

Understanding comorbidity of learning disorders: Task-dependent estimates of prevalence

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Abstract

Background:

Reading disorder (RD) and mathematics disorder (MD) frequently co-occur. However, the exact comorbidity rates differ largely between studies. Given that MD is characterized by high heterogeneity on the symptom level, differences in comorbidity rates may result from different mathematical subskills used to define MD. Comorbidity rates with RD are likely to be higher when MD is measured by mathematical subskills that do not only build on number processing, but also require language (i.e. arithmetic fluency), than when measured by magnitude processing skills.

Methods:

The association between literacy, arithmetic fluency and magnitude processing as well as the overlap between deficits in these domains were assessed in a representative sample of 1454 third Graders.

Results:

Associations were significantly higher between literacy and arithmetic, than between literacy and magnitude processing. This was also reflected in comorbidity rates: comorbidity rates between literacy and arithmetic deficits were four times higher than expected by chance, while comorbidity rates between literacy and magnitude processing deficits did not exceed chance rate. Deficits in the two mathematical subskills showed some overlap, but also revealed dissociations, corroborating the high heterogeneity of MD. Results are interpreted within a multiple-deficit framework and implications for diagnosis and intervention are discussed.

Conclusions:

The overlap between RD and MD depends on the subskills used to define MD. Due to shared domain-general factors mathematical subskills that draw on language skills are more strongly associated with literacy than those that do not require language. The findings further indicate that the same symptom, such as deficits in arithmetic, can be associated with different cognitive deficits, a deficit in language skills or a deficit in number processing.

Keywords: comorbidity, reading disorder, mathematics disorder, language skills, shared risk factor, symptom overlap

Understanding comorbidity of learning disorders: Task-dependent estimates of prevalence

Reading disorder (RD) and mathematics disorder (MD) are complex neurodevelopmental disorders of biological origin and are recognised as diseases in standard diagnostic manuals (DSM-5 and ICD-10: (American Psychiatric Association, 2013; World Health Organization, 1992)). They are among the most frequently diagnosed mental disorders with prevalence rates of 4-9% for RD and 3-7% for MD (Lewis, Hitch, & Walker, 1994; Reigosa-Crespo et al., 2012). Importantly, prevalence studies including more than one learning disorder indicate that RD and MD frequently co-occur (Thapar, Cooper, & Rutter, 2017). Between 11% and 70% of children with a deficit in one learning domain also experience a deficit in the other learning domain (Moll, Kunze, Neuhoﬀ, Bruder, & Schulte-Körne, 2014). Even though the exact comorbidity rates between RD and MD diﬀer largely between studies (Badian, 1983; Barbaresi, Katusic, Colligan, Weaver, & Jacobsen, 2005; Dirks, Spyer, van Lieshout, & de Sonnevile, 2008; Gross-Tsur, Manor, & Shalev, 1996; Landerl & Moll, 2010; Lewis et al., 1994; Moll et al., 2014), co-occurrence rates across studies are clearly higher than expected by chance; thus comorbidity between learning disorders seems to be the rule rather than an exception.

The fact that RD and MD frequently co-occur but can also occur in isolation raises the question of how protective factors and risk factors underlying learning disorders interact and how the diﬀerent behavioural outcomes are best explained. Comprehensive models of learning disorders need to be able to explain both isolated learning disorders that aﬀect one learning domain only and also comorbidity between them (Landerl, Göbel, & Moll, 2013).

Studies comparing individuals with isolated and comorbid learning disorders suggest that the neurobiological correlates and cognitive deﬁcits associated with RD and MD are distinct (Ashkenazi, Black, Abrams, Hoeft, & Menon, 2013; Landerl, Bevan, & Butterworth, 2004; Landerl, Fussenegger, Moll, & Willburger, 2009; van der Sluis, de Jong, & van der Leij, 2004; Willburger, Fussenegger, Moll, Wood, & Landerl, 2008). While a deﬁcit in phonological processing is assumed to be the core cognitive deﬁcit underlying RD (Vellutino, Fletcher, Snowling, & Scanlon, 2004), MD has been related to a domain-speciﬁc deﬁcit in processing numerosities (Butterworth, 2010; Geary, 2013). Distinct

core deficits explain why RD and MD can dissociate, however the exact conditions causing their co-occurrence as well as the conditions explaining the large variance in comorbidity rates observed between studies are not well understood yet. Against this background, the current study is aimed at a better understanding of the comorbidity between RD and MD.

