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Mathematics difficulties in children born very preterm: current research and future directions

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ABSTRACT

Children born very preterm have poorer attainment in all school subjects, and a markedly greater reliance on special educational support than their term-born peers. In particular, difficulties with mathematics are especially common and account for the vast majority of learning difficulties in this population. In this paper, we review research relating to the causes of mathematics learning difficulties in typically developing children, and the impact of very preterm birth on attainment in mathematics. Research is needed to understand the specific nature and origins of mathematics difficulties in very preterm children to target the development of effective intervention strategies.

Over the past three decades, there has been a substantial increase in survival rates for children born very preterm (VP; <32 weeks) or with very low birth weight (VLBW, <1500 g).[1] This has been accompanied by increasing preterm birth rates resulting in a growing number of preterm survivors in recent years.[2] Despite improved survival, long-term outcomes have remained remarkably consistent.[3 4] Although severe disabilities, such as neurosensory impairments and cerebral palsy are associated with VP birth, the most common childhood impairments are neurocognitive deficits.[5] The average weighted mean difference in general intelligence between children born <28 weeks/<1000 g (ELBW: extremely low birth weight) and their term-born peers has been reported as 11 IQ points, with greater deficits found for children born <26 weeks of gestation.[6 7]

Neurocognitive deficits can have a wide-reaching impact on children's learning and academic performance. As such, 53% of ELBW children are reported to have school problems in comparison with 13% of term-born peers.[8] These difficulties are observed in the pre-school years and persist throughout schooling.[9 10] There are also increased rates of special educational needs (SEN); up to 2/3 of children born <26 weeks/ELBW require SEN support in school.[11 12] Compared with term-born children, school difficulties and SEN are significantly increased in children born across the full spectrum of preterm gestations, including children born near term (37–38 weeks gestation).[13 14]

Although VP children have poor performance across all school subjects,[15 16] they have specific difficulties with mathematics.[8 17 18] A recent meta-analysis identified a 0.60 SD deficit in mathematics scores compared with a 0.48 SD deficit in reading.[19] These differences persist after controlling for IQ[11 16 20 21] or excluding children who have neurosensory impairments.[11 18] Using discrepancy-based measures (ie, a significant difference between IQ and academic attainment), VP children also have increased rates of learning difficulties in mathematics compared with other subjects: for example, 23% of VLBW children have specific mathematics difficulties compared with 10% in reading.[22] It has been suggested that mathematics difficulties become more pronounced with age in VP children, perhaps due to the increasing complexity of tasks, or to the cumulative effects of early problems, however, more thorough longitudinal studies are needed to confirm this.[10] As mathematics skills are predictive of overall educational attainment, future employment and economic productivity, the selective difficulty that VP children experience in this area is likely to have far-reaching consequences.[23 24] Although mathematics difficulties are widely reported, the nature and causes of these problems in preterm children are poorly understood.[10 25]

