3.22) | 26.48 (.001)** |

Significant group differences: *$p < .05$; **$p < .005$; VPT: very preterm born; FT: full-term born; *M*: mean; *SD*: standard deviation; TEMA-3: Test of Early Mathematics Ability – Third Edition; std.: standard score; WPPSI-IV: Wechsler Preschool and Primary Scale of Intelligence – Fourth Edition; FSIQ: full-scale IQ; FRI: Fluid Reasoning Index; PSI: Processing Speed Index; VCI: Verbal Comprehension Index; VMI: Beery–Buktenica Developmental Test of Visual–Motor Integration; BRIEF GEC: Behavior Rating of Executive Function Global Executive Composite; CANTAB SWM: Cambridge Automated Neuropsychological Test Battery spatial working memory; CTOPP-2: Comprehensive Test of Phonological Processing – Second Edition; NWR: Nonword Repetition; MABC-2: Movement Assessment Battery for Children – Second Edition.



$p = .022$). In addition, cognitive and behavioral scores were significantly different, with VPT-born children performing more poorly on VMI ($F$ [1,85] = 7.87; $p = .006$), BRIEF GEC ($F$ [1,85] = 4.49; $p = .037$), MABC-2 ($F$ [1,85] = 24.93; $p < .001$), CTOPP-2 Elision ($F$ [1,85] = 5.05; $p = .027$), and CTOPP-2 Nonword Repetition ($F$ [1,85] = 8.45; $p < .005$). The scores were not significantly different between groups on the CANTAB SWM task.

It is important to emphasize that both groups' mean scores for all measures were in the average normative range, with the exception of the total MABC-2 score. The mean score for the children born VPT was in the low average/borderline range. Yet, the VPT-born children, on average, perform more poorly on every measure of interest with the exception of the SWM task.

### Multiple mediation analysis

As previously mentioned, only variables that were significantly correlated with TEMA-3 scores were entered in the multiple mediation analysis. The final model included VMI, MABC-2 Total Score, VCI, CTOPP-Elision, and CTOPP-Nonword Repetition. In the analysis before entering the mediators, group was shown to be a significant predictor of TEMA-3 scores ($R^2$ = .0889, $F$ [1,85] = 8.00, $p$ = .006). This relationship is shown in part (a) of Figure 1. The total effect is 9.732, and this represents the $c$ path, and the significant relationship satisfies Step 1 of mediation.

The total overall effect was significant, indicating that Group and the full set of mediators were significant predictors of TEMA-3 scores ($R^2$ = .420, $F$ [6,81] = 9.273, $p$ < .001). While all variables were significantly related to group, only a subset of the variables significantly mediated the relationship between group and mathematics. WPPSI-IV VCI, VMI, and CTOPP-Elision were all significant mediators in the model (see Figure 1 for unstandardized path coefficients). Significant mediators were VCI (unstandardized $\beta$ = .270; $t$ [80] = 2.156; $p$ = .034), VMI (unstandardized $\beta$ = .347; $t$ [80] = 2.117.; $p$ = .038), and CTOPP Elision (unstandardized $\beta$ = 1.409; $t$ [80] = 2.353; $p$ = .021). Two of the mediators then predicting TEMA-3 were nonsignificant for CTOPP Nonword Repetition (unstandardized $\beta$ = .435; $t$ [80] = .929; $p$ = .356) and MABC (unstandardized $\beta$ = .326; $t$ [80] = .652; $p$ = .516). After inclusion of the mediators, the direct effect of group predicting TEMA-3 is no longer significant ($t$ = .489, $p$ = .626), indicating that mediation has occurred since the relationship