Currently, the dominant framework for understanding comorbidity is based on conceptions of multiple-deficit models. According to this approach, learning disorders are associated with multiple risk factors and result from complex interactions between core deficits that are specific to a given disorder (**Figure 1: grey arrows**) and domain-general risk factors that might be shared between disorders (Hulme & Snowling, 2013; Pennington, 2006). Thus, domain-general cognitive factors, such as memory, attention or processing speed, are likely to impact on learning in several domains (Moll, Göbel, Gooch, Landerl, & Snowling, 2016; Raddatz, Kuhn, Holling, Moll, & Dobel, 2017; Schuchardt, Maehler, & Hasselhorn, 2008; Slot, van Viersen, de Bree, & Kroesbergen, 2016; Willcutt et al., 2013). Deficits in these domain-general skills may explain why individuals are likely to be affected in more than one learning domain (**Figure 1: solid black lines**).

>Insert Figure 1 about here<

Another plausible explanation for comorbidity between disorders is that there are shared behavioural features related to distinct underlying cognitive deficits. Thus, different cognitive deficits may have identical behavioural manifestations (symptom overlap). Symptom overlap between RD and MD is related to the fact that MD is characterized by heterogeneity of symptoms. According to DSM-5 (American Psychiatric Association, 2013), deficits in four mathematical subskills are differentiated and listed as diagnostic criteria: difficulties in arithmetic fluency, in calculation, in mathematical reasoning and in understanding of numbers, magnitudes, and their relationship (basic number processing). It follows that individuals with MD can differ both in the mathematical subskills that are affected and hence their deficit profile (Geary, Hamson, & Hoard, 2000; Hanich, Jordan, Kaplan, & Dick, 2001) because different mathematical subskills involve different cognitive abilities. Of special interest with respect to the overlap between MD and RD are mathematical subskills, such

as arithmetic fluency, that do not only build on number skills but also require language (Geary & Hoard, 2001). Language skills are the precursors of verbal number skills, such as counting and transcoding (reading and writing numbers), which in turn affect arithmetic skills (LeFevre et al., 2010; Moll, Snowling, Göbel, & Hulme, 2015). Evidence that poor language indeed affects mathematical skills comes from studies showing that individuals with poor language or literacy skills perform more poorly in aspects of mathematics that depend upon verbal abilities (i.e., arithmetic fluency) compared to typically developing controls (De Smedt & Boets, 2010; Donlan, Cowan, Newton, & Lloyd, 2007; Fazio, 1996; Geary, 1993; Göbel & Snowling, 2010; Hanich et al., 2001; Miles, Haslum, & Wheeler, 2001; Moll, Göbel, & Snowling, 2015; Simmons & Singleton, 2006), whereas their nonverbal number skills (such as comparing magnitudes) are generally unaffected. In contrast, individuals with MD experience deficits in numerous mathematical skills, including verbal as well as non-verbal number skills (Butterworth, Varma, & Laurillard, 2011; Landerl, 2013; Landerl & Kölle, 2009). For them, problems in arithmetic seem to be linked to a deficit in representing numerosities (ANS-deficit; (Piazza et al., 2010)) or in accessing numerosities from symbols (access-deficit; (Rousselle & Noël, 2007)), rather than problems in language or phonological processing (Moll, Göbel, et al., 2015). Deficits in representing or accessing numerosities impact on effective number processing in a wide range of mathematical tasks. Thus, the identical symptoms, such as deficits in arithmetic fluency, may be the behavioural manifestations of different underlying cognitive deficits, a deficit in the language domain or a deficit in processing numerosities (**Figure 1: dashed lines vs. grey arrows**).

In spite of its implications for theory and practice, this hypothesis has received little research attention. Here, we report the first study analysing how comorbidity rates between RD and MD vary according to the behavioural measures used to identify MD with the aim of better understanding the comorbidity between learning disorders.

On the assumption that children may be diagnosed with MD for very different reasons, we hypothesized that whether or not a child receives a diagnosis would depend on the tests administered. More specifically, we predicted that assessing difficulties in mathematics through

verbally-based number tasks, such as arithmetic fluency, would not only identify children with MD, but also children with RD who have language-based difficulties. More generally, such a finding would mean that co-occurrence rates for learning disorders will be significantly higher when arithmetic fluency is used in the assessment as opposed to magnitude processing tasks.

