Do children with Developmental Dyscalculia **have an order processing deficit?**

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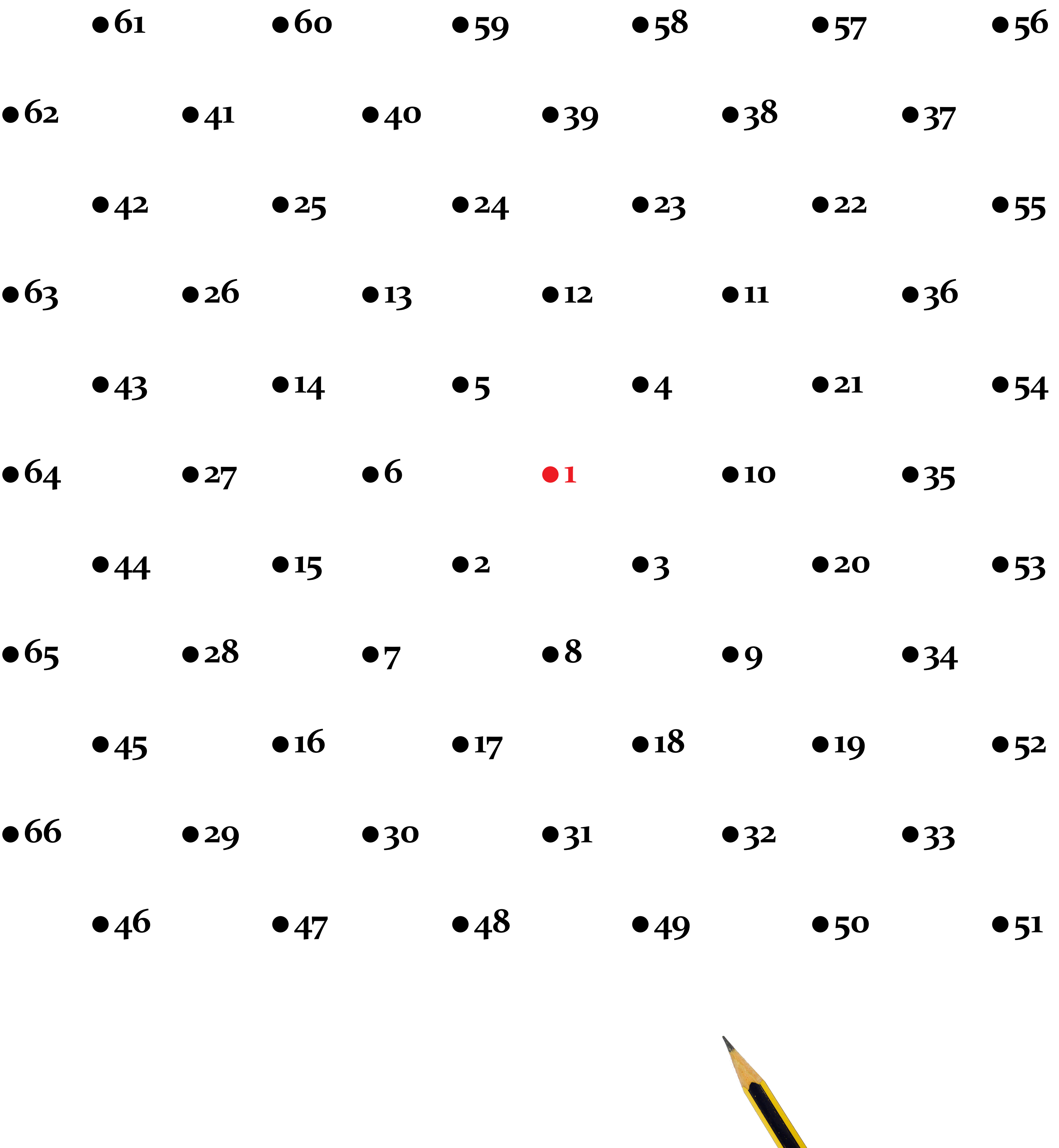

Contents

Research highlights

Study 1: The prevalence of specific learning disorder in mathematics (SLDM or dyscalculia)[1]

- This was the first prevalence study of SLDM since the publication of the new DSM-5 (Diagnostic and Statistical Manual of Mental Disorders) diagnostic criteria in 2013.

- We considered data from 2,421 children (their level of intelligence and educational achievement in mathematics and English were recorded over several school years).

- We investigated the effects of gender, socio-economic status, special educational needs (other than issues related to mathematics), and whether the child spoke English as their first language on mathematics achievement.

- 5.7% of the sample was identified as having SLDM.

- Compared to earlier (DSM-IV) diagnostic criteria, the prevalence of SLDM was almost 6 times higher.

- A child was more than a 100 times more likely to receive a diagnosis of dyslexia than SLDM, although prevalence rates are expected to be similar.

- A large proportion (80%) of children with SLDM had other comorbid conditions, but no child in our sample received multiple diagnoses.

- There were no gender differences either in the prevalence of SLDM or in the prevalence of exceptionally high performance in mathematics. This was in contrast with findings regarding dyslexia, which was twice as common among boys than girls in our sample.

- Girls, on average, had somewhat higher IQs and English performance than boys, and boys were more likely to have special educational needs than girls. Given these results, similar performance in maths for boys and girls can be interpreted as a relative underperformance in the case of girls.

- SLDM was closely associated with several demographic factors (such as socio-economic status and whether the child spoke English as their first language).

- There was a discrepancy between level of intelligence and mathematics achievement in the case of children with SLDM, but this was much smaller than the discrepancy expected on the basis of DSM-IV criteria.

- Current educational practice in Northern Ireland does not officially recognize and support children with serious and sustained mathematics difficulties.

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[1] Morsanyi, K., van Bers, B. M. C. W., McCormack, T. & McGourty, J. (2018). The prevalence of specific learning disorder in mathematics and comorbidity with other developmental disorders in primary school age children. *British Journal of Psychology.* DOI: 10.1111/bjop.12322.

Study 2: Order processing skills in SLDM[2]

- There is no agreement about the key cognitive processes that are implicated in mathematics learning difficulties.

- Whereas much research has focussed on magnitude processing skills (i.e., the ability to quickly compare the magnitude of numbers or quantities), more recently, ordering skills (i.e., the ability to judge if familiar items are in the correct order, or to memorize and reproduce the correct order of items) have also received much attention.

- The main aim of our study was to decide if magnitude processing or ordering skills predict better whether a child develops mathematics difficulties.

- Our set of ordering tasks included some novel measures of order processing ability, which did not involve using numbers.

- We compared the performance of 20 children with SLDM, and 20 typically developing children with average mathematics skills on a range of basic ordering, magnitude processing and inhibition tasks, most of which had been found to be related to mathematics performance in previous studies. Our aim was to identify a set of tasks that best discriminated between children with and without SLDM.

