Basic Number Processing in Children with Specific Learning Disorders: Co-morbidity of Reading and Mathematics Disorders

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Abstract

As well as being the hallmark of mathematics disorder, deficits in number processing have also been reported for individuals with reading disorder. The aim of the present study was to investigate separately the components of numerical processing affected in reading and mathematical disorders within the framework of the Triple Code Model (Dehaene, 1992, 2000). Children with reading disorder (RD), mathematics disorder (MD), comorbid deficits (RD+MD) and typically developing children (TD) were tested on verbal, visual-verbal and nonverbal number tasks. As expected, children with MD were impaired across a broad range of numerical tasks. In contrast, children with RD were impaired in (visual-)verbal number tasks, but showed age-appropriate performance in non-verbal number skills, suggesting their impairments were domain-specific and related to their reading difficulties. The comorbid group showed an additive profile of the impairments of the two single deficit groups. Performance in speeded verbal number tasks was related to RAN, a measure of visual-verbal access, in the RD but not in the MD group. The results indicate that deficits in number skills are due to different underlying cognitive deficits in children with RD compared to children with MD: a phonological deficit in RD and a deficit in processing numerosities in MD.

Keywords:

Reading disorder, mathematics disorder, comorbidity, number skills, Triple Code Model

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Poor literacy and numeracy are prime causes of educational underachievement. Whereas *Reading Disorder* (RD) is an impairment in word decoding and fluency, *Mathematics Disorder* (MD) is defined by a deficit in the acquisition of basic numerical operations. However, many children with reading disorder experience arithmetic problems and likewise, many with mathematical disorder also have reading problems (Badian, 1983; Dirks, Spyer, van Lieshout, & de Sonneville, 2008; Gross-Tsur, Manor, & Shalev, 1996; Landerl & Moll, 2010; Lewis, Hitch, & Walker, 1994). This high degree of comorbidity requires explanation.

On the cognitive level, there is evidence that a deficit in phonological processing is the proximal cause of reading difficulties (Vellutino, Fletcher, Snowling, & Scanlon, 2004), while MD has been related to a domain-specific deficit in processing numerosities. The exact nature of the number processing deficit underlying MD is debated. Two explanations have been forwarded: first, a deficit in *representing* numerosities (deficit in an innate approximate number sense - ANS: Butterworth, 2010; Piazza et al., 2010), and second, a deficit in *accessing* numerosities from symbols (access-deficit hypothesis: Rousselle & Noël, 2007), which, in turn, might result in deficits in non-symbolic number processing (Noël & Rousselle, 2011). Importantly, both explanations imply a core deficit in processing numerosities and predict problems in a wide range of number tasks. Therefore, regardless of its origin, the number processing deficit is considered to represent the core cognitive deficit associated with MD, being different from the core deficit in phonological processing associated with RD (Landerl, Bevan, Butterworth, 2004; Landerl, Fussenegger, Moll, & Willburger, 2009).

While the core deficits for RD and MD appear to be domain-specific, one proposal regarding the comorbidity of RD and MD is that domain-general deficits, such as deficits in processing speed or working memory (Bull & Johnston; Geary & Hoard, 2005; Willcutt et al., 2013) are shared between RD and MD and this could explain why these disorders frequently co-occur. Compared to previous studies which focused on the different core deficits underlying RD and MD or on domain-general risk factors that might be shared between disorders, the current study followed a different approach: An alternative or additional explanation to explain comorbidity between RD and MD is that, because mathematics has both verbal and non-verbal components, it could be that poor performance in mathematics is the behavioural consequence of different patterns of deficit in number processing in the case of RD and MD. According to this explanation, the same behavioural phenotype is associated with different cognitive risk factors: a language or phonological deficit in the case of RD and a deficit in processing numerosities in the case of MD (see Robinson, Menchetti, & Torgesen, 2002 for a similar distinction between MD versus RD+MD). The current study investigated this hypothesis by assessing the number processing skills of children with RD compared to children with MD and by examining whether the same behavioural phenotype (i.e., deficits in arithmetic) can be explained by different underlying cognitive deficits.