In the current study this hypothesis was tested by assessing both arithmetic fluency and magnitude comparison in a large representative sample of third graders. We focused on those two mathematical subskills which are listed as diagnostic criteria for ‘specific learning disorder with impairments in mathematics’ in DSM-5, as they clearly differ in their verbal foundation and are commonly used in diagnostic batteries (Brankaer, Ghesquière, & De Smedt, 2017; Brigstocke, Moll, & Hulme, 2016; Butterworth, 2003; Kuhn, Schwenk, Raddatz, Dobel, & Holling, 2017; Nosworthy, Bugden, Archibald, Evans, & Ansari, 2013). Including several arithmetic and magnitude comparison tasks further allowed us to analyse associations between number tasks and to investigate whether the two subskills (arithmetic fluency and magnitude comparison) can be clearly distinguished.

Methods

Participants

The study was approved by the institutional ethics committee and was performed in accordance with the Declaration of Helsinki and in compliance with national legislation. School authorities, teachers, parents and children were informed in detail about the aims and procedures of the study. Parents gave their written consent prior to inclusion in the study. A representative sample of 1487 third graders participated. Twenty-eight children were excluded due to incorrect completion of a test. Following DSM-5 diagnostic criteria for Specific Learning Disorder, another 5 children were excluded due to IQ-scores below 70. Thus, the final sample comprised 1454 children.

Participants were recruited from 135 classrooms in 46 primary schools which were distributed all over Munich to obtain a representative sample including both, large urban and small suburban schools and to take account for the differences in socioeconomic status (SES) between the 105 districts in Munich. Information about SES was obtained from the social service department of

Munich (<https://www.muenchen.de/rathaus/Stadtfinfos/Statistik.html>). The SES score is calculated based on several sociodemographic indicators (i.e., unemployment, social benefit, percentage of migrants, poverty among the elderly, and child support benefit). For each indicator, districts are ranked, and a summed score is calculated. Based on this summed score, districts are classified by the social service department into three categories ranging between 1 and 3, with higher scores indicating more needs for support and therefore reflecting lower SES. The mean SES score for the participating school districts did not differ significantly ($t = 1.45$, $p = .15$) from the mean score of all 105 Munich districts (Means (SDs): 2.14 (0.60) vs. 1.98 (0.60)), indicating that the SES score of our sample was representative for the region.

Tests and Materials

All tests were classroom administered by two trained research assistants per classroom.

Nonverbal IQ was assessed by the German version of the Culture Fair Intelligence Test ((Weiß, 2006); reliability = .92 according to manual). The test consists of four subtests: Series, Classification, Matrices, and Topology.

Reading. In the standardized reading fluency test ((Wimmer & Mayringer, 2014); parallel-test reliability $r = .95$ and content validity $r = .89$ according to manual) children were asked to read silently simple sentences and to mark them as semantically correct or incorrect (e.g., “Trees can speak”). After three minutes, the task was terminated and the number of correctly marked sentences was calculated (max. score = 100).

Spelling. The standardized spelling test ((Müller, 2004); split-half reliability = .95 according to manual) contained 44 words which were dictated and had to be written into sentence frames. Number of incorrect word spellings was scored (max. error score = 44).

Arithmetic fluency. Three subtests (addition, subtraction, and multiplication) of a standardized arithmetic fluency test were administered ((Haffner, Baro, Parzer, & Resch, 2005); one-to-two weeks test-retest-reliability between .80 and .86 according to manual). Children had to solve as many calculations as possible within two minutes and write down the correct answer (max. score

= 40). Each subtest starts with simple calculations (e.g., $1+6=_$) and increases in difficulty (e.g., $77+45=_$). For each subtest, an efficiency score was calculated based on the number of correctly solved items within the two minutes.

Symbolic magnitude comparison. An adapted version of the “Two-Minute Paper-and-Pencil Test of Symbolic and Nonsymbolic Numerical Magnitude Processing” (Nosworthy et al., 2013) was administered. Participants had to compare pairs of digits ranging from 1 to 9 and to cross out the larger number. The task was explained using two practice items, followed by ten practice items and 66 test items. Each digit pair was presented twice in order to counterbalance position (e.g., 3|7 and 7|3). The same pairs never occurred next to each other. Easier items (with large distance and small ratio: e.g., 1|9: distance = 8 and ratio [small / large number] = .11) were presented first, while more difficult items (with small distance and large ratio: e.g., 8|9: distance =1 and ratio = .89) were presented later in the booklet. The original test version including 56 items was adapted by adding 10 items of medium difficulty level in order to avoid ceiling effects. The mean ratio of the new version was .50. The 66 item pairs were presented in lines on three pages in a booklet. After one minute, the task was terminated and the number of correctly marked items was scored.