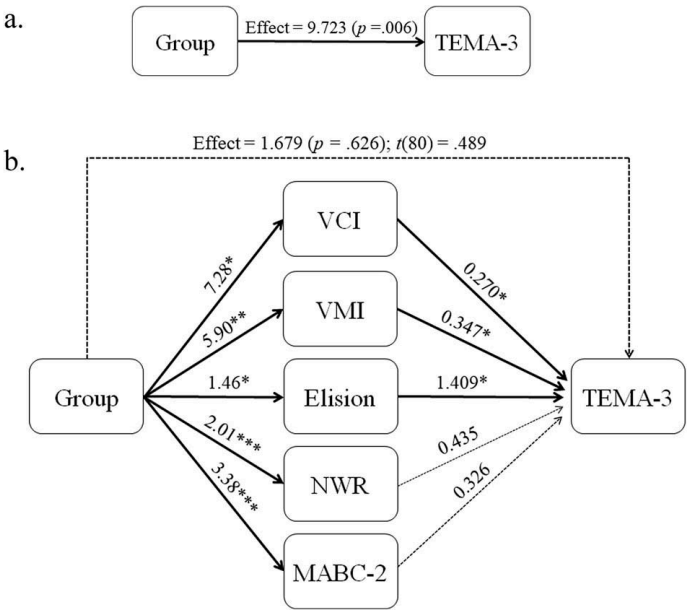


Figure 1. Values represent unstandardized coefficients (betas). Direct (a) values and indirect (b) models of the mediation analysis and path estimates. *$p$ < .05, **$p$ < .01, ***$p$ < .005. TEMA-3: Test of Early Mathematics Ability – Third Edition; VCI: Wechsler Preschool and Primary Scale of Intelligence – Fourth Edition Verbal Comprehension Index; VMI: Beery-Buktenica Developmental Test of Visual–Motor Integration; Elision: Comprehensive Test of Phonological Processing – Second Edition (CTOPP-2) Elision subtest; NWR: (CTOPP-2) Nonword Repetition subtest; MABC-2: Movement Assessment Battery for Children – Second Edition total score.

between group and TEMA-3 score is no longer significant with the mediators in the model, as it was in the total effects model shown in Figure 1, part (a). This final step satisfies step 4 of the requirements of mediation.

## Discussion

The present study evaluated mathematics ability in preschoolers born VPT and their term-born peers. We sought to expand on previous literature on VPT-born children by examining these skills together in one model. In line with previous studies, we found that although the group mean scores were in the average range, VPT-born children performed significantly worse than their full-term born peers on a measure of early mathematics ability. In the correlation analysis, we found that mathematics ability was significantly correlated with verbal reasoning abilities, VMI, phonological working memory, phonological awareness, and motor skills. In contrast, parent ratings of executive functioning on the BRIEF-P and SWM were not significantly correlated with mathematics ability in this cohort. While there was a significant group difference on the GEC of the BRIEF-P, neither group had mean scores in the clinically significant range. The limited range of scores across the groups, as well as group means in the nonclinically significant range, may explain why this measure of executive functioning was not a significant mediator in the model. The mediation analysis indicated that while many of the variables were significantly correlated with mathematics, general verbal abilities, visual-motor integration, and phonological awareness were significant in explaining the relationship between group and TEMA-3 when all were entered into the model simultaneously. It is important to note that a variety of skills were significantly correlated with mathematics, but these three were the most important for explaining the difference between VPT and FT children in mathematics at preschool age and represent possible criteria for detecting children at risk for difficulties.

The majority of these results are consistent with our hypothesized relationships between mathematics and preterm birth. A previous study of 7–9-year-old children concluded that phonological awareness (CTOPP-Elision) and simple arithmetic are highly correlated and likely have overlapping neural basis (De Smedt et al., 2010). Evidence of a shared neural basis comes from a recent functional MRI study of children and young adults. In this study, the left superior temporal and right middle temporal regions were activated during both reading and mathematics tasks (Evans, Flowers, Leutje, Napoliello, & Eden, 2016). There is also evidence of shared mechanisms between reading and mathematics via the commonalities in cognitive profiles as well as comorbidity of mathematics and reading disabilities (Simmons & Singleton, 2008). Additionally, studies have demonstrated overlap in the functional activation networks that are disrupted in both reading and math disabilities (Ashkenazi, Black, Abrams, Hoeft, & Menon, 2013). De Smedt et al. (2010) also found no correlation among mathematics and phonological working memory using the CTOPP-2 Nonword Repetition, the same task as in the current analysis. In that study, the lack of correlation was attributed to the children using a "retrieval strategy" and solving the math problems by relying on having previously memorized the answer. This is in contrast to a "problem-solving strategy," where they needed to use mathematics skills to find the solution for the majority of the large problems, which was correlated with phonological