In order to assess different components of number processing skills, the Triple Code Model (Dehaene, 1992, 2000) was used as theoretical framework. According to the Triple Code Model, the verbal code is one of three systems used for processing numbers. Consistent with this, longitudinal studies show that phonological processing skills predict individual differences in arithmetic in typically developing children (De Smedt, Taylor, Archibald, & Ansari, 2010; Hecht, Torgesen, Wagner, & Rashotte, 2001) and studies of individuals with RD have revealed difficulties with verbal aspects of mathematics, for example counting and recalling number facts (Göbel & Snowling, 2010; Simmons & Singleton, 2006). The second system, the visual code, is involved in processing Arabic number forms, and the third code, the analogue magnitude representation (also called approximate number sense, ANS) is used for representing and estimating numerosities. The differentiation between the three codes is also supported by fMRI studies showing that activation patterns differ according to task demands and that number-related processes are organized in three parietal circuits (e.g., Dehaene, Piazza, Pinel, & Cohen, 2003). It should be noted that the three codes interact during efficient number processing and cannot be strictly separated. However, number processing tasks differ in how strongly they draw upon the three codes.

The aim of the present study was to investigate number processing deficits in children with RD and MD within the framework of the Triple Code Model. Although there is evidence from behaviour-genetic analyses that reading and mathematics disorders share genetic variance (e.g., Knopik, Alarcón, & DeFries, 1997; Kovas et al., 2007), previous studies that have directly assessed the behavioural and cognitive profiles of RD and/or MD within the same study suggest that the cognitive core deficits underlying RD and MD are distinct (Andersson, 2008; Cirino, Fletcher, Ewing-Cobbs, Barnes, & Fuchs, 2007; Jordan, Hanich, & Kaplan, 2003; Landerl et al., 2004, 2009; van der Sluis, de Jong, & van der Leij, 2004; Willburger, Fussenegger, Moll, Wood, & Landerl, 2008; Willcutt et al., 2013). However, none of these studies has investigated the three number codes systematically in children with MD, RD and RD+MD or has analysed how number processing deficits are related to the different core deficits associated with RD versus MD. Thus, the present study investigates key components of numerical cognition, namely verbal and non-verbal number skills and the access to magnitudes from Arabic digits (symbols), in children with reading disorder (RD), children with mathematics disorder (MD), children with comorbid reading and mathematics disorder (RD+MD) and typically developing children (TD). The study aimed to test the following hypotheses:

1. *Children with RD* will experience specific deficits in the verbal code but their approximate number sense (ANS) will not be impaired. Deficits in the verbal code should be evident in numerical tasks tapping verbal skills such as counting. Performance is expected to be especially poorly on tasks that require literacy-related skills, such as transcoding (reading and writing) numbers. Moreover, since phonological processing deficits are thought to affect fact retrieval (Cirino et al., 2007; Geary & Hoard, 2001), children with RD should have particular problems with such skills.

2. *Children with MD* will show impairments in a wide range of number tasks, including symbolic number comparison, counting and arithmetic. Based on the theory that a deficit in number processing is the core deficit underlying MD, both groups with maths difficulties (MD and RD+MD) will show a generally larger deficit across number tasks compared to the RD only group, assuming their impairment is more selective. This should be the case on average, irrespective of the underlying deficit theory (ANS or access deficit). With respect to the ANS and access deficit theory, the following predictions can be made: If the impaired number sense theory is correct then we expect to find that children with MD have difficulties in non-symbolic number processing, calling upon the ANS. Expectations are less clear for the access deficit theory; here the core deficit is in accessing numerosity from symbols, e.g. writing, reading, identifying numbers and symbolic number comparison, but these deficits might in turn also affect non-symbolic number processing (Noël & Rousselle, 2011).

3. Based on previous research (Landerl et al., 2004, 2009; van der Sluis et al., 2004; Willburger et al., 2008) indicating thatthe cognitive deficits underlying RD and MD are domain-specific we hypothesise that *children with comorbid RD+MD* will show an additive profile of impairments reflecting the sum of the two single deficit groups. In contrast, an interactive pattern would reflect either under- or overadditivity. Here, underadditivity (less impairment in comorbid RD+MD compared to the sum of the single deficit groups) is interpreted as a shared deficit between RD and MD, while overadditivity (more impairment in comorbid RD+MD than the sum of the single deficits) indicates that the co-morbid group represents a separate disorder associated with additional risk factors that are distinct from those of the single deficit groups.