Nonsymbolic magnitude comparison. Participants had to compare pairs of dot patterns ranging from 5 to 21 dots with a mean of 12 dots and a mean ratio of .62 (range: .33 - .89). The minimum of 5 dots was chosen to ensure that the task measures the ability to compare large magnitudes rather than assessing subitizing processes (the ability to automatically perceive a small amount of objects) or counting skills. The use of counting strategies was further prevented by the time limit and by explicitly instructing children not to count but to estimate which box had more dots. To ensure that children made their judgement based on magnitude rather than surface area or dot size (perimeter) we controlled for these variables. In half of the trials dot patterns were matched for surface area, while in the other half they were matched for perimeter. In addition, all patterns included dots of different sizes (see (Nosworthy et al., 2013)). The format of the task was comparable to the symbolic magnitude comparison task. The task was explained based on two items, followed by

ten practice items and the 66 test items. The test started with easier items (e.g., 6 vs. 18 dots: ratio = .33), while more difficult items (e.g., 16 vs. 18 dots: ratio = .89) were presented later in the booklet. After one minute the task was terminated and the number of correctly marked items was calculated.

One-week test-retest-reliability for both basic number processing tasks was measured in a separate sample of 82 children of the same age in one of the participating schools. Retest-reliability was .75 and .70 for symbolic and non-symbolic magnitude processing, respectively.

Results

Descriptive statistics are reported in **Table 1**. All measures were reasonably normally distributed and no measure was subject to ceiling or floor effects.

>Insert Table 1 about here<

Factor analyses and correlations for number skills

A principal axis analysis with promax rotation method was conducted in SPSS (IBM SPSS statistics, version 24) including the five mathematical tasks in order to test whether two theoretically meaningful factors could be extracted that reflect the diagnostic and theoretical distinction between arithmetic and basic number processing skills (American Psychiatric Association, 2013; Dehaene, 1992). The results indicated a two factor solution explaining 66% of the variance. The three calculation subtests loaded on the first factor (arithmetic factor: eigenvalue = 2.35; factor loadings = .81, .93, and .79 for addition, subtraction, and multiplication), while the two magnitude comparison tasks loaded on the second factor (basic number processing factor: eigenvalue = 1.54; factor loadings = .75 for both symbolic and non-symbolic magnitude comparison respectively). The correlation between the two non-orthogonal factors was .43. In addition, a parallel analysis using R-package psych (Procedures for Psychological, Psychometric, and Personality Research, version 1.8.3.3.) was conducted to determine the number of factors to retain from factor analysis. The parallel analysis supported the two-factor solution.

In line with the two-factor solution, correlations between the three calculation measures ($r_s = .65 - .77$), and between the two magnitude comparison tasks ($r = .56$) were higher than between any of the arithmetic and magnitude comparison tasks ($r_s = .16 - .39$).

Following these findings, two composite factor scores were calculated based on z-standardized scores: an arithmetic factor based on the three arithmetic fluency subtests, and a basic number processing factor based on the two magnitude comparison tasks.

Relationship between literacy and number skills

In order to assess the relationship between literacy and number skills, a composite literacy score was calculated based on the z-standardized reading and spelling scores (the correlational pattern was comparable when calculating correlations for reading and spelling separately). The correlation between literacy and arithmetic skills ($r = .54$) was significantly higher than that between literacy and basic number processing skills ($r = .20$; $z = 12.70$, $p < .001$) and also higher than between arithmetic and basic number processing ($r = .34$; $z = 7.11$, $p < .001$). Zero-order correlations between all subtests are reported in **Table 2**. Controlling for non-verbal IQ slightly reduced all correlations but did not change the correlational pattern. Again higher correlations were found between literacy and arithmetic ($r = .47$) than between literacy and basic number processing ($r = .12$; $z = 12.10$, $p < .001$) and arithmetic and basic number processing ($r = .29$; $z = 5.84$, $p < .001$). The fact that the correlational pattern did not change after controlling for performance on a complex task (i.e., nonverbal IQ) further indicates that the strong association between arithmetic and literacy skills cannot solely be explained by similarities in task complexity. Together, these findings support the theoretical distinction between arithmetic fluency and basic number processing skills, and confirm the association between literacy and arithmetic skills.

