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Etiology of persistent mathematics difficulties from childhood to adolescence following very preterm birth

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ABSTRACT

Children born very preterm (VP; <32 weeks' gestation) have poorer mathematics achievement than term-born peers. This study aimed to determine whether VP children's mathematics difficulties persist from primary to secondary school and to explore the nature of mathematics difficulties in adolescence. For this study, 127 VP and 95 term-born adolescents were assessed at age 11–15 years. Mathematics achievement was assessed using the Wechsler Individual Achievement Test-II. Specific mathematics skills and general cognitive skills were assessed using standardized and experimental tests. VP adolescents had poorer mathematics achievement than term-born adolescents (−10.95 points; 95% CI −16.18, −5.73) and poorer number fact knowledge, understanding of arithmetic concepts, written arithmetic, counting, reading and writing large numbers, and algebra. Between-group differences in mathematics skills were no longer significant when working memory and visuospatial skills were controlled for (p's >0.05), with the exception of writing large numbers and conceptual understanding of arithmetic. In a previous study, 83 of the VP adolescents and 49 of the term-born adolescents were assessed at age 8–10 years using measures of the same skills. Amongst these, the between-group difference in mathematics achievement remained stable over time. This study extends findings of a persistent deficit in mathematics achievement among VP children over the primary and secondary school years, and provides evidence of a deficit in factual, procedural and conceptual mathematics skills and in higher order mathematical operations among VP adolescents. We provide further evidence that VP children's mathematics difficulties are driven by deficits in domain-general rather than domain-specific cognitive skills.

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Children born very preterm (VP, <32 weeks' gestation) are at high risk for cognitive and behavioral difficulties (Allotey et al., 2018; Twilhaar, Wade et al., 2018) resulting in an increased prevalence of special educational needs and poor academic achievement at school (MacKay et al., 2010; Twilhaar et al., 2018). As the risk for poorer employment

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prospects and wealth among VP adults (Bilgin et al., 2018) is mediated by academic achievement in childhood (Basten et al., 2015), it is imperative that research focuses on understanding educational difficulties to develop appropriate interventions.

Of all the subjects studied at school, VP children have greatest difficulties in mathematics (Allotey et al., 2018; Johnson et al., 2011; McBryde et al., 2020). Whilst a handful of studies have suggested that these difficulties stem from imprecise numerical representations (Guarini et al., 2014; Hellgren et al., 2013; Libertus et al., 2017), the majority have indicated that preterm children's mathematics difficulties are related to deficits in general cognitive skills, such as working memory, visuospatial skills, processing speed and inhibitory control (Aarnoudse-Moens et al., 2013; Akshoomoff et al., 2017; Twilhaar et al., 2020). We previously carried out a comprehensive evaluation of VP children's mathematics and general cognitive skills at 8–10 years of age in the Premature Infants' Skills in Mathematics (PRISM) Study. In addition to a substantial deficit in mathematical achievement, VP children had deficits in specific mathematics skills, namely the use of less sophisticated strategies to solve arithmetic problems and poorer counting. Notably, these were accounted for by their deficits in working memory and visuospatial skills (Simms et al., 2015). Similar results have been found for preschool children, in which the relationship between VP birth and mathematical achievement has been shown to be mediated by visual-perceptual skills (Van Veen et al., 2019), visuomotor integration, inhibitory control, verbal ability and phonological awareness (Adrian et al., 2020; Hasler & Akshoomoff, 2019).

Whether these difficulties persist into adolescence and whether the same general cognitive skills underlie later difficulties is unknown. With increasing age, mathematical topic content becomes more complex, building on arithmetic and expanding into topics such as algebra and geometry, which place greater demands on children's cognitive systems. As such, the mathematics deficits of VP children may be exacerbated in adolescence. Given that these advanced mathematical topics are "gatekeeper" topics for future engagement with and success in STEM (science, technology, engineering, mathematics) subjects in particular, as well as education more broadly (Panel, 2008), understanding preterm adolescents' difficulties with mathematics is important to improve their future educational attainment and employment opportunities.

Surprisingly, although VP children have persistent deficits in academic achievement over the primary school years (Odd et al., 2019; Twilhaar, de Kieviet et al., 2019), few studies have assessed academic achievement throughout secondary schooling. Early studies reported persistent or increasing deficits throughout development among VP or extremely low birthweight (<1000 g) adolescents (Botting et al., 1998; Clark et al., 2013; Litt et al., 2012; Saigal et al., 2000; Twilhaar et al., 2020), however most were of cohorts born in the 1980s (Botting et al., 1998; Clark et al., 2013; Saigal et al., 2000), before the dawn of modern neonatal care and associated increased survival of VP infants. The widespread use of surfactant therapy, improved developmental care and nutrition, and improvements in neuroprotective strategies since the 1980s may alter neurodevelopmental and cognitive outcomes. Moreover, these previous studies all used a single composite test to assess achievement in mathematics and so it is not possible to identify which specific components of mathematics contributed to VP adolescents' difficulties. There remains a lack of information about whether VP children born in the 21st century display increasing deficits in mathematics in adolescence and whether the same cognitive deficits account for their poor mathematical achievement across development.