- Children in the two groups were carefully matched on age, gender, socio-economic status, educational experiences, intelligence and reading ability.

- In line with earlier research, children with and without mathematics difficulties differed both in their magnitude processing and ordering abilities, but not in their inhibition skills.

- Nevertheless, the tasks that best discriminated between the groups were a parental questionnaire about everyday ordering skills and a task that measured memory for item order – two ordering tasks without mathematics content. In other words, our findings suggested that these tasks could be the most useful for diagnostic purposes.

- The dot comparison task, a magnitude processing task, which was the focus of much earlier research into SLDM, could also be used to discriminate between the two groups, but it was only useful to correctly identify children *without* SLDM. Children with SLDM varied in their performance on this task (i.e., on the basis of performance on this task, it was not possible to tell that a child with SLDM had mathematics difficulties).

- These findings can inform both theorizing about the origins of mathematics difficulties, and the development of novel diagnostic tools and intervention methods for SLDM.

[2] Morsanyi, K., van Bers, B. M. C. W., & O'Connor, P. A. & McCormack, T. (2018). Developmental dyscalculia is characterised by order processing deficits: Evidence from numerical and non-numerical ordering tasks. *Developmental Neuropsychology*. DOI: 10.1080/87565641.2018.1502294.

Study 3: Order processing skills and mathematics performance in typical development

- There is a debate in the literature regarding the nature of basic skills that support mathematics learning and understanding.

- Recently, evidence has emerged that ordering abilities might play a key role in the typical development of mathematics skills, as well as in complex mathematics performance in adults.

- We investigated the role of ordering abilities (together with magnitude processing skills and inhibition) in mathematics performance in a sample of 100 typically developing children between 8-11 years of age, also taking into account the effects of age, socio-economic status, intelligence and reaction times.

- We also investigated if the tasks were related to all aspects of mathematics performance (e.g., counting, calculation measurement, handling data, etc.), and whether performance across these tasks was related.

- The relationship of these tasks with reading ability was also investigated, because in typical development reading and mathematics skills are strongly related, and reading and mathematics difficulties also often co-occur. This suggests that at least some of the underlying basic processes are shared across mathematics and reading skills.

- Order working memory, number ordering, dot comparison and number line performance were robustly related to all aspects of mathematics performance, and they remained to be significantly related to mathematics skills, after the effects of age, socio-economic status, intelligence and reaction times were controlled.

- When the predictive value of these tasks was compared, order working memory, number ordering ability and number line performance were the strongest predictors of mathematics performance.

- Performance on these tasks was also related to reading ability, after the effects of age, socio-economic status, intelligence and reaction times were controlled. Additionally, some non-numerical ordering tasks (a parental questionnaire of ordering skills, and ordering of events in time) were also related to reading skills.

- The correlations between ordering and magnitude processing tasks revealed that the two types of tasks were often related, whereas within each category, tasks were not necessarily strongly related.

- These results add to our understanding of the basic skills that underlie mathematics performance in typically developing children, and the strong links between mathematics and reading skills.

- Ordering skills are not only important for mathematics, but also for reading, which makes them ideal targets for early intervention programmes.

Executive summary

Mathematics difficulties are common in both children and adults, and they can have a large impact on people's lives. A specific learning disorder in mathematics (SLDM or developmental dyscalculia) is a special case of persistent mathematics difficulties, where the problems with maths cannot be attributed to environmental factors or a general learning difficulty.

Our project had three main aims:

1) to complete a demographic study to establish the prevalence rate of SLDM, any gender differences in SLDM, and the most common co-morbid conditions. We also compared the prevalence rates of SLDM using the DSM-IV and DSM-5[3] criteria (see a summary of the key differences in Table 1).

2) to conduct a study with children with SLDM, and to test the hypothesis that these children are characterised by order processing deficits. Although our main focus was on ordering abilities, we also compared the importance of ordering skills with other skills that have been proposed to relate to maths difficulties, including magnitude processing/estimation skills and inhibition.

3) to investigate the role and relative importance of ordering abilities in the development of mathematics skills in children without mathematics difficulties.

Key findings:

The results of the demographic study revealed that 6% of our sample had persistent difficulties with mathematics, and after applying some exclusion criteria (based on DSM-5 guidelines), **5.7% of primary school children were identified as having an SLDM profile**[4]. This contrasted with the much lower prevalence rate of 1.1% that we obtained using the DSM-IV criteria. **The proportion of boys and girls with SLDM was equal.** However, girls were more likely to underperform in maths than boys, when their IQ and/or their special educational needs status was statistically controlled. **About half of the children with SLDM had both mathematics and language difficulties, and several children had other co-occurring conditions. Almost no child in our sample received a diagnosis of SLDM/dyscalculia.**

The experimental study with children with SLDM revealed problems in both ordering abilities and magnitude processing/estimation skills, but no impairment of inhibition processes. When we used a statistical model to predict the diagnostic status of the children, **ordering skills were the best predictors of diagnostic status.**

The **study with children without mathematics difficulties** also provided evidence for the important role of ordering abilities for maths performance (as well as for reading), although

[3] DSM stands for Diagnostic and Statistical Manual of Mental Disorders. It is a manual published by the American Psychiatric Association which includes all recognized mental disorders. The new DSM-5 criteria were published in 2013.

[4] Throughout this report, we will refer to the children as having SLDM, but are aware that in the absence of a clinical synthesis (see DSM-5 criteria), we cannot be fully confident that this is the case.

the set of ordering tasks that were important for maths were not exactly the same as in the study with SLDM participants. **Overall, these results show the central role of ordering abilities in both the typical and atypical development of mathematics abilities.** These results can inform intervention efforts, and could also contribute to the development of diagnostic tools for mathematics difficulties.

Table 1. ***Summary of the key differences in diagnostic criteria for Mathematics Disorder (DSM-IV) and Specific Learning Disorder in Mathematics (DSM-5).***

	Mathematics Disorder (DSM-IV)	**Specific Learning Disorder in Mathematics (DSM-5)**
Relation between mathematics performance, age and IQ	mathematics achievement is significantly below that expected for age, schooling and level of intelligence (a discrepancy of more than 2 *SD* between maths and IQ is expected, although sometimes a discrepancy of between 1-2 *SD*s is used)	mathematics performance is at least 1.5 *SD*s below the population mean (i.e., a standard score of 78 or less), in the presence of normal levels of intellectual functioning (IQ score of at least 70+/-5)
Persistence of difficulties	not mentioned explicitly	persistent difficulties in learning key academic skills (at least for 6 months), despite interventions that target those difficulties
Clinical synthesis	not mentioned explicitly, although it is expected that the problems exist in the presence of normal schooling; in the case of co-occurring difficulties, the problems with mathematics exceed the level normally associated with the co-occurring condition	no single data source is sufficient for a diagnosis; a synthesis of the individual's medical, developmental, educational and family history is necessary; problems with mathematics should exceed the level normally associated with co-occurring conditions
Estimated prevalence	1% for mathematics disorder (for learning disorders in general the estimated prevalence rate is 2-10% with a point estimate of 5%)	not specifically stated; between 5-15% including specific difficulties in reading, written expression and mathematics (prevalence in adults is approximately 4%)
Gender differences	not mentioned in the case of mathematics disorder	specific learning disorders in general are more common in males (ratios range from about 2:1 to 3:1)

The need for this research

Mathematics difficulties are common in both children and adults. It has been estimated that up to 25% of economically active individuals in countries such as the UK lack basic numerical knowledge, skills and understanding that would be essential for them to act confidently and independently in everyday life, educational settings and work (e.g., Snyder & Dillow, 2012).