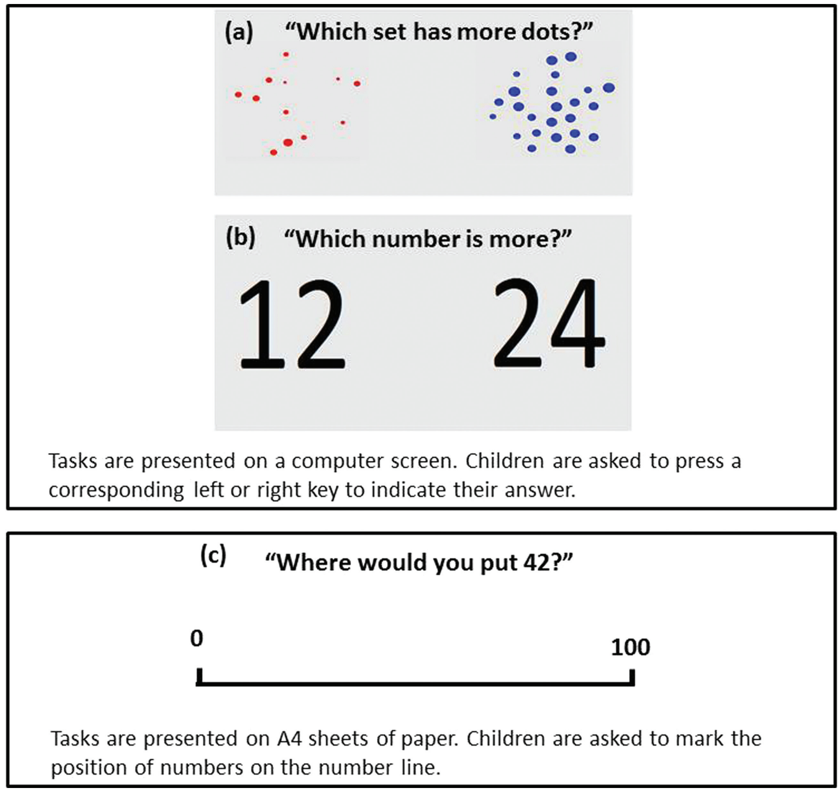
Solving mathematical problems uses numerous component processes, or domain-specific skills. Strengths and weaknesses in these domain-specific skills affect an individual's overall proficiency with mathematics and performance in curriculum-based achievement tests.[26] Additionally, a variety of more general cognitive skills, termed domain-general skills, contribute to overall proficiency.[27] In this paper, we review developmental psychology literature pertaining to domain-specific and domain-general factors underlying the typical development of mathematics before applying this to help advance our understanding of the nature and causes of mathematics difficulties in preterm populations.

DOMAIN-SPECIFIC PREDICTORS OF MATHEMATICAL ABILITY

There is burgeoning evidence that a range of domain-specific skills are required to perform mathematics. Numerous studies indicate that having precise and accurate internal representations of number has a positive effect on overall achievement.[28–30] Experimentally, the nature of numerical representations is explored by asking children to discriminate between sets of non-symbolic or symbolic quantities (figure 1a,b, respectively),[31] or to place numbers on a number line (figure 1c).[32] Neuroimaging research has indicated that the nature of internal numerical representations is linked to the functioning of the left and right horizontal intraparietal sulci, areas which are believed to be responsible for low-level numerical processing.[33]

Children's ability to carry out basic mathematical procedures, such as being able to count sets of objects (eg, accurately counting a set of buttons)

Figure 1 Examples of experimental tests used to assess non-symbolic numerical representations (a), symbolic representations (b) and number line tasks (c).



and recite a number word list (eg, counting accurately and unassisted) have also been identified as important predictors of mathematical success.[32] Additionally, the ability to assess, select and apply appropriate computational strategies is an important skill. Taking the development of addition strategies as an example, children develop from using predominantly finger-based counting strategies in the early years, to using verbal counting strategies, before reaching maturation with the dominance of retrieval strategies.[34 35] Mathematical success is related to the accurate and efficient application of the most appropriate strategies in different scenarios.[36 37]

Basic conceptual understanding of mathematics is also important for the development of mathematics skills: young children who show a grasp of the rules that govern the counting process, measured, for example, by pointing out when a cartoon character makes a counting mistake (figure 2a), outperform their peers on achievement tests.[38] Complex conceptual understanding of mathematical processes (figure 2b) is also linked to the successful development of calculation skills,[39] and has been shown to underpin complex mathematical processing providing a foundation stone for mathematical development.[26] These multiple domain-specific components are essential for success in mathematics and a difficulty with one component may cascade into problems with another.[40] This may be due to over-reliance on competent strategies or skills to the detriment of the development of more effective strategies.

