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Authors
Adrian, Julia Anna
Haist, Frank
Akshoomoff, Natacha

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Mathematics Skills and Executive Functions Following Preterm Birth: A Longitudinal Study of 5- to 7-Year Old Children

Julia Anna Adrian[1], Frank Haist[2], & Natacha Akshoomoff[2]
Department of Cognitive Science[1], Psychiatry[2], UC San Diego
9500 Gilman Drive, La Jolla, CA 92093

Abstract

Early mathematics skills are an important predictor of later academic, economic and personal success. Children born preterm, about 10% of the US population, have an increased risk of deficits in mathematics. These deficits may be related to lower levels of executive functions and processing speed. We investigated the development of mathematics skills, working memory, inhibitory control and processing speed of healthy children born very preterm (between 25 and 32 weeks gestational age, n=51) and full-term (n=29). Children were tested annually from ages 5 to 7 years. We found persistent lower overall mathematics skills in the preterm group, driven by differences in more informal skills (e.g. counting) at earlier time points, and by differences in more formal skills (e.g. calculation) at later time points. We did not find significant differences between preterm and full-term born children in spatial working memory capacity or processing speed. However, these cognitive measures were significant predictors of mathematics skills in the preterm but not the full-term group, hinting towards the use of different strategies when solving problems.

Keywords: Early Mathematics; Executive Functions; Cognitive Development; Preterm Birth; longitudinal;

Introduction

Mathematics skills are beneficial for success in life. Early mathematics skills at school-entry are predictive of later academic achievement (Duncan et al., 2007; Geary, Hoard, Nugent, & Bailey, 2013), and socioeconomic status (Ritchie & Bates, 2013).

Very preterm birth (before 33 weeks of gestation) has a negative effect on academic achievement in general (Johnson, Wolke, Hennessy, & Marlow, 2011), and mathematical ability in particular (Akshoomoff et al., 2017; Taylor, Espy, & Anderson, 2009). Every year about 15 million children are born preterm, with preterm birth rates ranging from 5-18% (Liu et al., 2016). Recent studies on the effects of preterm birth often examine children born extremely preterm (<28 weeks) and/or with very low birth weight (<1500g). However, these individuals make up a small proportion of the preterm born population. Furthermore, with medical advances, severe complications of preterm birth can be treated, and the rates of preterm born children without severe neurodevelopmental disorders have increased. Yet even in otherwise healthy children, preterm birth is associated with long-term cognitive consequences such as developmental and learning problems (Anderson, 2014).

Mathematical ability is related to executive functions and processing speed in typically developing children (Geary, 2011; Purpura, Schmitt, & Ganley, 2017). The core executive functions are working memory, inhibitory control and shifting (Miyake, Friedman, Emerson, Witzki, & Howerter, 2000). These cognitive skills are affected by preterm birth (Aarnoudse-Moens, Duivenvoorden, Weisglas-Kuperus, Van Goudoever, & Oosterlaan, 2012) and are likely to be related to mathematics deficits. Rose, Feldman, and Jankowski (2011) showed that differences in math and reading skills of 11 year old full-term and preterm children can be explained through preterm deficits in executive function and processing speed. They argue for a cascade of effects: preterm birth leading to lower processing speed, leading to lower executive functions, leading to lower math and reading scores. It is unknown when this cascade of effects begins and how processing speed, executive functions, and mathematics achievement are connected during early childhood.

While we know that preterm birth affects processing speed and executive functions, and that children born preterm exhibit deficits in mathematics achievement, to our knowledge no study has investigated these components longitudinally in preterm born children during childhood.

The Present Study

The present study examines how mathematics ability develops and how it is related to other neuropsychological functions following preterm birth. The children in this study were born between 25 and 32 weeks gestational age. They are considered healthy and do not suffer from any severe medical conditions or neurodevelopmental disorders. However, they make up about 2% of the general population in the US and are thus an important group to study. This longitudinal comprehensive study allows controlling for individual differences and will give insight into the development of the interplay of processing speed, executive functions, motor skills and mathematics ability.

Methods

Participants

Participants were preterm and full-term children who were tested at three time points, each about a year apart. First testing was performed within six months of starting kindergarten, at a mean age of 5.3 years (SD: 0.38). Mean age for the following two time points was 6.4 (SD: 0.37) and 7.3 (SD: 0.35), respectively. A total of 51 preterm and 29 full-term children completed the mathematics, working memory, and inhibition tests at all three time points. Not all of these children completed the other cognitive and behavioral measures; sample size for each of the subtests is stated below.