Comorbidity rates

To examine how comorbidity rates depend on the construct that is applied to define MD, comorbidity rates between literacy deficits (LitD) and arithmetic deficits (AD) were compared to those between literacy deficits (LitD) and number processing deficits (ND). Two deficit criteria were

defined to check that results do not depend only upon severity of MD. Following DSM-5 criteria, a strict deficit criterion was defined when a child scored at least 1.5 standard deviations below the sample mean. The more lenient criterion of 1 standard deviation was chosen based on evidence- and consensus-based clinical guidelines (Galuschka & Schulte-Körne, 2016). Comorbidity rates for both criteria are presented in **Figure 2**.

>Insert Figure 2 about here<

In line with previous research (Landerl & Moll, 2010; Moll et al., 2014), comorbidity rates were higher for the lenient criterion compared to the stricter deficit criterion. However, the novel finding was that, irrespective of the deficit criterion, comorbidity rates were significantly higher when arithmetic tasks were used to measure MD compared to when basic number processing tasks were used (1.5 SD criterion: 22% vs. 4%; $z = 3.36$, $p < .001$ and 1 SD criterion: 41% vs. 17%; $z = 5.59$, $p < .001$). This finding is in line with the correlational pattern reported above. **Figure 3** shows the overlap between deficits in literacy, arithmetic, and number comparison.

>Insert Figure 3 about here<

Next we calculated odds ratios for the 1.5 SD-criterion to compare the observed comorbidity rates in our sample with the rates expected by chance (Caron & Rutter, 1991). The expected comorbidity rates were calculated by multiplying the base rates of 5.2% for LitD with the base rate of 5.4% for AD or 4.5% for ND, respectively. The observed comorbidity rates for deficits in literacy and arithmetic fluency (LitD+AD) were more than four times higher than expected by chance (observed/expected = 4.25; $z = 2.85$, $p = .004$). In contrast, the observed comorbidity rates for deficits in literacy and number comparison (LitD+ND) were not above chance (observed/expected = 1.00). A direct comparison between the odds ratios of LitD+AD and LitD+ND revealed a significant difference between ratios ($z = 2.56$, $p = .010$). Although the overlap between deficits in the two mathematical subskills was higher than expected by chance (observed/expected = 2.75), the results also show that deficits in arithmetic and in basic number skills dissociate in a substantial number of children, which is in line with the only moderate correlations observed between the two skills. Calculating odds

ratios for the 1 SD-criterion resulted in a slightly smaller but largely significant difference between odds ratios for LitD+AD compared to those for LitD+ND (observed/expected = 3.15 vs. 1.43 for LitD+AD vs. LitD+ND; $z = 3.68$, $p < .001$).

Discussion

The present study aimed to better understand the comorbidity between RD and MD based on a population-sample. First, we examined the relationship between literacy and two mathematical subskills (arithmetic fluency and basic number processing) which differ in the amount they rely upon language skills. We found stronger associations between literacy and arithmetic fluency than between literacy and basic number processing skills and between the two mathematical subskills. Turning to comorbidity rates, we replicated earlier findings showing that learning disorders co-occur about three to four times more often than expected by chance (Landerl & Moll, 2010). The novel finding was that the large overlap between RD and MD was restricted to arithmetic fluency, as comorbidity rates did not exceed chance rate when MD was defined by deficits in basic number processing. These findings suggest that deficits in basic number processing and in literacy are distinct and that the large variation in comorbidity rates observed between prevalence studies is likely to result from differences in the way in which MD is assessed.

At first glance, the stronger association found between literacy and arithmetic than between the two mathematical subskills may seem counterintuitive, given that basic number processing skills are assumed to underlie mathematics development. However, there is evidence suggesting that the cognitive skills and the brain-based systems that are involved in mathematics differ depending on the behavioural measure used. For example, it has been argued that the brain networks supporting *approximate* arithmetic (i.e. estimating calculation results) and comparing magnitudes are separable from those supporting *exact* arithmetic (Dehaene, Piazza, Pinel, & Cohen, 2003). Especially relevant for the current study are findings showing that the representation of exact arithmetic recruits language-related networks (Dehaene et al., 2003; Evans, Flowers, Napoliello, Olulade, & Eden, 2014; Koerte et al., 2016) that are also involved in reading. Based on these findings, the association

between literacy and exact arithmetic found in the current study is to be expected and is in line with recent fMRI findings showing similar neural activation patterns in children with RD, MD and comorbid problems during arithmetic tasks (Peters, Bulthé, Daniels, de Beeck, & De Smedt, 2018).