4.We hypothesise that difficulties in verbal number tasks are associated with different underlying cognitive deficits in children with RD compared to children with MD. In children with RD, performance in verbal number tasks will be associated with performance in phonological processing (measured by phonological awareness and efficiency of visual-verbal access). In contrast, for children with MD who do not experience such phonological difficulties, performance in verbal number tasks will be caused by the same underlying cognitive deficit as difficulties in nonverbal number tasks. Therefore, we predict that controlling for individual differences in phonological processing will decrease the group differences in verbal number tasks between RD and TD, but not between MD and TD.

**Method**

**Participants**

Participants were drawn from an ongoing family-risk study (N=57: 18 RD, 7 MD, 7 RD+MD, 25 TD) or recruited via newspaper adverts, schools and support agencies for children with learning difficulties (N=32: 3 RD, 10 MD, 12 RD+MD, 7 TD), following the same recruitment procedure as for the family-risk study. All children came from British white families in the county of North Yorkshire, England, and had English as their first language. In total, 89 children aged 6 to 12 years participated: 21 children with RD (62% boys; aged 6 to 12), 17 children with MD (35% boys; aged 6 to 12), 19 children with RD+MD (63% boys; aged 6 to 12) and 32 typically developing children (TD) with age-adequate performance in literacy and mathematics (47% boys; aged 7 to 11). Children were classified as ‘impaired’ either because they received a diagnosis according to DSM-IV criteria (American Psychiatric Association, 2004) of RD and/or MD from an Educational Psychologist (N=26: 6 MD, 9 RD, 11 RD+MD) based on a comprehensive diagnostic test battery or because they obtained a standard score below 85 (16th percentile) on the literacy and/or mathematics measures used for classification in the current project. All children with a diagnosis were also tested on the classification measures used in the current study. Out of the 26 children with a diagnosis only four children with RD did not score below 85 on the literacy measures. Three of them scored more than half a standard deviation below the age-specific mean on one of the literacy measures and showed a discrepancy between literacy skills and IQ of at least 19 standard score points (between 19 and 26.5). Only 1 child with a diagnosis of dyslexia performed average on both literacy measures; however this child showed a marked difference of 38.5 and 32.5 standard score points between his literacy skills and his performance on the IQ and arithmetic measures. Separate analyses for the three deficit groups (RD, MD and RD+MD) showed no group difference in performance between children with and without a diagnosis on any classification measure (all *p*s >.05).

All children scored within the normal range on at least one the two IQ scales (verbal and nonverbal IQ), ensuring that children with general learning difficulties due to low cognitive abilities were not included in the sample.

Ethical approval was granted by the Research Ethics committee of the Department of Psychology, University of York; informed consent was given by caregivers.

**Group classification**

Literacy and mathematical skills were assessed using the Word Reading, Spelling and Numerical Operations subtests of the Wechsler Individual Achievement Test (*WIAT-II* – 2nd UK Edition, 2005). The *word reading* and *spelling subtests* require decoding/encoding of single words. The *numerical operations subtest* includes written calculation problems involving addition, subtraction, multiplication and division.

**Tests and Procedures**

Testing took place in a quiet room within the psychology department. All children were tested individually in two sessions by one of the authors or by trained research assistants.

**General cognitive ability.**Verbal and non-verbal IQ were assessed using the *Wechsler Abbreviated Scale of Intelligence (WASI*; Psychological Corporation, 1999). The test includes two subtests for each scale. The subtests ‘Vocabulary’ and ‘Similarities’ provide an estimation of Verbal IQ; ‘Block Design’ and ‘Matrix Reasoning’ provide an estimation of Performance IQ.

**Phoneme awareness.** In Phoneme Deletion (adapted from McDougall, Hulme, Ellis, & Monk, 1994) children had to delete a designated sound from a nonword (e.g., “say *bice* without the /b/ - ‘ice’”). There were 24 items of increasing difficulty (Cronbach’s Alpha .93). Test-retest- reliability (6 months) was .81.

**Rapid automatized naming (RAN).**An adapted version of the letter and digit naming RAN task developed by van der Sluis et al. (2004) was administered. Children were asked to name as quickly and accurately as possible a matrix of 40 stimuli. Partial correlations (with age) between RAN letters and digits were high in all four groups (between .67 and .77). Test-retest-reliability (6 months) was .88. The mean number of items named correctly per second over both conditions was recorded.