DOMAIN-GENERAL PREDICTORS OF MATHEMATICAL ABILITY

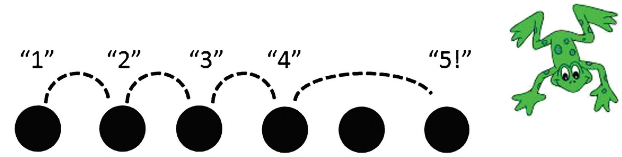
A range of domain-general factors, such as language,[41] processing speed[42] and general intelligence,[43] contribute to success in mathematics. In particular, executive functions; skills required to monitor and control thought and action, have been found to be critical. Correlational studies have demonstrated that working memory, the ability to hold and manipulate information in mind, accounts for unique variance in written and verbal calculation, as well as mathematical word problems, across a range of different age groups.[44] Experimental studies investigating the role of working memory in different strategies have shown that it plays a larger role in procedural strategies, particularly counting, compared with retrieval strategies.[45] Importantly, it is the ability to manipulate and update, rather than simply maintain information in working memory, that seems to be critical for mathematics proficiency. The executive skills of inhibition, the ability to suppress distracting information and unwanted responses[46] and shifting, the ability to flexibly switch attention between different tasks,[47] have also been implicated in mathematics achievement.

MATHEMATICAL LEARNING DIFFICULTIES

One way to identify the mechanisms underlying VP children's difficulties with mathematics is to examine the characteristics of term-born children who have mathematical learning difficulties. However, a critical issue here is differences in the criteria used for defining mathematical learning difficulties, stemming from a lack of consensus in the definition of the developmental disorder itself.[48] Research, to date, has used a variety of criteria, the most popular being a discrepancy-based definition; for example, a low mathematics test score (<25th or <30th percentile) in combination with low, average or above IQ (ie, scores of 80–120).[49] A major problem with discrepancy-based definitions is the lack of sensitivity of these criteria; children with a clear discrepancy between IQ and mathematical performance will be identified as having problems, however, children with low IQ, but who also have specific difficulties with mathematics, may not.[48] Mathematical learning difficulties in VP populations may, therefore, be underestimated using such criteria. Other conventional identification methods, such as low standardised mathematics scores irrespective of IQ (eg, <25th percentile on a standardised test),[50] or consistently poor mathematical

Figure 2 Examples of experimental tasks used to measure children's conceptual understanding of mathematics.

(a)



Children watched a frog count or miscount a set of items. Children were asked "Did Hoppy make a mistake, or no, he made no mistakes?" Children were given a forced-choice response option, either "Yes" or "No" (adapted from a task developed by LeFevre et al. (38)).

(b) (i)

94 + 68 = 162

68 + 94 = ?

(ii)

36 + 98 = 134

134 – 36 = ?

Children were presented with a problem with an answer, they were then presented with a related problem without an answer. Children are asked to give an answer to the second problem as quickly as possible. By responding within 10 seconds children show conceptual understanding of, for example, (i) commutativity and (ii) the reverse relationship between addition and subtraction.

achievement over a period of two school years,[51] may be more appropriate for this population.

Research with non-clinical populations has identified a variety of factors associated with mathematical learning difficulties. Two distinct profiles can be identified. Many children with mathematical learning difficulties may have poor domain-general skills, particularly working memory, visuospatial skills, or attention (eg, see ref [52] for a review). While their underlying difficulties may have a domain-general source, this results in a specific impairment with mathematics achievement. Other children appear to have a specific deficit with numerical representations, often termed 'Developmental Dyscalculia' (DD), which can lead to profound difficulties learning even basic mathematics. The underlying functional deficit is thought to be imprecise and inaccurate representations of numbers which may affect the representations of numerical symbols themselves, the representation of semantic magnitude information, or the connection between the symbolic and semantic information (eg, refs. 53–55). Nevertheless, these difficulties all lead to problems with simple tests of numerical magnitude (eg, figure 1a,b), as well as higher-order mathematical skills. Neuroimaging research has explored whether DD is associated with measureable differences in the structure or function of the intrapareital sulci, areas identified as key for basic numerical processing, with mixed results. While some studies have found evidence for differences between DD and control participants in activation patterns in this region,[56 57] others have found no difference.[58]

MATHEMATICAL DIFFICULTIES IN VERY PRETERM CHILDREN

Mathematics difficulties in VP children have been investigated as part of a comprehensive outcome assessment in population-based studies. Table 1 summarises case-control studies of mathematical achievement in cohorts born since 1990. As the achievement measures used vary between studies, standardised effect sizes are provided for comparison.