Low numeracy is not only linked to low academic achievement and restricted career opportunities, but it is also related to an increased risk of unemployment, mental and physical illness, as well as higher rates of arrest and incarceration. Many of these risks operate over and above those associated with social disadvantage, lack of qualifications and concurrent literacy problems. According to Gross, Hudson and Price (2009), the annual public cost associated with low numeracy is up to £2.4 billion.

A specific learning difficulty in mathematics (SLDM; also often referred to as developmental dyscalculia) is a special case of persistent mathematics difficulties, where the problems with maths cannot be attributed to environmental factors or a general learning difficulty (see Table 2 for a summary of the diagnostic criteria). Opinion is divided on whether mathematics difficulties are better explained by issues with some basic processes related to magnitude estimation (in particular, being able to quickly judge the approximate number of items in a display – e.g., Piazza, Facoetti, Trussardi, Berteletti, Conte, Lucangeli, Dehaene & Zorzi, 2010), or whether the problems with mathematics are related to more general learning abilities (such as memory capacity and intelligence) and attentional processes (e.g., Ashkenazi, Rubinsten, & Henik, 2009).

Table 2. ***The DSM-5 criteria for Specific Learning Difficulties in Mathematics***
• persistent, substantial difficulties in mathematics learning and using academic skills
• academic performance should be determined through standardized achievement measures and comprehensive clinical assessment
• a “clinical synthesis” should occur based on the individual’s developmental, medical, family, and educational histories, school reports, and psycho-educational assessment
• the difficulties must not be better explained by intellectual disabilities, mental, neurological, sensory (vision or hearing) or motor disorders
• the difficulties must not be better explained by psychosocial adversity, lack of proficiency in language of academic instruction, or inadequate educational instruction
• the deficits must cause significant interference with academic or occupational performance, or with activities of daily living.
• severity levels need to be specified

There is also no agreement on how prevalent mathematics learning difficulties are, how often they occur together with other developmental conditions or learning difficulties, and whether there is a difference between males and females in how prone they are to mathematics learning difficulties. Additionally, the diagnostic criteria for SLDM have been significantly revised in 2013 (with the publication of the 5th edition of the Diagnostic and Statistical Manual of Mental Disorders; DSM-5), and it is likely that this leads to changes in prevalence rates. We aimed to address these important basic issues regarding SLDM, as these are relevant for both policy and practice. In particular, these questions are important both for the diagnosis of SLDM, and for intervention efforts.

In order to better support the development of interventions into maths difficulties, it is essential to thoroughly investigate the intellectual profile of children with SLDM, including their relative strengths and weaknesses. Currently, there are no commonly accepted educational methods to support children with mathematics learning difficulties. This contrasts with educational support for children with reading difficulties, which is widely available and leads to significant benefits in terms of school achievement and everyday life skills. In order to provide the best support for children with mathematics difficulties, we need to understand better how they differ from other children in terms of their cognitive profiles.

Our particular focus was on order processing abilities (see examples of the tasks that we used in Table 3), as recent research findings provide strong support for their role in both typical mathematics skills (e.g., Lyons & Beilock, 2011) and mathematics difficulties (Attout & Majerus, 2014). Nevertheless, we did not investigate ordering skills in isolation, but together with other important basic skills (in particular, magnitude processing/estimation skills), in order to better understand their contribution to mathematics problems. We also investigated inhibition processes, which have been proposed to play a central role in mathematics difficulties (Szűcs, Devine, Soltész, Nobes & Gabriel, 2013)[5].

Finally, as the role of ordering skills in mathematics is a relatively under-researched topic, there are some basic questions that need to be answered. For this reason, we also investigated the contribution of order processing skills to mathematics abilities in typical development. One question is if the various order processing tasks, which have been used in this literature, measure a single underlying ordering skill, or if there are various types of ordering abilities that contribute to maths performance. The nature of the relationship between order processing and magnitude processing/estimation skills has also not been thoroughly examined, although it is possible that problems with one type of skill originate in deficits in the other skill. Alternatively, these tasks might make independent contributions to mathematics difficulties and mathematics skills in general. Similar to the study with children with SLDM, we also aimed to identify a set of tasks that were the best predictors of mathematics skills in typically developing children. In particular, we were interested in whether ordering skills are more strongly related to mathematics abilities than magnitude processing and inhibition skills.

Ordering skills have been found to be important not only for the development of mathematics abilities, but also for reading (e.g., Perez, Majerus, Mahot & Poncelet, 2012; Perez, Majerus & Poncelet, 2012). We also investigated this relationship.

Summary of aims

The aims of this research were threefold. First we wanted ***to investigate the prevalence of specific learning difficulties in mathematics*** (SLDM) in Northern Ireland, using the recently updated guidelines of the Diagnostic and Statistical Manual for Mental Disorders (DSM-5;

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[5] Magnitude processing tasks require participants to estimate the numerosity of a set of stimuli, to make comparisons between numerical or non-numerical magnitudes, or to link numbers to non-numerical representations of magnitude. Inhibition tasks require participants to inhibit an already initiated response, or to ignore irrelevant but salient details.

see Table 2). In this *demographic study*, in addition to prevalence rates, we also wanted to investigate gender distributions and comorbidity with other developmental difficulties.

The second aim of this research was ***to investigate the problems that underlie the mathematics difficulties of children with SLDM***. In the past decades, much research has focussed on the role of basic processes related to magnitude estimation in the development of mathematical abilities. It was assumed that these processes are important to typical mathematics development, and that an impairment in these mechanisms leads to specific learning difficulties in mathematics, even when an individual has normal or high intelligence levels. Nevertheless, both the typical methods used in these studies and the neurological evidence for this approach have been questioned (e.g., Szűcs et al., 2013).