Whereas arithmetic fluency depends, at least partly, on verbal processing and recruits language-related networks, other mathematical tasks (e.g., approximate calculation) depend upon the child's ability to represent and manipulate numerical magnitude (Dehaene, 1992; Von Aster & Shalev, 2007). The magnitude system is a pre-verbal system and deficits in the magnitude system, either in representing (Piazza et al., 2010) or in accessing magnitudes from symbols (Rousselle & Noël, 2007), are considered to underlie MD. Thus, mathematical tasks that strongly rely on the magnitude system are more likely to show higher overlap with magnitude comparison than with literacy skills.

An alternative explanation for the large overlap between RD and MD is that domain-general cognitive risk factors affect both learning domains. Although we did not assess domain-general risk factors directly, we compared the overlap between deficits in literacy and in two mathematical subskills (arithmetic and magnitude processing) that clearly differed in the amount they build on language skills since language skills are not involved in magnitude processing (Von Aster & Shalev, 2007); however the tasks used to assess the two mathematical subskills were largely similar in terms of other domain-general factors that may affect performance, such as attention or processing speed. Thus, the results most probably reflect the fact that deficits in language skills represent a shared risk factor that may impact on both literacy and arithmetic fluency skills.

Our findings have some important implications for practice. First, they show that children with RD frequently experience problems in verbal number tasks, although their magnitude processing skills are unaffected. On the other hand, whether or not a child with RD experiences problems in arithmetic fluency will depend on the deficit profile of the child and the combination of risk and protective factors, for example, those with weak language skills may be particularly vulnerable to arithmetic difficulties (Moll, Göbel, et al., 2015). Practitioners should keep in mind that

children with RD may have problems in arithmetic fluency while deficits in a wide array of mathematical skills are expected for children with MD. Second, our findings add to the discussion concerning the definition and diagnosis of MD. The current findings make the general point that when assessing educational attainments, assessment batteries should involve a variety of number processing tasks, including tests tapping arithmetic fluency and basic number processing. In the current study children with learning disorders were identified based on classroom assessments in a population-based sample. Future research based on clinical samples can help to specify these deficit profiles and to identify developmental changes in arithmetic problems in children with persistent RD.

It follows from the present findings that deficits in arithmetic are likely to require different interventions depending on the underlying cognitive deficits (Fuchs, Fuchs, & Compton, 2013). Given that children with RD show specific problems in arithmetic but not in mathematical skills that rely upon the magnitude system, it can be argued that they might especially benefit from training language related number skills that underlie arithmetic fluency, while intervention programmes for children with MD need to improve their understanding of numbers and magnitudes. Future intervention studies should assess the effectiveness of training different mathematical skills in children with RD, MD and comorbid problems.

To conclude, the current findings help to specify models of comorbidity between learning disorders by providing evidence for strong associations between literacy skills and aspects of mathematics that rely on language skills and by showing that symptom overlap affects comorbidity rates. They also advocate the assessment of a broad range of mathematical skills in order to differentiate between different deficit profiles underlying a MD diagnosis. Future studies will have to further specify the relationship between different domain-general cognitive skills (e.g., attention, memory, and processing speed) and domain-specific skills (including different number processing skills), and their relation to different aspects of mathematics.

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Table 1

Descriptive statistics (raw scores) for all measures

Measure	Mean (SD)	Minimum	Maximum	Skewness	Kurtosis
IQ [CFT 20-R]	30.83 (5.89)	14	48	-.18	-.19
Spelling [DRT]	17.29 (10.18)	0	44	.39	-.71
Reading [SLS 2-9]	34.21 (8.65)	8	69	.17	.24
Addition [HRT]	25.20 (4.77)	5	40	-.30	.04
Subtraction [HRT]	24.63 (5.65)	1	38	-.41	-.07
Multiplication [HRT]	16.84 (5.13)	3	37	.35	.09
Symbolic MC	49.48 (10.25)	0	66	-.61	1.39
Non-symbolic MC	42.49 (8.32)	3	64	-.43	1.04