 **Reaction time (RT).**Simple RT was measured using a computerized task with 36 trials developed in our lab. Children had to press the space bar as soon as an image of a dragon appeared on the screen. The stimulus was preceded by a fixation cross and a varied lag (300ms, 600ms or 900ms). Test-retest-reliability (6 months) was .69.

All measures were normally distributed (Kolomogorov-Smirnov-Z < 1.34, all *p*s > .05).

**Number processing and calculation tasks**

The tasks chosen to examine numerical cognition sampled a broad range of number processing skills with the aim of assessing the different components of the Triple Code Model. Calculation skills were added to the battery in order to assess fact retrieval, which is associated with the verbal code (Arsalidou & Taylor, 2011; Dehaene & Cohen, 1997). While it would be desirable to use pure tests of the verbal code, the visual code and the ANS, most number tasks tap several codes, though, depending on task demands, to varying extents. We describe here the tasks, beginning with (1) the (visual)-verbal tasks that do not involve the Arabic number form and therefore mainly tap the verbal code (verbal counting and dot counting), through (2) verbal-symbolic tasks including the visual code (identifying and transcoding numbers, calculation, and symbolic number comparison) to (3) non-verbal (non-symbolic) tasks tapping the ANS (numberline and non-symbolic number comparison).

**(1) Number tasks tapping the verbal code**

**Verbal counting.** Children were asked to count in twos as fast as possible for 20 seconds, first starting the counting sequence with number two (2, 4, 6…), then with number one (1, 3, 5...). Correlation between the two conditions was .61. The mean number of correctly counted items was calculated.

**Dot counting.**Thirty-two items comprising randomly arranged black dots (1-8 dots) were presented in a white square in the middle of the computer screen. Children were asked to count the dots as fast as possible and press the space bar whilst stating the answer verbally. Items were masked for 1500ms. Test-retest-reliability was .82. The percentage of items counted correctly and the mean RT for correct items were calculated for the subitizing (1-3) and the counting range (5-7) separately.

**(2) Number tasks tapping the symbolic code**

**Number identification.**Children had to mark the correct number corresponding to the number spoken by the tester. The target number was presented in a row printed in Calibri 16 on a DIN A4 paper together with 6 distracters that were visually and phonetically similar to the target (e.g., target = 309: 3009, 390, 39, 309, 903, 2090, 3900). Ten items were given, 5 within the hundreds and 5 within the thousands. Correlation between the two conditions was .80. The number of correctly identified items was calculated.

**Transcoding numbers.**Children were asked to write down 15 numbers that were dictated by the tester (5 each in the tens, hundreds and thousands). The same 15 numbers were presented approximately 2 hours later and children were asked to read them out aloud. Correlation between reading and writing numbers was .69. The number of correctly transcoded items (reading and writing) was calculated.

**Calculation.** This task measures arithmetic performance. Children were instructed to complete as many single digit additions/subtractions within one minute as possible (max = 30 per subtest). All operands and answers were below 20. Items 1 to 20 include only single digits as operands and answers (e.g., addition: 2+1; 2+5; subtraction: 2-1; 7-3), items 21 to 30 involve crossing the decade (e.g., addition: 5+7; 8+3; subtraction: 11-2; 14-6). The percentage of correct items (accuracy) and the number of correctly solved items per second (efficiency) were calculated. The efficiency score is a measure of fact retrieval; children who still rely on counting strategies will solve fewer items per second compared to those who are able to directly access arithmetic facts. Test-retest-reliability was .90 for addition efficiency and .89 for subtraction efficiency.

**Symbolic number comparison.**Forty-eight single-digit item-pairs were presented; children had to select as quickly as possible either the numerically smaller (Block 1) or larger (Block 2) of two Arabic numbers by pressing the left or right button on the keyboard corresponding to the position of the target item on the screen. Item pairs varied in their numerical distance with four items per distance. Correlation between the two blocks was .84. Small (1, 2, 3) and large (4, 5, 6/7) distance pairs were matched for problem-size (e.g., problem size of 13 for small distance pairs: 7 6 and large distance pairs: 9 4). Accuracy rates were close to ceiling; mean RTs were calculated for small and large distance items separately, pooled across blocks.