To address these questions, we re-assessed the PRISM cohort in adolescence and compared their performance with a term-born comparison group to establish if: (1) the substantial deficits observed in VP children's mathematical achievement at 8–10 years of age increased in adolescence; (2) the difficulties observed in VP children's specific mathematics skills extended to other more advanced skills, such as geometry and algebra; (3) working memory and visuospatial skills continued to explain any deficit in mathematics observed in adolescents born VP.

Materials and methods

Participants

Recruitment of the PRISM cohort has been previously described (for a flowchart see Trickett et al., 2020). All children born $<32^{+0}$ weeks' gestation from 01/09/2001 to 31/08/2003 and admitted for care in two UK neonatal centers were invited to participate at age 8–10 years. Of 266 eligible children, 115 who attended mainstream schools were recruited and assessed. These children were representative of the eligible population in sex, birthweight, gestational age and in socio-economic deprivation (measured by the National Statistics' Index of Multiple Deprivation (IMD), a composite measure of relative deprivation for small geographical areas across England) (Simms et al., 2015). A comparison group of 77 term-born (≥37 weeks' gestation) children was also recruited from age- and sex-matched classmates of the VP children (Simms et al., 2015).

For the present study, children in the PRISM cohort were invited to take part in an assessment in secondary school, of which the parents of 87 (76%) VP and 51 (67%) term-born participants provided consent. If an original term-born child did not take part in the assessment in adolescence or had moved to a different school to their matched VP child, a new term-born particpant was invited. In total, 31 new term-born adolescents matched for age and sex to a VP participant were recruited, resulting in a total of 82 adolescents in the comparison group. Two VP adolescents who now attended special school were excluded (as the study required participants to follow the national curriculum), one VP participant and one term-born participant withdrew from the study, and assessments could not be scheduled for one VP participant and three term-born participants. Therefore a total of 83 VP adolescents and 78 term-born adolescents were assessed.

To increase the sample size for cross-sectional analyses, VP adolescents born <32 weeks' gestation from 01/09/2001 to 31/08/2003 who were discharged alive from neonatal care in a third center (Nottingham, UK) were identified. Of 165 children identified, 8 had moved away from the local area and 22 could not be traced to determine their vital status and contact details. Therefore 135 children were invited to participate, of which 48 (36%) were recruited. Exclusion criteria were attendance at special school and severe neurosensory impairment that precluded participation in study assessments. Based on these criteria, two VP adolescents attending special school were excluded; no VP children were excluded due to severe neurosensory impairment. As assessments could not be scheduled for two VP adolescents, a total of 44 VP adolescents were assessed. Characteristics of these VP adolescents were compared to the remaining eligible population (N = 121). There were no significant differences in gestational age, birth-weight, deprivation (Smith et al., 2015) or sex, thus this sample was representative of the total population in this center. An additional 18 term-born classmates matched for age and sex to a VP participant were also recruited. As one classmate had not been educated in the UK, a total of 17 term-born adolescents were assessed.

Overall, 127 VP participants and 95 term-born participants were assessed at secondary school. Of these, 83 VP participants and 49 term-born participants were assessed at both primary and secondary school.

Procedure

Ethics approval was obtained from the Derbyshire NHS Research Ethics Committee (Ref 15/EM/0284). Parental consent and participant assent was obtained. Children were assessed in school (68%) or at home (32%) by one of two psychologists who were blind to study group membership. Inter-rater reliability was very high, with an average inter-class correlation of r = 0.997 over seventeen tasks.

Measures

Mathematics achievement

Mathematics achievement was assessed at both 8–10 and 11–15 years using the Wechsler Individual Achievement Test-II from which a mathematics composite score was derived. This provides an age-standardized composite score (mean 100; SD 15) which assesses children's ability to perform numerical operations and their mathematical reasoning.