Table 2

Zero-order correlations between all subtests

	1.	2.	3.	4.	5.	6.	7.	8.
1. IQ	-	.33***	.36***	.28***	.34***	.30***	.17***	.24***
2. Reading		-	.60***	.44***	.43***	.43***	.27***	.19***
3. Spelling			-	.40***	.44***	.47***	.12***	.06*
4. Addition				-	.77***	.65***	.39***	.29***
5. Subtraction					-	.70***	.32***	.21***
6. Multiplication						-	.26***	.16***
7. Symbolic MC							-	.56***
8. Non-symbolic MC								-

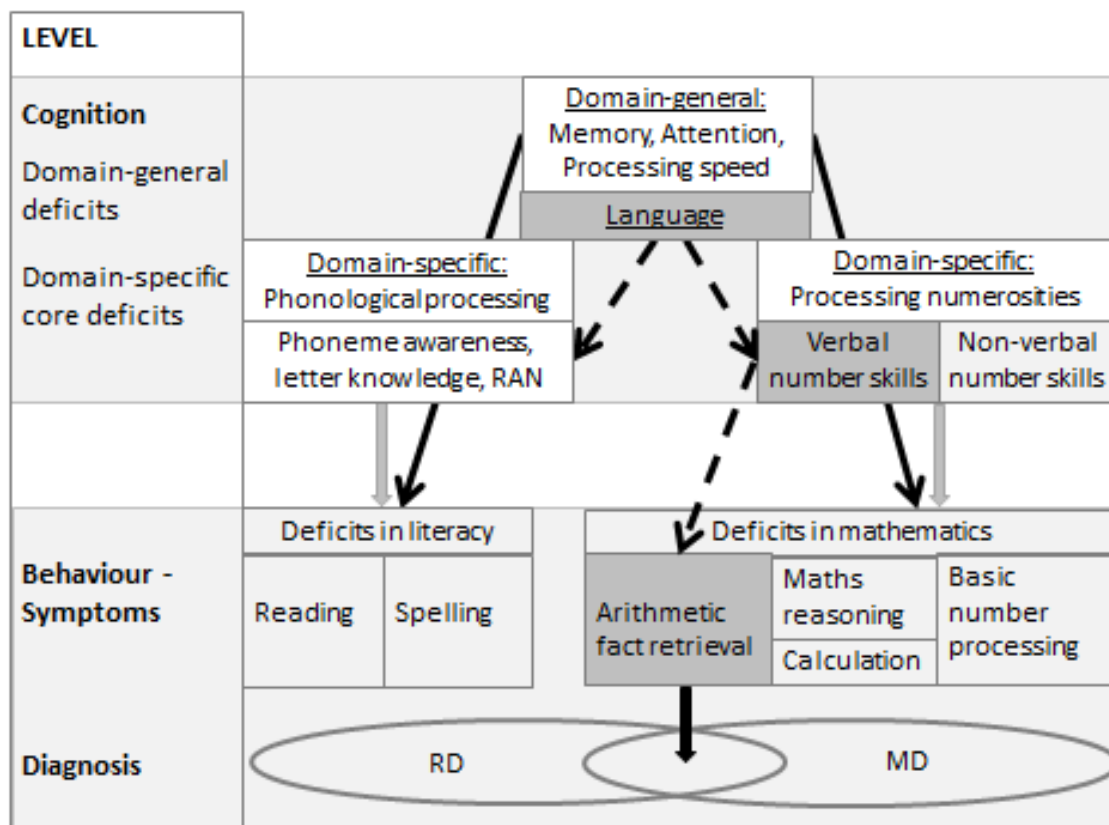


Figure 1

Model for understanding comorbidity between RD and MD: solid lines indicate impact of domain-general skills on behavioural outcome, dashed lines show pathway leading to symptom overlap.