Thus, the current project involved tasks measuring estimation abilities, but our main aim was to investigate an alternative proposal. Recent studies highlighted the role of ordering abilities in mathematics learning, mathematics difficulties, as well as in high-level mathematics performance in adults. Some researchers have also suggested that a problem with order processing abilities might underlie SLDM (Attout, & Majerus, 2014; Rubinsten & Sury, 2011). Nevertheless, there is disagreement in whether this deficit is specific to numerical ordering abilities, or whether the ordering problems extend beyond the domain of numbers. For example, clinical descriptions of people with mathematics difficulties often note impairments in recalling the sequence of past and future events, and in the ability to follow sequential instructions. We investigated these questions in our *order processing in SLDM study*.

A third aim was ***to better understand the role of various ordering abilities in typical mathematics development***. For this reason, we investigated performance on a range of ordering tasks. Additionally, the relationship between ordering and magnitude processing/estimation skills were also examined, and we aimed to identify a set of tasks that most strongly related to mathematics achievement. We also investigated the role of ordering abilities in typical reading development. We focussed on these questions in our study on *the role of ordering skills in typical mathematics development*.

Methods

The methods used in each study are summarized in Table 3.

Demographic study

Nineteen schools from Northern Ireland were involved in the study, representing a mix of urban schools and outlying rural schools. The catchment areas of the schools ranged from areas with very low levels of deprivation to medium levels of deprivation. Nevertheless, 33% of children were eligible to free school meals, which is similar to the figure for Northern Ireland (30.3%) according to the 2017-2018 statistics published by the Department for Education 2017-2018[6]. At the time of the study, 22.4% of the children in our sample were registered to have special educational needs, which is also close to the official statistics for Northern Ireland (23.1% for primary and secondary school students combined). This suggests that the sample might be broadly representative of the child population of Northern Ireland.

[6] https://www.education-ni.gov.uk/sites/default/files/publications/education/School%20enrolments%202017-18.pdf

The schools maintain electronic databases of children's performance on standardized mathematics, reading and intelligence tests. These tests are administered from year 3 of primary school. Typically, schools administer the reading and mathematics tests each year, and the IQ tests at least twice during the primary school years. Additionally, the same database includes records of children's age, gender, socio-economic status, potential special educational needs and diagnoses of mental or physical disabilities, and whether they speak English as their first language.

We have accessed the electronic database of 19 primary schools, which included records of 3,345 children. As the DSM-5 criteria for SLDM require the presence of persistent maths difficulties, and that children do not have an intellectual disability, we only included children in the study who had records of standardized maths scores from at least two school years, and IQ from at least one school year. Excluding children with incomplete records resulted in a final sample of 2,421 children. Two independent coders completed the selection process, and any disagreements were resolved by discussions. Initial agreement between coders was very high (99.8%). We have applied the DSM-5 criteria to establish the prevalence of SLDM in this sample of children.

Table 3. Summary of the methods used in each study	
Study 1: Demographic study	**Participants:** 2,421 children from years 4-7 of primary school **Materials:** The schools' records of children's performance on standardized tests of mathematics, English and intelligence over several school years were used, as well as details about the children's demographic characteristics.
Study 2: Order processing in SLDM	**Participants:** 20 children with SLDM and a closely matched control group of 20 children without special educational needs. **Materials:** The children were administered several tasks to measure their order and magnitude processing skills, and inhibition. We also measured the children's level of intelligence and their basic reaction times.
Study 3: Order processing in typical development	**Participants:** 100 children from years 5-7 of primary school without special educational needs. **Materials:** The children were administered the same tasks as in Study 2.

Order processing in SLDM and in typical development

Selection of participants

One hundred-and-twenty children from the original sample of 2,421 pupils, who attended years 5, 6 or 7 of seven different primary schools, were invited to participate in a screening session. The seven schools were selected on the basis that they had a relatively high number of children with a potential diagnosis of SLDM (this was established when we inspected the schools' records for the purposes of the demographic study). Forty children were invited for potential inclusion in the SLDM group, and eighty children were selected for potential inclusion in the control group. Children in the potential SLDM group were identified on the basis that, according to their schools' records, their average standardized maths scores from at least two school years were 85 or lower (i.e., their scores were at least 1 standard deviation below the population mean). Children were invited to the potential control group if they attended the same schools and classes as the children in the potential SLDM group, and they were similar in age, gender, and their recent reading and IQ scores (based on the schools' records). The mathematics scores of the children in the potential control group were in the normal range with no indication that they had mathematics difficulties. Children with an official diagnosis of a developmental disorder (other than cognitive and learning difficulties in the case of the potential SLDM group) were excluded from the study. This is a conservative approach, as we can expect that children with comorbidities would show weaker performance on some tasks than children with mathematics difficulties only. Nevertheless, we did this to ensure that we could investigate the effects of mathematics difficulties in isolation, without the potential effects of any other co-occurring conditions.

As the next step of the selection process, all children were administered standardized tests of mathematics, reading and IQ by the researchers. Children from the potential SLDM group were included in the final SLDM sample if this additional testing confirmed that they had a standardized score of 85 or lower on the maths test, and they had a discrepancy between their IQ and mathematics score of at least 7 standardized points (i.e., a magnitude of 0.5 standard deviation relative to population standards) or a discrepancy of at least 7 points between their standardized mathematics and reading scores, as measured by the researchers[7]. We aimed to recruit children with a relatively large discrepancy between their mathematics and IQ/reading scores, in order to make sure that children in the SLDM group had specific difficulties in mathematics. On the basis of these criteria, we identified 20 children with SLDM[8]. Based on a combination of information from the schools' records and individually administered standardized tests, we could establish with confidence that all children in the SLDM group had serious, sustained difficulties with mathematics, although none of these children received an official diagnosis of SLDM (which is unsurprising, given the findings of the demographic study, which showed that, with the exception of a single pupil, no child had received an official diagnosis of SLDM/dyscalculia – see below).

Children from the potential control group were excluded from the final sample if they had standardized mathematics scores under 90 from any academic year (based on either the scores collected by the schools or the researchers). We did this to make sure that none of the children in the control group had any hint of mathematics difficulties. Additionally, we selected the children in the control group, so that they were matched to the children in the SLDM group as closely as possible on age, gender, socio-economic status, and IQ and standardized reading scores, as measured by the researchers. Additionally, these children were selected from the same schools and classrooms as the children with SLDM. The final

[7] Although the DSM-5 diagnostic criteria for dyscalculia/SLDM (in contrast with the DSM-IV criteria) do not require a discrepancy between maths scores and IQ, for the purposes of this study, we recruited children with a significant maths-IQ (or maths-reading) discrepancy, as this can help in disentangling the effects of low maths scores vs. low IQ/reading scores on their performance on the tasks. We also did this so that we could obtain samples with IQs in the normal range.