The preterm sample was primarily recruited from the UC San Diego High-Risk Infant Follow Up Clinic. Inclusion criteria was gestational age at birth of <33 weeks. Out of the 51 children in the preterm group, 10 children were born <28 weeks gestational age, and 41 children between 28 and 32 weeks gestational age. We did not find a correlation between gestational age at birth and mathematics performance within the preterm group, therefore the children were not further divided into subgroups. In the following the term preterm includes both the extremely and very preterm born children of this study.

Exclusion criteria from the preterm sample were a history of severe brain injury (e.g., cystic periventricular leukomalacia), disability (e.g., bilateral deafness or blindness), genetic abnormalities likely to affect development, and acquired neurological disorder unrelated to preterm birth.

Inclusion criteria for the full-term sample was gestational age at birth of >38 weeks and no history of neurological, psychiatric, or developmental disorders. All participants had a score of 80 or higher on the Verbal Comprehension Index of the Wechsler Preschool and Primary Scale of Intelligence (WPPSI-IV) to insure comprehension of tasks (Wechsler, 2012).

Participant characteristics are summarized in Table 1. A social economic status (SES) score was calculated as the sum of rank in maternal education and household income. Maternal education was ranked as 1: high school, 2: 1-3 years of college, 3: four year college, 4: professional/ post-graduate degree. Household income was ranked as 1: less than $50,000, 2: $50,000 - $99,999, 3: $100,000 - $199,999, 4: $200,000 and above.

By definition, the preterm and full-term group differed in gestational age at birth ($F=693.86$, $p<0.0005$) and birth weight ($F=338.96$, $p<0.0005$). They were not significantly different in terms of gender composition, household income or socioeconomic status (SES) composite. Maternal education was significantly higher in full-term compared to preterm children ($F=4.74$, $p=0.033$). They did not differ in age at any testing time.

Table 1: Participants characteristics. GA: gestational age, SES: socioeconomic status

	Preterm (n=51)	Full-term (n=29)
GA at birth (weeks): mean (min-max)	29.5 (25-32)	39.7 (38-41)
Birth weight (g): mean (min-max)	1328 (680-2410)	3411 (2353-4422)
Gender (% female)	47.1	48.3
SES composite: mean (min-max)	5.0 (2-8)	5.43 (2-8)
Maternal education	2.47 (1-4)	2.93 (1-4)
High school	13.7%	10.3%
1-3 years college	35.3%	20.7%
College graduate	41.2%	34.5%
Professional	9.8%	34.5%
Household income	2.52 (1-4)	2.50 (1-4)
Less than $50,000	15.7%	3.4%
$ 50,000 - $99,999	31.4%	44.8%
$100,000 - $199,999	35.3%	44.8%
$200,000 and above	15.7%	3.4%

Cognitive and Behavioral Measures

Measures of mathematics ability, working memory, inhibitory control, processing speed, and motor skills, were examined. A number of tasks were drawn from the Cambridge Neuropsychological Testing Automated Battery (CANTAB). These tasks are well established and standardized computerized non-verbal tasks, administered on a touch screen. They are suitable for children 4 years of age and older. In addition, a more challenging task was administered that can be thought of as a composite measure of executive functions and motor skills, the Head Toes Knees Shoulders (HTKS) Task. To be able to parse apart the effect of motor function on HTKS performance, the Movement Assessment Battery for Children (MABC-2) was administered.

Mathematics Ability was assessed via the Test for Early Mathematics Ability, Third Edition (TEMA-3, Ginsburg & Baroody, 2003). It is designed for children between 3:0-8:11 years of age. It comprises up to 72 items. The items can also be broadly categorized into informal and formal mathematics, and more specifically into seven subcategories: Verbal Counting, Counting Objects, Numerical Comparison, Numeral Literacy, Set Construction, Calculation, and Number Facts (Ryoo, et al. 2015). Measure of overall performance is the TEMA-3 total (raw) score.

Spatial Working Memory was assessed via the CANTAB Spatial Working Memory (SWM) task. The participant's task is to find a token that is hidden under one of several colored boxes. Once found, the token is hidden again, but not under the same box twice. Thus the participant has to remember where the tokens were previously found. The number of trials is gradually increased up to eight boxes. Working memory is measured inversely based on the number of errors made (searching under the same box multiple times).