General cognitive skills

A range of general cognitive skills were assessed at both 8–10 and 11–15 years. (1) Non-verbal IQ was assessed using the Raven's Colored Progressive Matrices (R-CPM) at 8–10 years and the Raven's Standard Progressive Matrices (R-SPM) at 11–15 years (mean 100, SD 15). (2) Working memory was assessed at both 8–10 and 11–15 years using a backwards digit recall task, a backwards word recall task and the "Mr X" visuospatial working memory task from the Automated Working Memory Assessment (Alloway, 2007). An average of the raw score on all three tests was used to compute a composite working memory score. (3) Processing speed was assessed at both 8–10 and 11–15 years using a composite of raw scores (reaction time) on the Rapid Automatized Naming Test (Wolf & Denckla). (4) At both 8–10 and 11–15 years, visuospatial processing, specifically the ability to judge line orientation, was assessed using the NEPSY-II (Korkman et al., 2007) Arrows subtest (mean 10, SD 3) in which children were shown an array of arrows arranged around a target and asked to indicate the arrow(s) that point to the center of the target. (5) Inhibition was assessed at both 8–10 and 11–15 years using the NEPSY-II Inhibition subtest (mean 10, SD 3) in which children were shown a series of black and white shapes or arrows and named either the shape or direction or an alternate response, depending on the color of the shape or arrow.

Specific mathematics skills

A range of skills that have been identified as separable components of mathematics were assessed at 11–15 years using experimental measures based on existing tasks used in the mathematical cognition literature.

(1) The precision of numerical representations was assessed via three computerized tasks in which participants were shown two quantities on a computer screen and were asked to select the more numerous. (1a) In a non-symbolic magnitude comparison task, participants compared two dot arrays. Quantities ranged from 5 to 30 and the ratio between the quantities varied (0.5, 0.6, 0.7, 0.8). The task consisted of 80 trials and performance was assessed using percentage accuracy. (1b) In a symbolic magnitude comparison task, participants compared two Arabic numerals. Quantities ranged from 5 to 30 and the ratio between the quantities varied (0.5, 0.6, 0.7, 0.8). The task consisted of 80 trials and performance was assessed using median RT for correct responses. (1 c) In a cross-notation task matching across notations, participants were asked to select which of two dot arrays matched a given Arabic numeral (40 trials) and which of two Arabic numerals matched a given dot array (40 trials). Quantities ranged from 5 to 28 and the ratio between the response options varied from 0.5 to 0.7. Percentage accuracy was recorded.

(2) Numerical estimation was assessed using a number line task in which participants were asked to mark the position of 22 different numbers on a series of blank number lines, with the left end labeled 0 and the right labeled 1000. Performance was assessed as the mean percentage absolute accuracy (100 – average distance between the actual and estimated positions of the numbers relative to the scale of the line).

(3) To assess basic number skills, participants completed three tasks. (3a) In a verbal counting task, participants were asked to count aloud four ascending (e.g., 2995–3004) and four descending number sequences (e.g., 325–317); total percentage accuracy was calculated. (3b) In a number reading task, participants were asked to read aloud a series of multidigit numbers presented on a computer screen (16 trials); numbers ranged from 853 to 2,543,703. (3 c) In a number writing task, participants listened to a series of spoken multidigit numbers and were asked to write these in digit form (16 trials); numbers ranged from 701 to 3,043,096. Percentage accuracy was recorded.

(4) Four tasks were used to assess arithmetic skills. (4a) Number fact knowledge was assessed by reading 16 simple arithmetic problems to participants and asking them to respond with the correct answer as quickly as possible. Correct answers produced within 3 seconds were considered to be known facts and the percentage of known facts was calculated. (4b) Mental arithmetic was assessed by presenting 12 single and double digit arithmetic problems and asking participants to solve these using any mental strategy they wished. Median response time for correctly solved problems was recorded. (4c) Written arithmetic was assessed by presenting 16 multidigit arithmetic problems (four each of addition, subtraction, multiplication and division) and asking participants to solve these on paper without a time limit. Percentage accuracy was recorded. (4d) Understanding of arithmetic concepts was assessed by presenting 26

pairs of large-number arithmetic problems on the computer. The correct answer to the first problem was presented and participants were asked to determine whether or not the first problem could be used to derive the answer to the second. On 18 trials the pairs of problems were related (by principles of subtraction-complement, inversion and associativity), and on 8 trials the problems were unrelated. Percentage accuracy in identifying whether or not problems were related was recorded.

(5) Algebra was assessed using 15 items from the Concepts in Secondary Mathematics and Science algebra test (completed on paper) (Hodgen et al., 2010). Percentage accuracy was recorded. The items required participants to compare the magnitude of algebraic expressions, perform simple arithmetic with algebraic expressions, and reason about algebraic expressions.

(6) Geometry was assessed using the first 15 items from the Van Hiele-Revised geometry test (completed on paper) (Usiskin, 1982). Percentage accuracy was recorded. The items required participants to identify regular and irregular shapes and to answer multiple-choice questions about the properties of individual and intersecting shapes.