[8] A particular difficulty of recruiting children for this study was that only a small number of children from each class were invited to participate, and for this reason, some parents did not give their consent for their child to participate. Nevertheless, we do not think that this affected the representativeness of our sample of children with SLDM, as they were selected on the basis of predetermined criteria (thus, our selection procedure was not random in the first place).

control sample included 20 children. There was one child in the SLDM group and two children in the control group who did not speak English as their first language. Nevertheless, these children performed well on the cognitive tasks, including the language-related measures, and for this reason they were retained in the sample.

In the study on order processing in typical development, we collected data from 100 children (the 20 control children from the order processing in SLDM study were also included). We considered this small overlap appropriate, as the two studies focussed on different research questions (i.e., the SLDM study was focussed on differences between groups, whereas the study with typically developing children focussed on the relations between ordering, magnitude processing and inhibition skills, and their contribution to mathematics and reading performance in children without developmental disabilities). The 20 children who were included in both studies did not differ in their age, gender or mathematics abilities from the other children in the sample. The overall sample represented a very diverse range of mathematics and reading abilities, IQ and socio-economic background. Although the children were initially recruited with the possibility in mind that they might be selected for inclusion in the control group for the order processing in SLDM study, the only exclusion criterion used in recruitment was that the children had no official diagnosis of a developmental disorder, and no indication of sustained mathematics difficulties. For these reasons, we believe that the sample was representative of the typically developing child population.

Materials

The **order processing tasks** are presented in Table 4. The *parental order processing questionnaire* was adapted from O'Connor, Morsanyi and McCormack (2018), the *number ordering task* was based on Lyons and Beilock (2011), the *yearly events ordering task* was based on Friedman (2002), the *order working memory task* was adapted from Majerus, Poncelet, Greffe and van der Linden (2006), and the *backward matrices task* was based on Mammarella, Hill, Devine, Caviola and Szűcs (2015). These tasks assessed numerical and non-numerical ordering skills, and both short- and long-term memory for ordered sequences.

Alongside the order processing measures, additional tasks were administered to assess **magnitude processing and estimation** performance. These tasks included a *number line estimation* task (marking the approximate location of a number on a line that represents a 1-100 or a 1-1000 scale – Siegler & Opfer, 2003), and a *dot comparison task* (Price, Holloway, Räsänen, Vesterinen & Ansari, 2007). In this task, children were presented with two sets of dots on each side of the computer screen (each containing between 1-9 dots that varied in size). Once the dot displays disappeared from the computer screen (after 1 second), the children had to indicate whether the set on the left or the right side contained more dots. A *number comparison task* (Dehaene, Dupoux, & Mehler, 1990) was also administered to children where they were presented with two one-digit numbers (e.g., 4 8), and they had to decide quickly and accurately whether the number on the left or on the right side of the screen was larger.

Table 4. ***Tasks used in the studies to measure order processing abilities***

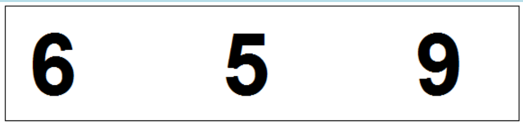
Parental order processing questionnaire

The questionnaire included 7 items that measured children's ability to perform everyday tasks with a requirement to consider order information. For example:

My son/daughter can easily recall the order in which past events happened.
(1=very much disagree; 7=very much agree)
1----2----3----4----5----6----7

Number ordering task

Children were presented with three numerals on the computer screen, and they had to decide as quickly and accurately as possible whether the numbers were in the correct ascending order, or they were in an incorrect order.

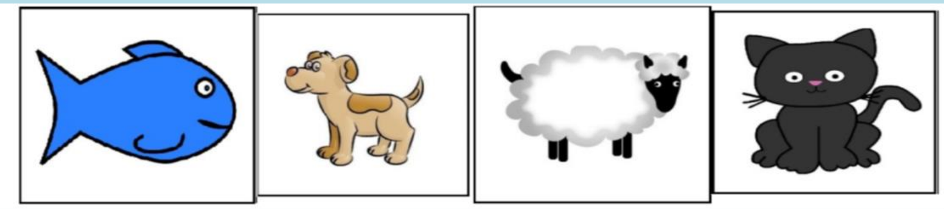


Yearly events ordering task

Children were asked to decide as quickly and accurately as possible, whether three yearly events (for example, Valentine's day, Halloween and Christmas) were presented in the correct order (as they would happen during a calendar year) or if they are presented in an incorrect order.

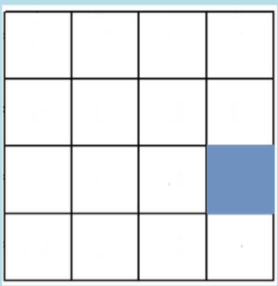
Serial order memory task

Children had to listen to a list of animal names. Then they were given play cards that represented the animals in the list, and they were asked to put these cards in the correct order as they were presented in the list.



Backward matrices task

Children had to recall backwards a sequence of locations in a 4x4 grid on the computer screen.



A task measuring response **inhibition** was also administered (based on Logan & Cowan, 1984). In this task, children were presented with a series of arrows, which either pointed left or right, and they had to press a left/right button accordingly. On some trials, the presentation of the arrow was followed by a sound. In these cases, children had to withhold their response. Susceptibility to interference (another aspect of inhibition) was measured by the *dot comparison* task, as children had to ignore the physical size of the dots and the total surface area that they covered, and base their responses solely on the numerosity of dots. The congruency of perceptual and numerical information was systematically manipulated in the task. In congruent trials, the dot pattern that had a larger number of dots was also physically larger. In incongruent trials, the dot pattern with more dots was physically smaller.

Children's **basic choice reaction times** (Fry & Hale, 1996) were also measured by asking them to press a red or a blue button in response to the presence of a red or a blue circle on the computer screen.

Key findings

Demographic study

The results of this study showed that 6% of children had persistent difficulties with mathematics, and 5.7% were identified as having SLDM when the DSM-5 diagnostic criteria were applied. This contrasted with findings obtained using the DSM-IV criteria, which identified only 1.35% of the total sample as having a mathematics disorder (Table 1 gives a summary of the main differences between the two sets of diagnostic criteria).

Persistent maths difficulties, as well as SLDM, were equally common among boys and girls. Children with persistent maths difficulties were more likely to live in deprived areas and to be eligible to free school meals, to not speak English as their first language, to have relatively low IQ and English performance, to have lower school attendance rates, and to have special educational needs. Regarding special needs and comorbid conditions, about half of the children with SLDM had some form of language or communication difficulty. Some children with SLDM also had a diagnosis of autism, social, emotional and behavioural difficulties or attention deficit and hyperactivity disorder.