**(3) Number tasks tapping the approximate number sense**

**Numberline task.**A computerized numberline task (Landerl et al., 2009) with a horizontal line of 25cm was shown on the screen. The line was labelled with “0” on the left and 100 or 1000 on the right. The target number (100: 2, 11, 42, 4, 18, 6, 94 and 1000: 71, 230, 4, 18, 920, 6, 25) appeared on the top of the line and children were asked to point to the corresponding position on the line. Correlation between the two conditions (100 and 1000) was .81. The measure was the absolute deviance from the correct position in pixels for the two conditions (100 and 1000 numberline).

**Non-symbolic number comparison.**Two grey displays including different numbers of yellow squares (varying from 20 to 72) were presented on the left and right of the computer screen. Children had to select the display with more squares by pressing the corresponding button on the keyboard. The difference between the number of squares in the two displays ranged from 8 to 25, with four items per distance. Each item pair was presented twice, once with the smaller numerosity on the left and once on the right; surface area was controlled and squares of different sizes (12 to 28 pixels) were included. In each trial at least 1/6 of the squares were small and 1/6 large, with the remaining squares ranging in size in-between. The 72 items were presented in a pseudo-randomized fixed order. Guttman’s split half reliability was .78. Accuracy rates were calculated separately for the 24 items with small (8-13), and for the 24 items with large (20-25) distances.

**Results**

Table 1shows the descriptive statistics for the four groups together with statistics for the between groups comparisons. The groups did not differ significantly in age or simple RT, therefore any speed differences observed in the numerical tasks cannot be explained by differences in processing speed.

In line with their classification, the two groups with literacy difficulties (RD/RD+MD) did not differ significantly from each other in reading or spelling, but their scores were significantly lower than those of the MD and TD groups, who, in turn, did not differ. Similarly, the groups with mathematics difficulties (MD/RD+MD) did not differ from each other in mathematics performance, but they performed worse than the RD and TD groups, who did not differ. Consistent with the view that deficits in phonological processing underlie literacy difficulties, the two groups with reading disorder performed significantly worse in tests of phonological awareness and rapid automatized naming (RAN) 1 than the MD and TD groups.

**Number processing and calculation**

Data for the numberline task are missing for one child with RD+MD and data on transcoding, identifying numbers and on verbal counting are missing for three children with MD, one child with RD+MD and five TD children. To investigate group differences in number processing we ran a series of 2x2 factorial analyses investigating separately the effects of mathematics disorder and reading disorder, on number processing and calculation. This design allows us to examine whether the profile of the comorbid group reflects the sum of the two single deficit groups (additive profile) or shows an interactive pattern (hypothesis 3). An interactive pattern is evident if the interaction term mathematics ability by reading ability reaches significance (for a similar procedure see e.g., van der Sluis et al., 2004; Willburger et al., 2008; Willcutt et al., 2001). For the experimental tasks with more than one condition, condition was included as a within subjects factor. Although the groups did not differ in their mean age, age was entered as a covariate in all analyses in order to account for the age range in our sample. For each analysis we report the effects of mathematics (deficit (MD/RD+MD) versus no deficit (RD/TD)) and literacy (deficit (RD/RD+MD) versus no deficit (MD/TD)) on performance with age controlled. For the mixed designs, we also report the significance of the within subjects factor and the group by condition interactions. Since the mean FIQ of the typically developing group was above average, we reran all analyses with a reduced TD group, excluding children that scored more than 1.5 SD above the average, resulting in a mean within the higher but normal range (N= 21; Mean FIQ = 113; cutoff FIQ = 124). The pattern did not change; therefore we report the results for the whole sample. 2

Group means and standard deviations for all number processing tasks are reported in Table 2along with the main effects of mathematics and literacy in the rightmost columns**.** Results from the post-hoc group comparisons are indicated by subscripts. The interaction between mathematics and literacy was not significant in any analysis and is therefore not reported in Table 2.

**(1) Number tasks tapping the verbal code**

**Verbal Counting.**Both MD and RD groups were significantly impaired in number counting, resulting in main effects of maths and literacy. The groups with mathematics deficits counted on average only 14 and 13 numbers correctly, whereas TD children counted 22 numbers. RD children scored in-between the groups with MD and TD children, counting 17 numbers correctly.

**Dot Counting.**Performance was compared in the subitizing (1-3) and counting range (5-7) across groups (Figure A). In terms of accuracy, all groups were at ceiling in the subitizing range. Therefore we analysed the effects of mathematics and reading ability on accuracy rates for the counting range only. A significant effect of mathematics ability emerged, while the effect of literacy was not significant, indicating that the two MD groups counted less accurately than the RD and TD group.