Socio-economic status

An Index of Multiple Deprivation (IMD) score and rank was derived for each participant from their postcode of residence using National Statistics' English Indices of Deprivation (Smith et al., 2015) as a measure of socio-economic status (SES). Using national data, participants' IMD rank was classified into one of three groups representing low, middle and high areas of deprivation.

Statistical analysis

Group differences between VP and term-born participants on all measures were assessed using independent samples t-tests. Effect sizes were assessed using Cohen's *d* obtained using an online calculator (Lenhard & Lenhard, 2016). Bonferroni correction was applied to correct for multiple comparisons at domain level (i.e., general cognitive skills $p < 0.01$; specific mathematics skills $p < 0.004$). Multivariate analyses of covariance were conducted to assess differences between groups (VP vs. term-born) in mathematical achievement and specific mathematics skills controlling for working memory and visuospatial skills; effect sizes were reported as partial eta squared. Separate mixed ANOVAs were used to assess between-group (VP vs. comparison groups) and within-group (age at test: primary vs. secondary) main effects and interactions for mathematics achievement and general cognitive skills; effect sizes were reported as partial eta squared.

Results

Participant characteristics

Participant caracteristics are shown in Table 1. There were no significant differences in age, sex or SES between VP and term-born adolescents.

Analysis of dropouts (Table S1; Appendix) showed no significant difference between VP participants who were and were not re-assessed in adolescence in gestational age,

Table 1. Participant characteristics.

		Term-born adolescents N = 95	Very preterm adolescents N = 127	*p*
Gestational age, weeks	Mean (SD)	-	28.74 (1.91)	-
<28 weeks	N (%)	-	31 (24%)	-
28–31 weeks	N (%)	-	96 (76%)	-
Birthweight, grams	Mean (SD)	-	1219 (330)	-
<1000 g	N (%)	-	39 (31%)	-
1000–1499	N (%)	-	57 (45%)	-
≥1500 g	N (%)	-	31 (24%)	-
Male sex	N (%)	48 (51%)	71 (56%)	0.427
IMD score[a]	Mean (SD)	17.66 (16.09)	19.81 (15.87)	0.323
Low deprivation	N (%)	49 (52%)	57 (45%)	0.326
Mid deprivation	N (%)	26 (27%)	32 (25%)	-
High deprivation	N (%)	20 (21%)	38 (30%)	-
Age at assessment	Mean (SD)	13.70 (0.74)	13.87 (0.68)	0.076
School year at assessment		-	-	0.525
Year 7	N (%)	6 (6%)	4 (3%)	-
Year 8	N (%)	34 (36%)	41 (32%)	-
Year 9	N (%)	43 (45%)	60 (48%)	-
Year 10	N (%)	12 (13%)	22 (17%)	-

[a]IMD: Index of Multiple Deprivation (Smith et al., 2015)

birthweight, IQ or sex. However, fewer VP participants who were re-assessed in adolescence lived in areas of high deprivation than those who were not re-assessed (37% vs. 62%). Among term-born participants, there was no significant difference in children re-assessed and not re-assessed in IMD and sex. However, term-born children who were re-assessed had higher IQ than those who were not.

Mathematics achievement

VP adolescents had poorer achievement in mathematics, measured using the WIAT-II Mathematics Composite score, than term-born adolescents (difference in means −10.95; 95% CI −16.18, −5.73; Cohen's *d* 0.56). This remained significant after correction for multiple comparisons (Table 2).

Due to the Flynn effect, in which there is an upward drift in standardized test scores over time, it is recommended to use contemporaneous controls rather than normative test data for classifying impairment. Therefore, using the comparison group mean (SD) as the reference, low achievement in mathematics was classified using WIAT-II Mathematics Composite scores <73 (i.e., scores < −2 SD of the comparison group). Overall, 16 (13%) VP adolescents had low achievement compared with 3 (3%) term-born adolescents (Odds Ratio 4.42; 95% CI 1.23, 15.64).

General cognitive skills

As shown in Table 2, VP adolescents had poorer working memory (difference in mean raw composite score: −1.76; 95% CI −2.87, −0.65; *d* 0.44) and visuospatial skills (difference in mean scaled score: −1.16; 95% CI −2.00, −0.32; *d* 0.37) than term-born adolescents, both of which remained significant after correction for multiple comparisons. There were no significant between-group differences in IQ, processing speed or inhibition.

Table 2. Adolescents' performance on achievement tests, domain general cognitive tests and specific mathematics tests.