awareness. We also found that phonological awareness, and not phonological working memory, was predictive of mathematics. This may be because the types of items on the TEMA-3 cause the younger children to employ a similar strategy, "problem solving," as the previous study found older children were using for more complex problems. This would indicate that preschoolers are using a similar strategy for simple mathematics as older children are for more complex problems; hence, why we found the same lack of significant correlation between Nonword Repetition and TEMA-3. General verbal abilities and phonological processing have also been linked to mathematics via processing of linguistic symbols and linking of numeric values with linguistic equivalents during development (Pinel & Dehaene, 2010). A previous study also found that motor skills and a measure of attention and executive function did not explain a significant amount of variance in mathematics in children born VPT (Simms et al., 2013), as seen in the current study. Overall, the current analysis indicates that general verbal skills, VMI, and phonological awareness are the most important for explaining the observed group differences in TEMA-3 scores. Scores on the VMI task have been shown to be significantly related to mathematics (Verdine, Irwin, Golinkoff, & Hirsh-Pasek, 2014). One study has suggested that relative strengths in motor control and ability to reproduce the spatial aspects of the figures on the VMI are indicators of underlying numerical processing abilities (Carlson, Rowe, & Curby, 2013). Once we better understand the relationship between measures of specific skills and mathematics, they can be used as markers to determine if a child may be at risk for falling behind their term-born peers in mathematics. For example, if a teacher or parent is concerned that a VPT-born child is struggling with reading or not performing well in verbal or spatial tasks, it may be appropriate to assess further for possible difficulties in mathematics. This study also demonstrated that these types of effects can be found as early as preschool.

This study does have some limitations. A previous study found poorer performance on the CANTAB SWM task in VPT compared to FT-born children at 7–9 years of age (Luciana, Lindeke, Georgieff, Mills, & Nelson, 1999). In our study, the VPT group did not perform significantly worse than the FT-born group. This may be due to the difficulty of this task for children who are of preschool age. This task will continue to be administered each year of the study, and as these children get older, the differences seen in other studies may emerge. In addition, we used a single parent-report measure of executive functioning, rather than a direct measure of executive functioning. Therefore, our judgment of the functioning of these children is dependent on their parent's responding honestly and accurately on this measure. A teacher report version of this measure would be informative in future studies. In the future to provide additional evidence of current executive functioning, a direct measure of the children's behavior related to executive functioning, such as the Test of Everyday Functioning for Children (Manly et al., 2001) or Head-Toes-Knees-Shoulders task (Ponitz, McClelland, Matthews, & Morrison, 2009) should be used in further examining the relationship between executive function and mathematics. The group of FT-born children in this study performs well on the measures and tends to have highly educated parents. The FT-born group was recruited from the same area and often attended the same schools as the VPT-born children. There were no significant differences between the groups on SES, income, or maternal education. Therefore, we do not have any reason to believe that these children are not representative controls. Lastly, as part of the intentional design of the larger study, this investigation included children who were born preterm with a relatively uncomplicated

prenatal and neonatal history. Health-related inclusion criteria previously mentioned as well as the requirement that participants obtain a VCI of at least 80, intentionally excluded children with severe cognitive impairment and the most serious health and developmental consequences of preterm birth. Therefore, the VPT children in this study are not expected to have scores in the severely impaired or intellectual disability range. Despite this, these children performed significantly worse than their term-born peers who were recruited as part of the study. Therefore, this is not necessarily a limitation to the current study, but it may limit the current study's generalizability to other populations of children who were born VPT and have more complicated histories or frank deficits.

Future directions for this study include correlating the behavioral and neuropsychological results with neuroanatomical data. The children in this study undergo structural magnetic resonance imaging as well as diffusion-tensor imaging each year of the study. In addition, as previously mentioned, these data are part of an ongoing, longitudinal study and this analysis includes only the first of three yearly visits. We also plan to expand the current investigation by performing the same analysis at the completion of the study, when these children have completed 2 years of formal schooling.



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