All differences between VP and term-born children in standardised mathematics tests are of moderate to large effect sizes, with the greatest effect found for children who were born extremely preterm/ELBW.[16] Remarkably similar effect sizes have also been observed using curriculum-based measures[21] and teacher reports.[16 18 20] This suggests that simple teacher ratings, such as the Teacher Academic Attainment Scale (TAAS), can be used with confidence to assess achievement in mathematics where standardised tests are not feasible.[11] Given the wide variation in mathematics tests, comparing between studies is problematic. However, when identical measures are used, such as the Woodcock–Johnson-III, a similar pattern of difficulties is observed across studies with VP children displaying larger deficits in the Applied Problems subscale compared with the Math Fluency subscale[59 60]; this indicates greater difficulty with the application of mathematical concepts, rather than with knowledge of basic mathematics facts. Thus, VP children's problems in mathematics may be related to the application of domain-specific skills in more complex mathematical problem-solving scenarios, rather than performance in low-level mathematical tasks. Importantly, a major problem with the use of standardised tests is that it is impossible to pinpoint the specific areas of mathematics with which children struggle. Although significant progress has been made in understanding the aetiology of general cognitive deficits in VP children,[61 62] the exact nature and causes of their difficulty with mathematics remain poorly understood.[25 63]

Domain-specific predictors of mathematical difficulties in very preterm children

A major limitation of existing studies is their reliance on standardised tests. These very general tests provide a single composite measure of attainment in mathematics and do not allow exploration of specific areas of difficulty. Only a handful of studies have used tests of domain-specific skills in an attempt to pinpoint areas of deficit, from which it has been suggested that

Table 1 Summary of studies with preterm children (born after 1990) using measures of achievement in mathematics

Study	Birth year	Age (years)	Sample number: Index	Sample number: Control	Index Selection Criteria: Birth weight (g)	Index Selection Criteria: Gestational age (weeks)	Achievement test	Effect size
Anderson & Doyle (2003)	1991–1992	8	275	223	<1000	<28	WRAT arithmetic	0.64
							CSSS mathematics	0.65
Esbjorn, Hansen, Greissen & Mortensen (2005)	1994–1995	5	207	76	<1000	<28	WPPSI arithmetic	0.50
Pritchard, Clark, Liberty, Champion, Wilson, & Woodward (2009)	1998–2000	6	102	108	–	<33	WJ-III math fluency	0.77
							Mean stage on numeracy framework	0.61
							Teacher rating below average/delayed maths	0.67
Taylor, Klein, Anselmo, Minich, Espy & Hack (2011)	2001–2003	5.96	148	111	<1000	<28	WJ-III math fluency	0.31
							WJ-III applied problems	0.65
							Sum of teacher ratings of learning progress; Maths	0.63
Aarnoudse-Moens, Oosterlaan, Duivenvoorden, van Goudoever & Weisglas-Kuperus (2011)	1996–2004	8	200	230	–	<30	Dutch National Pupil Monitoring System	
							Pre-school Reasoning Test	0.4
							Primary Mathematics/ Arithmetic Test	0.6
Johnson, Wolke, Hennesy & Marlow (2011)	1995	10.9	219	153	–	<26	WIAT-II numerical operations	1.5
							WIAT-II mathematical reasoning	1.3
							teacher-rated assessment; Maths	1.4
Rose, Feldman & Jankowski (2011)	1995–1997	11.18	44	90	<1750	< 37	WJ-III math fluency	0.22
							WJ-III applied problems	0.53
Litt, Taylor, Margevicius, Sschluchter, Andreias, & Hack (2012)	1992–1995	8	181	115	<1000	–	WJ-R calculation	0.88
		14					WJ-R calculation	0.63

All effect sizes were reported or calculated based on unweighted means and SDs.
CSSS, Comprehensive Scales of Student Success; WIAT-III, Weschler Individual Achievement Test-III; WJ-III, Woodcock Johnson-III; WJ-R, Woodcock Johnson-Revised; WPPSI, Weschler Preschool and Primary Scale of Intelligence Revised; WRAT, Wide Range Achievement Test.