Although the proportion of boys and girls with persistent maths difficulties was equal, girls were more likely to underperform in maths relative to boys with a similar IQ and a similar special educational needs status. This suggests that girls might not achieve their full potential in maths, even if their performance is similar to boys. A possible explanation of these gender differences is that girls and boys differ in their attitudes and anxiety related to mathematics. It has been reported that girls tend to lose interest in subjects related to science, engineering, technology, and mathematics during the primary school years (e.g., Kerr & Robinson Kurpius, 2004), and they also report higher levels of anxiety about mathematics learning and test situations (e.g., Hill, Mammarella, Devine, Caviola, Passolunghi & Szűcs, 2016).

In the total sample, only one child received a diagnosis of dyscalculia (interestingly, this child did not actually have persistent difficulties with mathematics). This finding was in contrast with the prevalence of dyslexia – a specific learning disorder in reading. 108 children (4.46% of the sample) had an official diagnosis of dyslexia. This suggests that currently mathematics difficulties do not receive as much attention from educational psychologists as reading difficulties.

Order processing in SLDM study
Children with SLDM showed evidence of order processing deficits. Specifically, they obtained lower scores on the ***parental order processing questionnaire***, and on the ***order working memory*** and ***backward matrices*** tasks. Additionally, they were less able to recognize incorrectly ordered triads in the case of the ***number ordering and yearly event ordering tasks*** than controls (although their total scores on these tasks were not significantly different from the typically developing controls). In sum, there was evidence of impaired performance for children with SLDM on all order processing tasks (see Table 5 for descriptive statistics and comparisons between groups on all tasks).

In addition to demonstrating order processing deficits, children with SLDM also performed more poorly than controls on the ***dot comparison task*** and ***number line estimation task***. Nevertheless, there was no difference between groups in *number comparison performance*[9]. There was no difference between the two groups on the *response inhibition* and *basic reaction time* measures. Children with SLDM also did not show stronger congruency effects in the case of the *dot comparison task*[10]. Thus, there was no evidence of impairments in response control, suppression of interference or processing speed.

Table 5. ***Comparisons between groups on the ordering, magnitude processing and inhibition tasks***

	SLDM Mean *(SD)*	**Typically developing Mean *(SD)***	***t*(38)**
Parental Order Processing Questionnaire	35.85 *(8.26)*	41.45 *(6.27)*	2.42*
Number ordering (accuracy)	.82 *(.16)*	.91 (.14)	1.88
(reaction time)	3371.70 *(1430.55)*	2448.30 *(837.54)*	2.49*
Yearly events ordering (accuracy)	.70 *(.17)*	.78 *(.17)*	1.50
(reaction time)	3791.43 *(1901.13)*	4024.70 *(1674.41)*	.41
Order working memory	10.75 *(3.14)*	13.60 *(3.35)*	2.78**
Backward matrices	4.60 *(1.82)*	5.75 *(1.59)*	2.13*
Dot comparison	.91 *(.06)*	.95 *(.03)*	2.83**
Number comparison (accuracy)	.86 *(.20)*	.93 *(.15)*	1.16
(reaction time)	1275.52 *(552.24)*	964.05 *(267.27)*	2.27*
Number line task	123.19 *(48.55)*	84.70 *(38.02)*	2.79**
Stop signal task	.86 *(.09)*	.83 *(.13)*	.78
Choice reaction time	607.96 *(160.33)*	539.77 *(114.88)*	1.55

* $p \leq .05$ (statistically significant at the 95% confidence level)
** $p \leq .01$ (statistically significant at the 99% confidence level)

In the case of each task, we have also analysed group differences in the way participants were affected by within-task manipulations (e.g., distance effects, stop signal delay in the case of

[9] There was a group difference in response times on the number comparison task, but when the effect of basic choice reaction times was taken into account, this difference was no longer significant.
[10] It is easier to decide that a set of dots contains more items, if the set is physically larger than another set that contains fewer items. This congruency effect was equally strong in the case of both groups.

the response inhibition task, congruency effects in the dot comparison task and type of number line). We have found no group differences in the effect of within-task manipulations. This suggests that children in both groups responded to the tasks using similar strategies (there was no evidence of qualitative differences). Nevertheless, in several tasks there were quantitative differences between the performance of the two groups.

For diagnostic purposes, it is important to identify tasks that can reliably discriminate between individuals with and without SLDM. Given that there were several tasks that reliably discriminated between the two groups, we were interested in selecting the best predictors of group membership from this set of tasks. To do this, we conducted a stepwise logistic regression analysis, which was aimed at predicting diagnostic status (i.e., SLDM/non-SLDM). The best model which only included significant predictors of diagnostic status included the order working memory task, the parental order processing questionnaire and the number line task. This model explained 63% of the variance in group membership, and was able to categorize correctly 80% of the participants as SLDM/non-SLDM. Thus, a combination of these tasks could be used to identify children with SLDM with high precision. Notably, only one out of the three tasks included numbers, which shows the importance of non-numerical skills in the development of SLDM.

Order processing in typical development study

In this study, we first identified the tasks that were related to performance on a standardized maths test, after controlling for the effects of age, socio-economic status, verbal and non-verbal intelligence and choice reaction time (Table 6). Four measures showed significant partial correlations with mathematics skills: order working memory, and the number ordering, dot comparison and number line tasks. We have conducted a stepwise multiple regression analysis to find the best predictors of mathematics skills in this sample. Our final model included the order working memory, number ordering and number line tasks as significant predictors. Together these three tasks explained 31% of the variance in mathematics skills. When we also added the significant general predictors of mathematics performance (i.e., age, and verbal and non-verbal intelligence) to these tasks, the model explained 49% of the variance in mathematics skills. Interestingly, the same tasks, as well as the parental order processing questionnaire, also significantly related to reading skills.

Table 6. Correlations between the ordering, magnitude processing and inhibition tasks with maths and reading ability, after controlling for the effects of age, SES, intelligence and choice reaction time

	Mathematics skills	Reading skills
Parental Order Processing Questionnaire	.18	.31**
Number ordering	.31**	.24*
Yearly events ordering	.17	.17
Order working memory	.34**	.35**
Backward matrices	.09	.07
Dot comparison	.23*	.17
Number comparison	.19	.08
Number line task	.31**	.22*
Stop signal task	.13	.04

* $p \leq .05$ (statistically significant at the 95% confidence level)
** $p \leq .01$ (statistically significant at the 99% confidence level)

We have also investigated the relationships between the various order processing tasks, and between the ordering and magnitude processing measures (Table 7). After controlling for the effects of age, socio-economic status, verbal and non-verbal intelligence and choice reaction time, we have found that performance on the different ordering tasks was generally unrelated, with the exception of a strong correlation between number ordering and annual event ordering. Number ordering performance was also moderately related to number comparison. Dot comparison and scores on the parental order processing questionnaire were also related.