Inhibitory Control was assessed via the CANTAB Stop Signal Task (SST). The participant has to choose between pressing one of two buttons depending on where an arrow points. If they hear an auditory signal when the arrow appears, the participant has to withhold their response and not press the button. Performance is measured via the stop signal reaction time in the second half of the task, were poor performance is reflected in longer reaction times.

Processing Speed was assessed via the CANTAB Reaction Time Task (RTI). The participant holds a button at the bottom of the touch screen. Above the button are five circles. Once a yellow dot appears in one of the circles, the participant releases the button at the bottom and taps the circle with the dot. Performance is measured via median response time of pressing the circle in which the yellow dot appeared. 10 preterm children from the full sample did not complete the RTI, resulting in a sample size of 41 preterm and 29 full-term children.

The Head Toes Knees Shoulders (HTKS) Task can be seen as a composite measure of executive function and motor skills (Ponitz et al., 2008). It has three rounds: In the first round the participant has to touch their toes when the examiner says to touch their head and vice versa. In the second round the participant has to touch their knees whenever the examiner says to touch their shoulders and vice versa. The third round includes all four body parts and requires remapping of the previously learned instructions. This task requires working memory, as the participant has to keep in mind which body part to touch instead of the one the examiner said; inhibitory control, as the participant has to keep themselves from plainly following the instruction, shifting, as the instructions change; and motor control. The task was added while the study was already ongoing, leading to a relatively small sample of 33 preterm and 13 full-term children who were assessed at all three time points.

Motor Skills were assessed using the Movement Assessment Battery for Children-2 (MABC-2; Henderson, Sugden, & Barnett, 2007). It tests manual dexterity, aiming & catching, and balance. The total test scores were used to compare motor skills. In this analysis, the MABC-2 is used to disentangle wheather performance differences in the HTKS are due to differences in motor or executive function. Thus the MABC-2 was examined on the same sample as the HTKS. It was administered at time point 1 and 3 only.

Results

Executive Functions, Processing Speed & Motor Skills

Group differences in cognitive and behavioral measures other than mathematics ability are summarized in Table 2. Spatial working memory scores did not differ significantly between preterm and full-term children at any time point. The stop signal reaction time in the SST was significantly longer in the preterm group at time 1 and 2, and approached significance at time 3. A longer reaction time indicates more difficulty with inhibitory control. Processing speed as measured via reaction time in the RTI did not differ significantly between groups in the 5 choice version of the RTI. Performance on HTKS was significantly lower in preterm children at all three time points. Preterm children also scored significantly lower on MABC-2 at the two time points in which motor function was measured.

Correlation analysis between performance on these cognitive and behavioral tasks controlled for time point, SES, and group revealed that performance on HTKS was correlated with errors on the SWM (r=-0.204, p=0.035), SST reaction time (r=-0.202, p=0.036), and reaction time on RTI (r=-0.313, p=0.001). Importantly, HTKS and MABC-2 total scores were not correlated (r=0.097, p=0.317). Thus differences in HTKS reflect differences between participants other than motor function.

Table 2: Group differences in performance on the spatial working memory (SWM), the stop signal task (SST), the reaction time task (RTI), the Head Toes Knees Shoulders (HTKS) task, and the Movement Assessment Battery for Children-2 (MABC-2) as measured via ANOVA. ° no significant difference, ↑ sign. longer in the preterm group, ↓ sign. lower in preterm group. n.d.: no data.

Task		Time point 1		Time point 2		Time point 3
		F (p)		F (p)		F (p)
SWM	°	0.507 (0.478)	°	3.374 (0.070)	°	0.218 (0.642)
SST	↑	4.627 (0.035)	↑	6.503 (0.013)	°	3.328 (0.072)
RTI	°	0.302 (0.585)	°	2.128 (0.149)	°	1.205 (0.276)
HTKS	↓	7.648 (0.008)	↓	8.628 (0.005)	↓	4.685 (0.008)
MABC-2	↓	14.303 (<0.0005)		n.d.	↓	24.092 (<0.0005)

Mathematics Skills

Preterm born children had lower TEMA-3 total scores compared to full-term born children on all three time points. The difference decreased from time 1 to 2, and increased again at time 3 (figure 1, table 3). Categorization of TEMA-3 test items into subcategories according to Ryoo et al. (2015) revealed that differences between preterm and full-term children did not share a common developmental pattern. Verbal Counting, a more informal skill showed group differences at age 5 and 6 that diminished at age 7 (figure 2). Similarly, other skills such as Numerical Comparison and Counting Objects showed a narrowing of the performance gap between preterm and full-term born children between time point 1 and 3. In contrast, at age 5, preterm children did not score significantly lower on items testing for Set Construction, a more formal, skill. Over time, the a deficit emerged such that preterm born children scored about 15 percent points below full-term children at age 7. Differences in Calculation skills were present at all time points. Notably, the differences show a high increase over time, with about twice the effect size at time point 3, compared to 1 and 2. Performance of both groups on Number Facts was a floor at time point 1, and at time point 2, preterm and full-term children did not score significantly differently. However, by time point 3, large differences emerged, with lower scores in the preterm sample.