VP children have basic numerical processing deficits similar to children with DD. A neuroimaging study found that VP (<33 weeks) children with calculation difficulties had significantly less grey matter in the left parietal lobe than those without calculation problems.[22] As this area is believed to be responsible for basic numerical processing,[64] the authors concluded that impairments in these types of low-level skills were responsible for poor achievement in mathematics. However, no other domain-specific skills were assessed, and conflicting evidence from another sample of VP children suggests similar basic number processing as term-born controls, implying that these basic processes are an unlikely source of VP children's mathematical difficulties.[65] In only one other study in which diagnostic interviews were used, specific issues with number sequences, number identification and place value were identified as problems areas.[18] Due to the lack of research investigating low-level numerical processes in VP children, it is difficult to establish whether these factors do indeed contribute to their deficits in mathematics and impossible to ascertain whether they have similar cognitive profiles as children with DD.

In a recent report from the EPICure Study cohort, we established that basic number processing, as measured by a brief estimation test like those shown in figure 1, predicted mathematical performance in extremely preterm children and, thus, provided evidence of a domain-specific deficit in this population. However, this was alongside domain-general simultaneous and sequential processing skills, reading ability and visuospatial skills, which were also significant predictors of achievement.[66] In fact, these domain-general skills explained substantially more variance in mathematics scores for the extremely preterm population compared with controls (70% vs 48%, respectively). Thus, we hypothesise that the mathematics difficulties associated with preterm birth are likely to be the result of a complex interplay between both domain-specific and domain-general factors.

Domain-general predictors of mathematical difficulties in very preterm children

Although little research has been focused on domain-specific mathematics processes, there is now a large body of studies that have investigated the impact of VP birth on domain-general cognitive skills, and these have highlighted a variety of potential causes for difficulty with mathematics. A number of studies suggest that VP children's difficulties with mathematics originate from poor IQ[7]; that is, general intelligence impairments impact more substantially on mathematical attainment than any other academic subject. Deficits in speed of processing, over and above poor IQ, are commonly observed, which may also contribute to mathematical difficulties.[15] As many attainment tests are timed, the effect of slow encoding and processing of information can have obvious effects on performance. In fact, slow processing speed has been suggested as a core deficit underlying numerous cognitive deficits in this group.[59] VP children also find simultaneous processing of information a particular struggle; this is a pertinent ability for mathematics, for example, being able to encode various pieces of concurrently presented information in order to successfully carry out a mental calculation.[11 16]

Executive functions have also been identified as an important set of skills for mathematical attainment in VP children.[25 67] Particular areas of deficit include verbal fluency, planning and verbal/spatial working memory.[68] As already mentioned, working memory is critical for mathematical performance, and spatial working memory and spatial span length have been shown to be strong predictors of mathematical performance in VLBW children.[10] Poor visuospatial skills are also common in VP children and have been shown to contribute to their difficulty in mathematics.[16 17 69 70] Even at 3–4 years of age, deficits in visuospatial processing and spatial working memory are evident[71]; such skills may be important for the development of early number skills, particularly, learning the process of counting.[72] Poor early number knowledge, such as difficulties in mastering counting and sorting in preschool, has also been suggested as a potential cause of poor mathematical skills in VLBW children, however, these developmental pathways have not been robustly tested.[21]

FUTURE DIRECTIONS FOR RESEARCH

There are a number of key methodological issues relating to existing research into mathematical difficulties in VP children. First, the selection of control groups is pertinent. Mathematical performance is affected by educational experience and, therefore, the use of appropriate controls is important. Numerous studies either compare the performance of preterm children to set norms,[22] or to groups of children from different schools.[7] Future studies should endeavour to carefully match preterm children to term-born classmates in order to reduce the impact of different educational input on assessment of performance.