Overall, these results suggest that the various ordering measures do not capture a single underlying ordering skill, with the exception of the number and annual event ordering tasks, which share much common variance (see also Morsanyi, O'Mahony & McCormack, 2017; Vos, Sasanguie, Gevers & Reynvoet, 2017). Similarly, the dot comparison and number comparison tasks (which are supposed to measure magnitude processing skills) were unrelated. The number ordering task shared variance with number comparison. These findings broadly replicate the findings of previous studies (e.g., Lyons & Beilock, 2011; Morsanyi et al., 2017; Sasanguie, Lyons, de Smedt & Reynvoet, 2017), but also extend existing results, because so far no study included all of these measures together.

Table 7. Correlations between the tasks, after controlling for the effects of age, SES, intelligence and choice reaction time

	1.	2.	3.	4.	5.	6.	7.	8.
1. Parental Order Processing Questionnaire								
2. Number ordering	.03							
3.Yearly events ordering	.07	.47**						
4. Order working memory	.08	.13	.10					
5. Backward matrices	.12	.09	.13	.10				
6. Dot comparison	.22*	.19	.12	.16	-.07			
7. Number comparison	.07	.27**	.19	.14	.16	.05		
8. Number line task	.15	.14	.10	.06	.04	.02	.21*	
9. Stop signal task	.02	.07	.05	.07	.001	.03	.08	.07

* $p \leq .05$ (statistically significant at the 95% confidence level)
** $p \leq .01$ (statistically significant at the 99% confidence level)

Summary of key findings and recommendations

1) On the basis of the findings of the ***demographic study***, it is apparent that about 6% of primary school children have very serious, persistent difficulties with mathematics.

On the basis of the DSM-5 criteria, 5.7% fall in the SLDM category[11]. Nevertheless, in our sample only one child (who did not actually show very serious maths difficulties) received a diagnosis of dyscalculia. By contrast, 108 children in our sample received a diagnosis of dyslexia, which is supposed to have a similar prevalence. From these results it can be inferred that most children with persistent difficulties with mathematics do not receive educational support, which can have serious consequences on the future prospects of these children.

Recommendation: Educational professionals should receive up-to-date information about the diagnostic criteria of SLDM. Given that schools administer standardized, curriculum-based tests of mathematics in every school year, and a diagnosis of SLDM is made on the basis of persistently low performance on standardized, curriculum-based mathematics tests, recognizing children who are at risk of SLDM would require minimal resources.

2) Mathematics difficulties also often co-occur with other neurodevelopmental disorders. Nevertheless, no child received a double diagnosis. This indicates that children with some relatively common developmental conditions (e.g., autism, ADHD) are unlikely to receive support with their mathematics difficulties.

Recommendation: Educational professionals should be made aware that comorbidity between developmental disorders is very common, and, in these cases, the child should receive multiple diagnoses. Children with serious mathematics difficulties should receive educational support, even if their primary diagnosis (e.g., autism) can partially explain these problems.

3) About half of the children within the SLDM group had language difficulties in addition to their problems with mathematics. It is possible that the SLDM children with/without language difficulties have different cognitive profiles, and would benefit from different interventions (e.g., Rourke & Finlayson 1978; Rourke & Strang 1978; Szűcs, 2016).

Recommendation: Heterogeneity in the cognitive profiles of children with mathematics difficulties is well-documented. The cognitive profiles of children with SLDM with various co-morbid conditions should be investigated further in future studies.

4) Girls were more likely than boys to underperform in maths relative to their IQ and their special educational needs status, although, in general, boys and girls were equally likely to display persistent difficulties in mathematics (as well as to show consistently high performance in maths). On the basis of the current results, it is not possible to tell what might lead to this relative underperformance in the case of girls.

Recommendation: Teachers should take note when a child underperforms in a subject relative to their typical performance in other subjects, even if the child's overall educational achievement is good. Girls might need support to fulfil their potential in mathematics (possibly in the form of boosting confidence and attitudes towards mathematics). More research is needed in this area to better understand the reasons for relative underperformance in the case of girls, and the most efficient intervention methods.

[11] Please note again that we were not able to perform a clinical synthesis, and for this reason, we were not able to confirm the children's diagnostic status with certainty.

5) Children with persistent maths difficulties and SLDM were more likely to live in deprived areas and to be eligible to free school meals, to not speak English as their first language, to have relatively low IQ and English performance, to have lower school attendance rates, and to have special educational needs. These results show the importance of some environmental factors in the development of mathematics difficulties. For example, the 2017/2018 statistics of the Department of Education show a dramatic decline in educational outcomes for newcomer pupils, compared to previous years[12]. Nevertheless, some of our results (for example, that the proportion of children with mathematics difficulties decreased in higher school grades) hint at the possibility that mathematics difficulties might be malleable, and could be remediated by educational interventions.

Recommendation: Teachers should be made aware of the importance of environmental risk factors, in particular, the importance of socio-economic background and newcomer status. Children who are at risk of developing mathematics difficulties, should be offered additional support in the first school years.

6) The ***order processing in SLDM study*** provided evidence for deficits in SLDM in the following areas: memory for order information (including both familiar and novel sequences), ordering ability in everyday contexts and magnitude comparison and estimation skills. We have found that a combination of the parental order processing questionnaire, and the order working memory and number line tasks was particularly useful for discriminating between children with and without SLDM.

Recommendation: Number lines are routinely used in early mathematics classrooms, but ordering ability in general is not usually the focus of mathematics classes, although it is implicit in many mathematical operations (e.g., some procedures have to be performed in a set order, order information is essential for understanding place values). Activities to improve ordering abilities should be utilized in early mathematics education. The potential to use ordering tasks for diagnostic purposes should also be explored further in future studies.

7) It is notable that two of the tasks that best discriminated between children with and without SLDM did not include numbers. This is a particularly interesting result, as the predictive value of these tasks was contrasted with numerical tasks that are traditionally considered to be essential for the development of numerical skills and have been found to be implicated in SLDM by previous studies. This provides a fresh perspective on the origins of SLDM and the cognitive characteristics of children with mathematics difficulties. Both numerical and non-numerical ordering abilities were also related to reading skills.

Recommendation: Future studies should explore the role of ordering skills in mathematics and reading together. Such studies might also shed light on the reasons for the high comorbidity between mathematics and reading difficulties.

8) Our findings could also be used to inform efforts to identify young children who might be at risk of developing SLDM before they start to struggle with maths at

[12] https://www.education-ni.gov.uk/sites/default/files/publications/education/Newcomer%20pupils%20in%20education%202017-18.pdf

school. Specifically, children from an early age are able to carry out (non-numerical) tasks that require sequential actions in a fixed order (for example, getting dressed), and they can also make judgments about the order of familiar events (for example, whether having lunch happens after the child goes to the nursery). Children who struggle with these everyday activities might be at risk of developing problems with mathematics (see also O'Connor, Morsanyi & McCormack, 2018).