In the following Verbal Counting and Calculation skills, as well as the overall TEMA-3 performance are analyzed in more detail. These skills were chosen as they exemplify the differential trajectories of informal and formal skills.

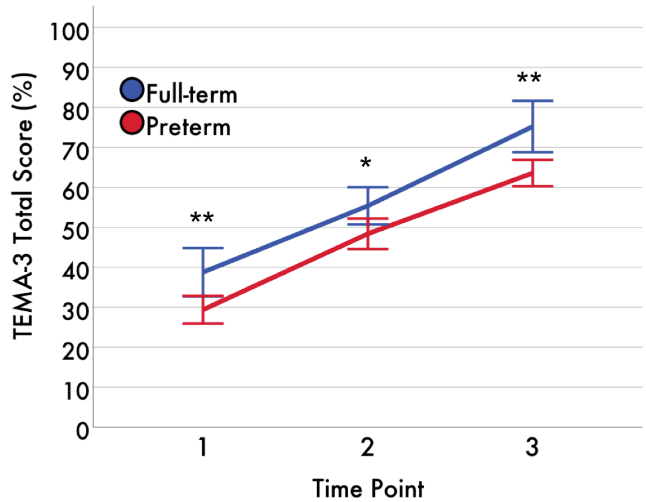

Figure 1: Standardized mathematics ability score of preterm and full-term group. The preterm group has a lower score at all three time points. * p < 0.05, ** p < 0.01.

Repeated measures ANOVAs showed a significant interaction of time and group for Verbal Counting (F=4.234, p=0.016, η^2=0.051) and Calculation (F=7.079, p=0.001, η^2=0.083). TEMA-3 total score showed a significant effect of time and group, but not their interaction (F=1.272, p=0.283, η^2=0.016). A three-way ANOVA with time and skill (Verbal Counting/Calculation) as within subject repeated measures and group as between subjects factor revealed a significant interaction between time, skill, and group (F=11.191, p<0.005, η^2=0.125).

Table 3: Summary of TEMA-3 overall performance (total score) and score of distinct skills as defined by Ryoo, et al. (2015). Scores presented as percentage of total possible score. M: mean, SD: standard deviation, group comparisons via ANOVA.

	Time point 1			Time point 2			Time point 3		
	Full-term	Preterm		Full-term	Preterm		Full-term	Preterm	
Skill	M (SD)	M (SD)	F (p)	M (SD)	M (SD)	F (p)	M (SD)	M (SD)	F (p)
Total score	38.75 (15.89)	29.36 (12.30)	8.689 (0.004)	55.36 (12.26)	48.37 (13.57)	5.265 (0.024)	75.19 (16.92)	63.56 (11.76)	13.065 (0.001)
Verbal Counting	50.49 (26.72)	34.87 (20.24)	8.693 (0.004)	75.86 (18.05)	63.03 (19.68)	8.343 (0.005)	86.95 (13.51)	83.19 (11.32)	1.763 (0.188)
Counting Objects	77.34 (19.66)	64.99 (14.37)	10.403 (0.002)	89.66 (12.01)	85.99 (12.61)	1.611 (0.208)	97.04 (5.89)	92.16 (10.81)	5.056 (0.027)
Numerical Comparison	37.55 (16.38)	27.67 (15.46)	7.234 (0.009)	51.72 (8.54)	43.33 (13.34)	9.186 (0.003)	60.92 (12.46)	54.68 (10.15)	5.904 (0.017)
Numeral Literacy	40.95 (24.07)	24.26 (16.09)	13.765 (<0.0005)	66.81 (19.27)	58.82 (18.42)	3.361 (0.071)	86.64 (14.15)	75.98 (13.66)	10.971 (0.001)
Set Construction	50.57 (13.80)	46.62 (11.76)	1.838 (0.179)	72.03 (16.96)	59.48 (13.67)	13.065 (0.001)	87.74 (14.95)	72.11 (14.80)	20.455 (<0.0005)
Calculation	23.75 (13.19)	15.90 (13.01)	6.668 (0.012)	49.04 (18.43)	37.04 (22.07)	6.136 (0.015)	88.89 (44.64)	59.48 (27.83)	13.197 (0.001)
Number Facts	Performance at floor			10.73 (15.57)	5.66 (16.24)	1.852 (0.177)	49.43 (31.23)	23.53 (23.59)	17.544 (<0.0005)