Second, the over-reliance on standardised tests does not help identify specific areas of difficulty. In order to develop effective educational interventions, it is essential to identify common specific difficulties and their underpinning cognitive factors.[25] The use of more detailed mathematical diagnostic tests and experimental measures of basic mathematics skills (such as those detailed in figures 1 and 2) should enable a better understanding of VP children's mathematical processing profiles.

Third, as the vast majority of previous studies have focused predominantly on general cognitive processes *or* used very brief measures of specific mathematical skills,[66] it is difficult to identify the cognitive mechanisms that underpin VP children's difficulties. Future studies should explore multiple domain-specific components[27 39] and *concurrently* investigate domain-general cognitive skills in order to quantify the relative contributions of these factors to curriculum-based achievement.

IMPLICATIONS

Many VP children have particular difficulty with mathematics. Therefore, clinicians and teachers may wish to monitor performance in this subject. There are a number of standardised assessment batteries that may be suitable in this case. For example, the Weschler Individual Achievement Test[73] includes assessments of numerical operations (paper and pencil calculations) and mathematical reasoning skills (applying mathematical skills to real-world scenarios, eg, telling the time or using money). Careful analysis of errors on these tests may indicate specific areas of difficulty for individual children. The Test of Early Mathematics Ability[74] is also a useful diagnostic tool in the form of a semistructured interview focusing on informal and formal mathematics concepts. This assessment can be used to identify strengths and weaknesses in children's knowledge and also provides some suggestions for interventions. As with numerous other cognitive difficulties, early identification and intervention appears to have most success in improving mathematical outcomes.[75]

As we do not currently know the specific areas of mathematics with which VP children struggle, or the cognitive mechanisms that underpin these difficulties, we cannot as yet recommend appropriate interventions. However, we can make some suggestions for interventions that may show promise for VP children. In relation to domain-general skills, the adaptive computerised working memory intervention 'Cogmed'[76] has received recent interest in terms of transfer to performance on untrained working memory skills,[77 78] attention[77] and non-verbal IQ.[78] Recently, there has been some success with this intervention with small groups of VLBW pre-schoolers[79] and ELBW adolescents,[80] with improvements in a variety of memory tasks and attention. However, more carefully controlled intervention studies are required to confirm the efficacy of this intervention and to demonstrate evidence of transfer to academic performance, which is currently lacking.[81] For domain-specific skills, simple board games have been noted to improve the internal numerical representations of children from low-income backgrounds, with evidence of transfer to simple additional fact retrieval, a core skill in basic mathematics.[82] The use of concrete Q9
manipulatives, such as blocks or rods, in the classroom has also had some success in improving mathematical performance (75 for review). However, again, more wide-scale, well-controlled studies are required to substantiate the effects of these interventions. It is anticipated that with a deeper understanding of VP children's specific difficulties in mathematics, targeted and effective interventions can be developed.

CONCLUSIONS

VP children have specific difficulties in mathematics that can have lifelong consequences. A major limitation of existing research is the reliance on standardised tests that provide a single, composite measure of achievement. Cognitive psychologists are continuing to develop experimental paradigms for assessing components of mathematics skills, but as yet, research has not capitalised on these advances to study preterm populations. Among the handful of studies that have investigated the impact of preterm birth on specific components of mathematics, the results are equivocal and suggest both low-level and higher-order mathematics skills may be affected. As yet, no studies have concurrently investigated both domain-general and domain-specific skills. Such studies are needed to determine the nature and cause of mathematics difficulties in preterm populations. VP children are part of a new generation of children with complex learning difficulties who are different in nature to those found in more mature populations.[83] Understanding the similarities and differences in the processes underlying mathematics difficulties between VP and term-born children is needed for developing intervention strategies to improve achievement in this core academic subject, and also the lifelong outcomes of this growing population.

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