Recommendation: Previous efforts focussed mostly on training magnitude processing and estimation skills, and this resulted in modest success in some cases (e.g., Kucian, Grond, Rotzer, Henzi, Schonmann et al., 2011). Future intervention efforts should also include ordering tasks (including both familiar and novel items, as well as tasks with non-numerical content). Tasks with non-numerical content could be particularly useful for children with limited knowledge of numbers, such as preschool children.

9) A very important contribution of the ***order processing in typical development*** study is that it demonstrated that performance on various ordering tasks as well as various magnitude processing tasks are not necessarily related, although we have also identified some significant overlaps.

Recommendation: It is important to further investigate the basic cognitive building blocks that contribute to performance on these tasks. Such knowledge could be very useful for the development of both diagnostic tools and novel intervention methods.

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Acknowledgements

We would like to say thank you to John Eakin for his great help with recruiting schools for these studies, and facilitating interactions with local educational psychologists and school principals. We also thank Gail Crawford for her help with organizing a professional development day for educational psychologists. The contribution of Jemma McGourty was invaluable in recruiting schools for the project, and collecting much of the data for the demographic study. Patrick O'Connor designed the computer-based tasks, and he has contributed greatly to data collection for the studies on order processing abilities. We also thank Martina Maggio and Francesca Mastrantonio for their help with data collection and data entry.

This project was supported by the Nuffield Foundation. (Research and Innovation project: "Do children with developmental dyscalculia have an order processing deficit?" Grant reference number: EDU/42027.)

The Nuffield Foundation is an endowed charitable trust that aims to improve social well-being in the widest sense. It funds research and innovation in education and social policy and also works to build capacity in education, science and social science research. The Nuffield Foundation has funded this project, but the views expressed are those of the authors and not necessarily those of the Foundation. More information is available at www.nuffieldfoundation.org

Appendix: Infographics

Developmental Dyscalculia in Northern Ireland

This infographic presents a summary of the key results of the study “The prevalence of specific learning disorder in mathematics”.

Developmental Dyscalculia is linked to order processing deficits

This infographic presents a summary of the key results of the study “Order processing skills in SLDM”.

Developmental Dyscalculia in Northern Ireland

QUEEN'S UNIVERSITY BELFAST

Nuffield Foundation

1

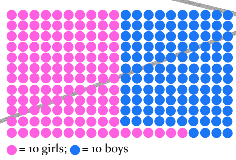
What is developmental dyscalculia (DD)?

A specific learning disorder in maths (SLDM).
Prevalence estimates vary between 1.3-13.8% of schoolchildren, but the most common estimate is between 3.5-6.5%.

2

What did we want to find out?

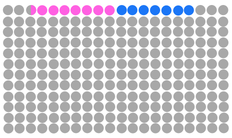
What is the prevalence rate of SLDM?
What are the most common co-morbid conditions?
Are there any gender differences in SLDM?



3

What did we do?

We collected scores of maths, reading and intelligence tests and demographic characteristics of 2421 children (52.5% girls) in years 4-7 in primary schools in Northern Ireland.



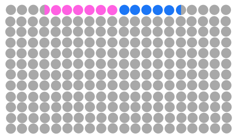
4

How many children have persistently low maths scores?

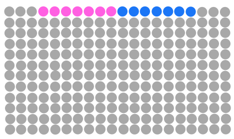
6% (146 children; 74 girls and 72 boys)

How many children have consistently high maths scores?

5% (121 children; 65 girls and 56 boys)



5



How many children with persistently low maths scores are identified as having SLDM?

5.7% (139 children; 70 girls and 69 boys), when we apply DSM-5 diagnostic criteria.
This is much higher than the 1.4% obtained when using the earlier DSM-IV diagnostic criteria, which required that standard maths scores should be at least 15 points lower than children's IQ.

6

What are the demographic characteristics of the different maths performance groups?

Compared to the average and high maths performance groups, children in the maths difficulty group were more likely to: come from disadvantaged backgrounds; be newcomers; have lower school attendance rates and have lower IQ and English scores.

7

What are the most common co-morbid conditions?

45% of children with SLDM were identified as having mild or moderate learning difficulties
12% had a diagnosis of speech and language difficulties
6% had a diagnosis of dyslexia
4% were identified as having social, emotional and behavioral difficulties
3% had a diagnosis of autism
2% were identified as having communication and interaction difficulties
1% had a diagnosis of ADHD

8

Is SLDM or talent in maths linked to a child's gender?

The proportion of male and female pupils with SLDM was not significantly different.
The proportion of male and female pupils that have consistently high maths scores was also not different.

9

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www.nuffieldfoundation.org/developmental-dyscalculia-and-order-processing

Developmental Dyscalculia **is linked to order processing deficits**

QUEEN'S UNIVERSITY BELFAST

Nuffield Foundation

1

What is developmental dyscalculia (DD)?

A specific learning disorder related to maths.
Prevalence estimates vary between 1.3-13.8% of schoolchildren, but the most common estimate is between 3.5-6.5%.

2

What are the problems underlying DD?

Order processing? Magnitude estimation skills? Visual-spatial processes? Inhibition skills?

3

What did we do?

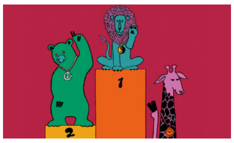
We compared the performance of 20 children with DD and 20 children without mathematical difficulties on order processing, magnitude estimation, visual-spatial memory and response inhibition tasks.

4

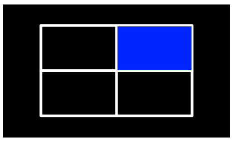
The order processing tasks:

Number ordering task


Annual event ordering task

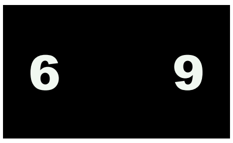

Order working memory task

Parental order processing questionnaire

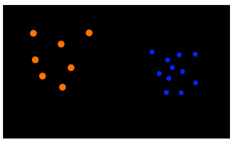

Visual-spatial working memory task

5

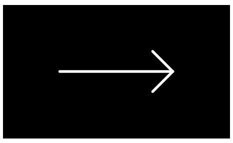
The other tasks:



Number comparison task


Dot comparison task

Number line estimation task


Response inhibition task

6

What are the results?

The groups differed in both ordering and magnitude processing/estimation abilities.
Both numerical and non-numerical ordering skills were impaired in DD, as well as performance on the dot comparison and number line tasks.
A combination of the parental order processing questionnaire, and the order working memory and number line estimation task could be used to correctly identify 80% of the participants as dyscalculic or non-dyscalculic.
This suggests that one of the distinctive features of dyscalculia is that these individuals have poor ordering skills.

7

Future directions:

These findings open up new avenues for designing diagnostic tests and interventions for individuals with maths difficulties.

8

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