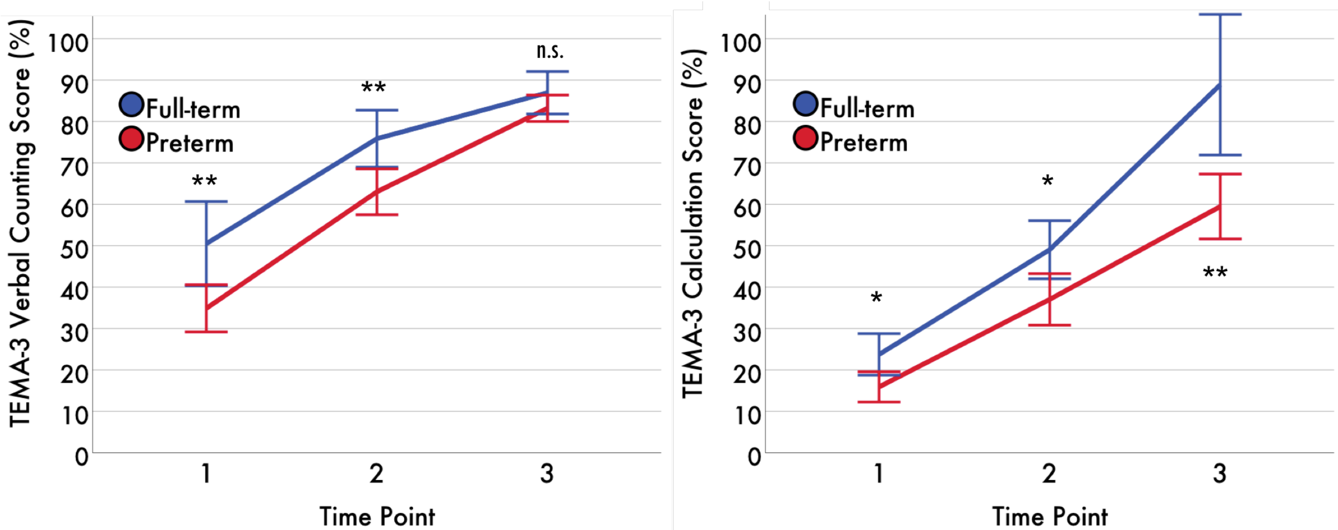

Figure 2: Development of Verbal Counting (left) and Calculation skills (right) as measured via the Test of Early Mathematics Ability – Third Edition (TEMA-3). Error bars: 95% confidence interval. * $p < 0.05$, ** $p < 0.01$, n.s.: $p > 0.05$

Effect of Executive Functions and Processing Speed on Mathematics Skills

Linear models were used to determine which of the cognitive and behavioral measures are predictive of mathematics skills. As the sample size for HTKS is considerably smaller, two separate models were evaluated: Model 1 used SWM, SST and RTI as predictors, while model 2 used HTKS score as predictor (table 4). Time point, SES and gender were included in all models. Time point and SES were significant predictors for both groups, and gender was a significant predictor in the full-term but not the preterm group.

In model 1, SWM and SST were predictive of Verbal Counting and Calculation in the preterm group. RTI was predictive of Verbal Counting but not Calculation. In contrast, SWM was not predictive in the full-term group for either skill, and SST was a significant predictor only for Verbal Counting. RTI did not significantly predict either skill.

Model 1 was a better fit when predicting Verbal Counting (r^2=0.6293) compared to Calculation skills (r^2=0.4580) in the preterm group. Conversely, the model performed slightly better when predicting Calculation (r^2=0.5743) compared to Verbal Counting (r^2=0.5261) skills in full-term children.

Model 2 showed that in both groups performance on HTKS was predictive of Verbal Counting, but not Calculation. Consequently, it was a better fit when predicting Verbal Counting compared to Calculation skills.

Table 4: Summary of linear models predicting Verbal Counting and Calculation Skills in full-term and preterm born children, respectively. Time point, SES and gender are included in all models. Model 1 additionally uses SWM, SST and RTI as predictors, model 2 uses HTKS.