	Term-born adolescents		Very preterm adolescents				
Measure	N	Mean (SD)	N	Mean (SD)	Difference in means (95% CI)	p	Cohen's d
Mathematics achievement							
WIAT-II Mathematics CompositeST	95	107.46 (17.10)	127	96.51 (21.19)	−10.95 (−16.18 to −5.73)	<0.001*	0.56
General cognitive skills							
Non-verbal IQST	95	98.26 (18.10)	127	94.13 (17.84)	−4.13 (−8.93 to 0.67)	0.091	0.23
Working memory^{Raw}	92	16.36 (4.18)	125	14.60 (4.04)	−1.76 (−2.87 to −0.65)	0.002*	0.44
Speed of processing^{cRT}	95	23.68 (4.65)	125	25.24 (7.75)	1.56 (−0.21 to 3.33)	0.083	0.24
Visuospatial skills^{SC}	95	10.21 (3.00)	127	9.05 (3.24)	−1.16 (−2.00 to −0.32)	0.007*	0.37
Inhibition^{SC}	95	8.87 (3.42)	127	8.00 (3.70)	−0.87 (−1.83 to 0.08)	0.073	0.24
Specific mathematics skills							
Non-symbolic magnitude comparison$^{\%A}$	95	82.97 (7.99)	127	83.67 (7.01)	1.01 (−1.29 to 2.69)	0.491	0.09
Symbolic magnitude comparison^{mRT}	95	0.76 (0.18)	127	0.78 (0.21)	0.02 (−0.04 to 0.07)	0.578	0.00
Cross notation comparison$^{\%A}$	95	74.99 (9.25)	127	72.94 (9.94)	−2.04 (−4.62 to 0.54)	0.120	0.21
Number line estimation$^{\%A}$	95	96.08 (1.94)	127	94.98 (3.72)	−1.10 (−1.93 to −0.28)	0.009	0.36
Reading large numbers$^{\%A}$	95	96.78 (7.57)	127	92.77 (10.87)	−4.01 (−6.58 to −1.45)	0.002*	0.42
Writing large numbers$^{\%A}$	95	91.38 (10.83)	127	83.12 (17.75)	−8.26 (−12.32 to −4.20)	<0.001*	0.54
Counting skills$^{\%A}$	95	81.84 (17.84)	127	71.56 (23.13)	−10.29 (−15.91 to −4.66)	<0.001*	0.49
Number fact knowledge$^{\%A}$	95	77.43 (20.97)	127	67.52 (24.60)	−9.91 (−16.09 to −3.73)	0.002*	0.43
Mental arithmetic^{mRT}	95	7.49 (3.27)	124	8.93 (3.87)	1.45 (0.47 to 2.42)	0.004	0.39
Written arithmetic$^{\%A}$	95	76.78 (18.77)	127	66.68 (23.91)	−10.09 (−15.94 to −4.25)	0.001*	0.46
Understanding of arithmetic concepts$^{\%A}$	95	92.24 (10.33)	127	84.65 (16.52)	−7.59 (−11.39 to 3.79)	<0.001*	0.53
Algebra$^{\%A}$	95	66.11 (19.39)	127	53.96 (25.45)	−12.14 (−18.31 to −5.98)	<0.001*	0.53
Geometry$^{\%A}$	95	48.98 (15.00)	127	45.25 (14.37)	−3.73 (−7.65 to 0.18)	0.061	0.25

Note: ST Standard scores (Mean 100, SD 15). ^{SC} Scaled scores (Mean 10, SD 3). $^{\%A}$ Percent accuracy score. ^{Raw} Raw composite score for verbal and visuospatial working memory (range 5.7–25.0). ^{cRT} Composite reaction time (seconds). ^{mRT} Median reaction time (seconds). 3 participants do not have a composite working memory score due to experimenter error in task administration.
*Significant after correction for multiple comparisons: Mathematics achievement $p < 0.05$; general cognitive skills $p < 0.01$; specific mathematics skills $p < 0.004$.

Specific mathematics skills

As shown in Table 2, there was no significant difference in the precision of numerical representations between VP and term-born adolescents, measured using either the non-symbolic magnitude comparison task, symbolic comparison task or cross-notation matching task. However, VP adolescents had significantly poorer performance than term-born adolescents on tests of reading and writing large numbers, counting, number fact knowledge, written arithmetic, understanding of arithmetic concepts and algebra, all with small to medium effect sizes (Cohen's *d* 0.42 to 0.54). These remained significant after correction for multiple comparisons. VP adolescents also had poorer performance on tests of number line estimation and mental arithmetic, however these differences were not significant after correction for multiple comparisons. There was no significant between-group difference in geometry.

Controlling for working memory and visuospatial skills

As shown in Table 3, between-group differences in specific mathematical skills were no longer significant when working memory and visuospatial skills were controlled for, with the exception of writing large numbers and conceptual understanding of arithmetic. The between-group difference in mathematics achievement (WIAT-II Mathematics Compsite score) also remained significant after controlling for working memory and visuospatial skills.