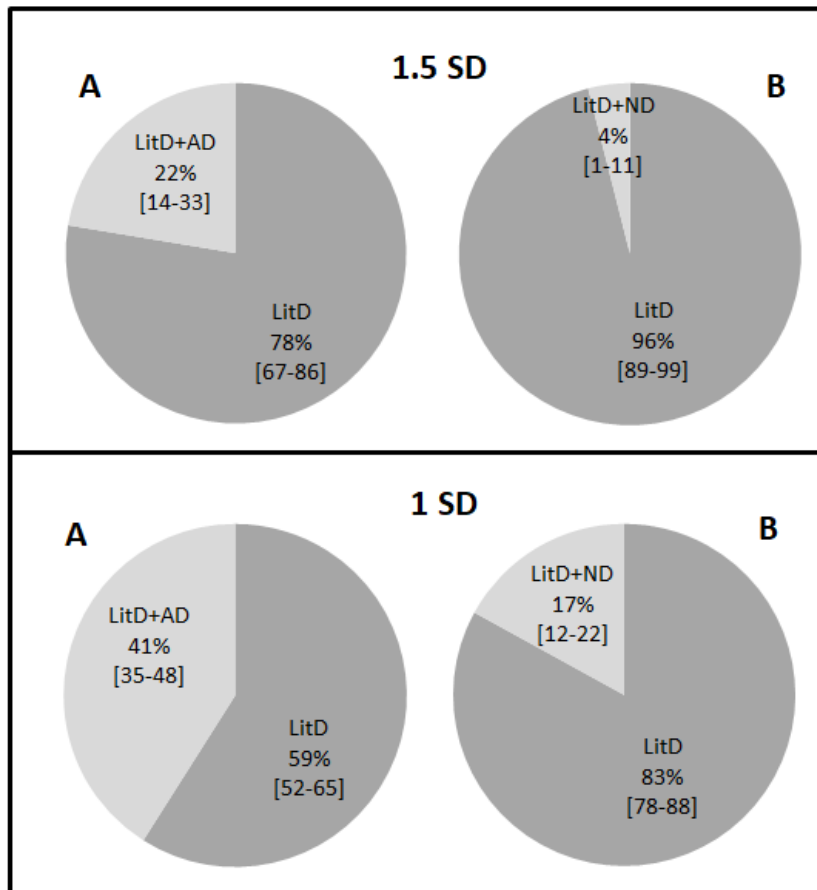


Figure 2

Percentages [95% confidence intervals] of children with literacy deficits based on 1.5 SD (upper graph) and 1 SD deficit criterion (lower graph) showing a literacy deficit only (LitD) or comorbid deficits with arithmetic (LitD+AD: panel A) or with number comparison (LitD+ND: panel B).

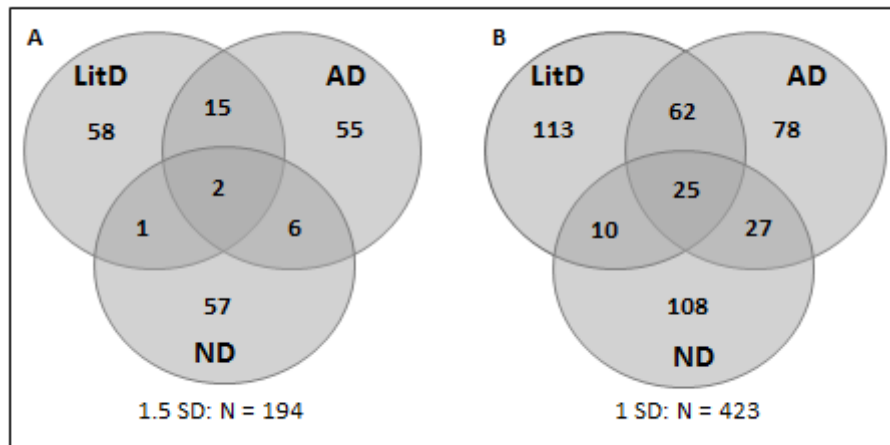


Figure 3

Overlap between deficits in literacy (LitD), arithmetic (AD), and number processing (ND) for 1.5 SD (A) and 1 SD (B) criterion.

Keypoints:

- Reading disorder (RD) and mathematics disorder (MD) frequently co-occur, but the exact comorbidity rates differ largely between studies.
- We assessed whether comorbidity rates depend on the constructs used to define MD.
- Comorbidity rates were higher when MD was measured by mathematical subskills that build on language skills (i.e., arithmetic fluency) than when defined by deficits in basic number processing.
- Comorbidity between RD and arithmetic deficits can be explained by domain-general risk factors (i.e. language skills) and by symptom overlap.
- The findings have implications for diagnosis and intervention: Assessment batteries need to differentiate between different number processing tasks. Children with arithmetic deficits will require different interventions depending on the underlying cognitive deficits.