	Verbal Counting		Calculation	
	Full-term	Preterm	Full-term	Preterm
Base Model – predictors: Time point, SES, gender				
Adj. r^2	0.4974	0.5852	0.5275	0.4166
Model 1 – n(preterm)=41, n(full-term)=29				
Adj. r^2	0.5261	0.6293	0.5743	0.4580
Predictors: std. β coeff. (p)				
SWM	-0.0259 (0.2084)	-0.0309 (0.0137)	-0.0376 (0.0522)	-0.0245 (0.0190)
SST	-0.0080 (0.0129)	-0.0037 (0.0309)	-0.0043 (0.1426)	-0.0035 (0.0155)
RTI	0.0003 (0.9025)	-0.0036 (0.0299)	-0.0025 (0.0844)	-0.0009 (0.5056)
Model 2 – n(preterm)=33, n(full-term)=13				
Adj. r^2	0.5549	0.6528	0.4942	0.4061
Predictors: std. β coeff. (p)				
HTKS	0.0570 (0.0316)	0.0559 (0.0008)	0.0473 (0.1607)	0.0233 (0.1351)

Discussion

The present study examined the trajectories of specific mathematics skills and overall mathematics ability in preterm and full-term born children from before starting kindergarten to the end of first grade (age 5 to 7). Consistent with previous studies, we found lower overall mathematics score in the preterm born group at all time points. This observation by itself masks the fact that the differences between preterm and full-term group are not consistent over time. Importantly, one has to distinguish between the developmental trajectory of informal skills (e.g. Verbal Counting) and formal skills (e.g. Calculation).

We found a deficit in Verbal Counting skills in preterm compared to full-term children at time point 1 and 2. However, by time point 3, there were no significant group differences. This type of developmental pattern signals an initial delay of Verbal Counting skills in preterm children, followed by catch up in skill level.

In contrast, the difference in Calculation skills between preterm and full-term group increases over time. This is likely because more formal mathematics skills are commonly introduced in kindergarten, and rapidly develop with schooling. We predict that this deficit in the preterm group will persist over time, and possibly increase further. In line with this, mathematics deficits have been found in pre-teens (Akshoomoff et al., 2017; Rose et al., 2011), and teenagers (Litt et al., 2012) born preterm. The same applies for other aspects of formal mathematics, such as Set Construction and Number Facts.

Differences in mathematics skills might be mediated to some extent by differences in other cognitive functions (Mulder, Pitchford, & Marlow, 2010). We examined measures of spatial working memory, inhibitory control, processing speed, and motor function. Interestingly, while there were no group differences in SWM, we found that it is predictive of both Verbal Counting and Calculation skill in preterm but not full-term children. Similarly, we did not find significant differences in processing speed between preterm and full-term children, and performance on RTI was predictive of Verbal Counting in the preterm group only. This may indicate that the two groups are employing different problem-solving strategies. Children born preterm may rely on different cognitive processes as they develop mathematics skills.

Preterm compared to full-term children show significantly longer reaction times at the SST, an inverse measure of inhibitory control, at time point 1 and 2. While SST is predictive of Verbal Counting in both groups, it is predictive of Calculation in the preterm group only. This may be another hint towards more effortful task completion in the preterm born children, and potentially having to recruit inhibition skills to a greater extent than full-term children.

The HTKS, a task requiring working memory, inhibitory control, shifting, and motor skills, revealed deficits of the preterm compared to the full term group at all time points. Since there was no correlation between performance on the HTKS and the MABC-2, it appears to reflect group differences in composite executive function ability that is not driven by the group differences in motor control.

Performance on the HTKS has previously been shown to be predictive of academic achievement of typically developing children in kindergarten (McClelland et al., 2014). Consistent with this, we found that HTKS scores were a significant predictor for Verbal Counting, but not Calculation for both groups. However, the number of participants who were administered the HTKS was smaller, and it remains to be examined if the results hold up with a larger sample size.

Our study is an important contribution to the existing body of literature as it examines the crucial transition from preschool through the end of first grade, capturing the first formal instruction of mathematics in school. Further follow-up of these children, and their formal mathematics skills in particular, would give valuable insight into the potential differences in developmental trajectory of preterm and full-term born children from childhood through adolescence.

It should be noted that this preterm group had no significant neonatal complications and was considered healthy. Nevertheless, we found deficits in mathematics skills, particularly in formal skills at age 7, that may be heralds of important inequalities later in life (Basten, Jaekel, Johnson, Gilmore, & Wolke, 2015). These differences are important to consider for parents and teachers of preterm born children, and for our society at large.

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