Change over time in mathematics achievement and general cognitive skills

Overall, 83 VP adolescents and 49 term-born adolescents were assessed at both ages. Descriptive statistics for their performance on tests of mathematical achievement and general cognitive skills are shown in Table 4 and tests of differences between groups and age at assessment, and their interaction, are shown in Table 5 and Figure 1. Significant main effects indicated that VP participants performed worse than term-born participants in mathematical achievement ($p < 0.001$) and that mean WIAT-II scores increased over time in both groups ($p = 0.011$). However, as the group x time interaction was not significant ($p = 0.896$), the between-group difference in mathematical achievement remained stable over time. A similar pattern of results was found for the general cognitive skills assessed in this study, in which there was a significant main effect of group, with term-born participants outperforming VP

Table 3. Multivariate analyses of covariance results for group differences in mathematics achievement and specific mathematics skills between 122 very preterm adolescents and 92 term-born adolescents controlling for working memory and visuospatial skills.

Measure	df	F	p	Partial η2
Mathematics achievement	1, 210	5.70	0.018	0.026
Number line estimation	1, 210	0.86	0.354	0.004
Reading large numbers	1, 210	1.82	0.178	0.009
Writing large numbers	1, 210	5.67	0.018	0.026
Counting skills	1, 210	2.56	0.111	0.012
Number fact knowledge	1, 210	1.32	0.253	0.006
Mental arithmetic	1, 210	3.18	0.076	0.015
Written arithmetic	1, 210	3.25	0.073	0.015
Understanding of arithmetic concepts	1, 210	5.39	0.021	0.025
Algebra	1, 210	3.78	0.053	0.018

Table 4. Descriptive statistics for test results among 83 very preterm adolescents and 49 term-born adolescents assessed at both primary (age 8–10 years) and secondary (age 11–15 years) school.

	Term-born adolescents						Very preterm adolescents					
	Primary (8–10 years)			Secondary (12–14 years)			Primary (8–10 years)			Secondary (12–14 years)		
	N	Mean	SD	N	Mean	SD	N	Mean	SD	N	Mean	SD
Mathematics achievement	49	107.86	18.34	49	110.51	18.60	83	93.07	19.86	83	95.47	21.33
Nonverbal IQ	49	109.90	14.70	49	100.41	17.23	83	100.35	17.24	83	93.80	17.87
Working memory	46	14.54	3.69	46	17.51	4.58	81	11.88	3.18	81	14.72	4.28
Processing speed	49	29.26	5.62	49	23.32	4.47	80	33.64	10.03	80	24.95	5.91
Visuospatial skills	49	10.94	2.72	49	10.78	3.07	82	8.91	3.53	82	8.98	3.43
Inhibition	49	10.04	3.18	49	9.39	3.26	83	8.54	3.54	83	7.90	3.76

Table 5. Differences in mathematics achievement and general cognitive skills between groups (very preterm [n = 83] vs. term-born [n = 49]) and age at assessment (primary vs. secondary school), and group by time interactions.

	Group				Age at assessment				Group x age interaction			
	df	*F*	*p*	Partial η2	df	*F*	p	Partial η2	df	*F*	*p*	Partial η2
Mathematics achievement	(1,130)	18.81	<0.001	0.126	(1,130)	6.65	0.011	0.049	(1,130)	0.02	0.896	<0.001
Nonverbal IQ	(1,130)	8.82	0.004	0.064	(1,130)	32.48	<0.001	0.200	(1,130)	1.09	0.299	0.008
Working memory	(1,125)	17.21	<0.001	0.121	(1,125)	92.43	<0.001	0.425	(1,125)	0.05	0.828	<0.001
Processing speed	(1,127)	6.53	0.012	0.049	(1,127)	164.19	<0.001	0.564	(1,127)	5.85	0.017	0.044
Visuospatial skills	(1,129)	14.31	<0.001	0.100	(1,129)	0.03	0.868	<0.001	(1,129)	0.133	0.716	0.001
Inhibition	(1,130)	7.70	0.006	0.056	(1,130)	3.84	0.052	0.029	(1,130)	<0.001	0.982	<0.001

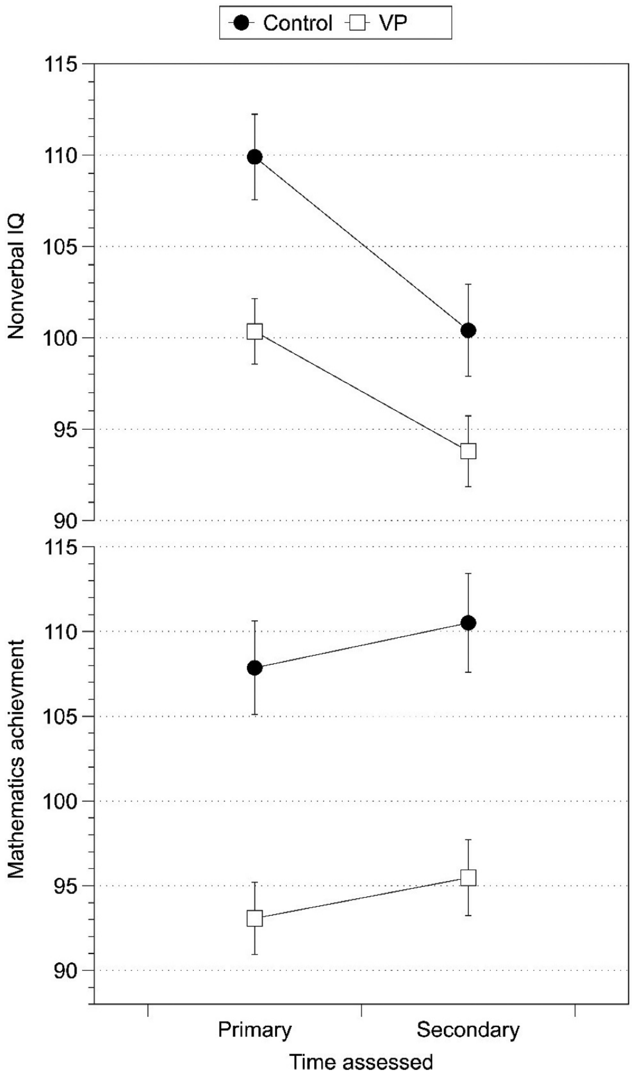

Figure 1. Non-verbal IQ and mathematics achievement at primary (age 8–10 years) and secondary school (age 11–15 years) in very preterm (n = 83) and term-born adolescents (n = 49). Error bars represent standard error. IQ at primary school was assessed using Raven's Colored Progressive Matrices, and at secondary school using Raven's Standard Progressive Matrices. Mathematics achievement was assessed using the Wechsler Individual Achievement Test 2nd Edition at both time points.

participants on all measures, and a significant main effect of age for non-verbal IQ, working memory and processing speed; non-verbal IQ decreased over time and performance on working memory and processing speed tests improved over time in both groups. However, there was no significant group x time interaction for non-verbal IQ, working memory, visuospatial skills and inhibition. The exception was processing speed for which VP individuals performed worse than term-born individuals in primary ($F(1,127) = 7.84$, $p = 0.006$) but not secondary school ($F(1,127) = 2.74$, $p = 0.100$).

Discussion

To our knowledge, this is the first study to comprehensively assess VP adolescents' mathematics skills. We found that VP adolescents had poorer performance than their term-born classmates on tests of six domain-specific skills, namely, knowledge of basic number facts, conceptual understanding of arithmetic, written arithmetic, counting, and reading and writing large numbers. We also found that whilst VP adolescents had similar performance in geometry, they were poorer at algebra than their term-born peers. Thus VP adolescents displayed deficits in multiple separable components of mathematics including a range of factual, procedural and conceptual skills and higher order mathematical operations.

In our previous study we showed that VP children had deficits in working memory and visuospatial skills and that these accounted for their deficits in domain-specific mathematics skills, namely counting and the use of mature strategies to solve arithmetic problems at age 8–10 years (Simms et al., 2015). Similarly, the between-group differences observed in VP adolescents' specific mathematics skills and algebra were negated after controlling for working memory and visuospatial skills, with the exception of writing large numbers and conceptual understanding of arithmetic. This is consistent with our previous findings and with those of others who have demonstrated that general cognitive skills mediate the relationship between VP birth and achievement in mathematics (Aarnoudse-Moens et al., 2013; Adrian et al., 2020; Akshoomoff et al., 2017; Hasler & Akshoomoff, 2019; Twilhaar et al., 2020; Van Veen et al., 2019). VP adolescents' poorer performance in writing but not reading numbers may have persisted after adjustment for working memory and visuospatial skills due to the well-documented deficits in fine motor skills in VP populations (Allotey et al., 2018). The between-group difference in conceptual understanding may also have persisted as this relies less on executive functions (e.g., working memory) than factual and procedural skills (Cragg et al., 2017). Notably, VP adolescents did not have poorer performance on tests of numerical representations. This replicates and extends our findings at age 8–10 years (Simms et al., 2015) and provides further evidence that VP children's mathematics difficulties are driven by deficits in domain-general rather than domain-specific cognitive skills.

We also found that the substantial deficit in VP children's mathematics achievement in primary school (*d* 0.62) (Simms et al., 2015) persisted with a similar magnitude in secondary school (*d* 0.56). This was contrary to our expectation that the deficit might have increased over time due to an increasingly complex mathematics curriculum that exerts greater cognitive demands in secondary school. This study extends findings of a persistent deficit in mathematics achievement among VP children over the primary school years (Twilhaar, de Kieviet et al., 2019) and in global academic achievement throughout compulsory schooling amongst all children born preterm (Odd et al., 2019). Moreover, it is consistent with earlier longitudinal studies of VP/ELBW cohorts born in the 1980s (Botting et al., 1998; Clark et al., 2013; Saigal et al., 2000).

Our exploration of the change in general cognitive skills from primary to secondary school also showed that the deficit in VP children's non-verbal IQ, working memory and visuospatial skills observed at age 8–10 was still evident at age 11–15 years. Given the association of working memory and visuospatial skills with VP adolescents' mathematics skills, the continued deficit in these skills is likely to go some way in explaining the persistent deficit in mathematics achievement. Our findings are commensurate with other studies in which stable deficits in IQ have been observed from childhood to adulthood in individuals born very and extremely preterm (Breeman et al., 2015; Linsell et al., 2018; Mangin et al., 2017). In contrast, we found that VP adolescents' deficit in processing speed decreased over time, however this did not appear to impact on their mathematics achievement. This finding may be explained by improved shape/letter/color knowledge or automaticity of naming in adolescence but requires further investigation in longitudinal studies to determine the developmental trajectory of different components of processing speed in the VP population.

As mathematics difficulties cast a long shadow over an individual's lifelong health, economic potential and employment prospects (Crawford & Cribb, 2013), interventions are needed to improve achievement in VP populations. Attention has been paid to the potential for working memory or executive function training programmes to improve performance at school. However, as yet there is no robust evidence of their beneficial effect on achievement (Anderson et al., 2018; Melby-Lervag et al., 2016). There is also growing interest in spatial training for improving performance in mathematics which has shown promising results (Gilligan et al., 2020), but has not yet been trialed in preterm populations. Alternative approaches to intervention may lie in improving education professionals' knowledge of the impact of prematurity and their skills in adapting the learning environment to accommodate VP children's general cognitive difficulties (Johnson et al., 2019), but this requires further evaluation to determine its efficacy in improving children's educational outcomes.

The strengths of this study lie in the recruitment of a cohort that was representative of the VP population in baseline clinical characteristics, a term-born comparison group matched on key characteristics affecting outcomes, the detailed assessment of a range of specific mathematics skills using both standardized and experimental measures alongside general cognitive skills and achievement at school, and the longitudinal nature of the study comprising assessments at both primary and secondary school age.

The study is not without limitations. Where possible, identical measures were used at both time points. If this was not possible, tests of the same skills were adapted to be developmentally appropriate to facilitate the comparison of outcomes over time. However, the age at which the two assessments were conducted necessitated the use of different versions of the IQ test. As such, IQ scores were observed to decline over time, perhaps due to the change in the measure, whilst achievement test scores using the same measure, in particular those using raw scores, generally increased over time. In order to minimize problems associated with the use of different measures, the same comparison group was used at both ages to allow us to interpret any changes over time in the VP group. The study was also affected by attrition as only 76% of the parents of VP children and 67% of parents of term-born children assessed at age 8–10 years provided consent for their child to be re-assessed in adolescence. To explore the potential effect of attrition, our dropout analysis revealed that VP adolescents assessed at both time points had similar characteristics to those that were lost to follow up but were less likely to live in areas of high deprivation. Similarly, term-born participants assessed in adolescence had higher IQ than those who were not re-assessed. Given the association of socio-economic factors with neurodevelopmental outcomes, this may have resulted in overestimation of cognitive abilities and mathematical achievement relative to the total population in both groups. It is also important to note that, as VP adolescents in special schools were excluded, we may have underestimated the total impact of VP birth on cognitive and academic outcomes. Moreover, for participants recruited in adolescence, we did not have data on their neonatal course to be able to compare risk factors for poor neurodevelopmental outcomes between VP children who were and were not recruited to the study for this sub-sample.

In summary, VP adolescents had substantially poorer achievement in mathematics than their term-born peers and poorer performance on tests of number fact knowledge, counting, reading and writing numbers, written arithmetic, understanding of arithmetic concepts, and algebra. Their lower achievement in mathematics persisted from primary to secondary school, as did their underlying general cognitive deficits, which largely accounted for their poorer performance in mathematics. Educational support is needed from the earliest opportunity to facilitate improved outcomes for VP children.

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