For response latencies, we found main effects of mathematics and of literacy, as well as a strong main effect of condition, *F* (1, 84) = 108.39, *p* < .001, ŋ2 = .56, with longer RTs in the counting than in the subitizing range. These main effects were modified by a three-way interaction of RD by MD by condition, *F* (1, 84) = 4.62, *p* < .05, ŋ2 = .05. In the subitizing range, the comorbid group scored marginally lower (longer RTs) than TD children (*p* = .075), whereas the other three groups did not differ from each other. In contrast, in the counting range all three deficit groups showed longer RTs than the TD group.

**(2) Number tasks tapping the symbolic code**

**Number identification and transcoding.**Children with MD and children with RD were less accurate in identifying and transcoding numbers. For number identification, the effect of MD was larger than the effect of RD, ŋ2 = .28 vs. ŋ2 = .08, which is in line with the findings reported for the counting tasks. In contrast, the effects of MD and RD were comparable in transcoding numbers ŋ2 = .19 and .18.

**Calculation.** There were significant effects of MD and RD on accuracy scores. Overall, fewer subtractions were solved correctly than additions, *F* (1, 84) = 6.68, *p* = .011, ŋ2 = .07. There was an interaction of MD by condition, *F* (1, 84) = 4.20, *p* = .044, ŋ2 = .05; children with MD showed a larger difference between subtraction and addition, with poorer performance on subtraction compared to TD children.

Turning to the efficiency of calculation there were main effects of MD and RD, but none of the interactions were significant. Children with either RD or MD solved fewer items correctly than TD children in both addition and subtraction, as indicated by the non-significant effect of condition, *F* (1, 84) = 0.33, *p* > .05, ŋ2 < .01.

**Symbolic number comparison.**The RT analysis for small versus large numerical distances revealed main effects of MD, RD, and condition, *F* (1, 84) = 26.11, *p* < .001, ŋ2 = .24. The effect of condition reflects the distance effect (Moyer & Landauer, 1967) with shorter RTs for items with large than small distances. Importantly, the condition effect was modified by a condition by MD interaction, *F* (1, 84) = 5.00, *p* = .028, ŋ2 = .06. In order to further investigate the distance effect in the four groups, regression slopes over the six distances were calculated for each participant. Steep slopes reflect a large distance effect, whereas shallow slopes indicate a smaller difference between item pairs with small and large distances. Group comparisons revealed that children with RD+MD showed a significantly larger distance effect (*p* = .028) than TD children (slopes [unstandardized coefficient B]: RD+MD = -77 versus TD = -50, Table 2), although the overall group effect did not reach significance, *F* (3, 84) = 1.68, *p* = .178, ŋ2 = .06.

**(3) Number tasks tapping the approximate number sense**

**Numberline.** While the results in the verbal(-symbolic) number tasks and in calculations showed an effect of MD as well as of RD, there was no effect of RD, but a strong main effect of MD, on children’s accuracy in the numberline task. Children’s judgements were more accurate in the 100 compared to the 1000 numberline, *F* (1, 83) = 31.22, *p* < .001, ŋ2 = .27. The condition effect was modified by a condition by MD interaction, *F* (1, 83) = 12.55, *p* = .001, ŋ2 = .13, indicating that the group difference between both mathematics deficit groups versus the RD-only and TD groups was larger in the more difficult condition.

**Non-symbolic number comparison.**As expected, there was a significant effect of MD on non-symbolic number comparison, but no significant effect of RD. The distance effect was marginally significant, *F* (1, 84) = 3.82, *p* = .054, ŋ2 = .04, reflecting better performance for item pairs with large than small distances. None of the interactions reached significance.

The pattern of results for all ANCOVAs is summarized in the Appendix.

**Number processing skills in comorbid RD+MD**

In line with the idea that the cognitive deficits underlying RD and MD are domain-specific (hypothesis 3), the comorbid group showed an additive pattern: For none of the number processing tasks did the interaction term RD by MD reach significance. The only exception was the three-way interaction RD by MD by condition in the Dot counting task, indicating poorer performance of the comorbid group in the subitizing range.

In number processing tasks with significant main effects of both RD and MD, an additive pattern predicts poorer performance in the comorbid compared to the two single deficit groups (reflecting the sum of the deficits in the single deficit groups). Indeed, post-hoc tests revealed that the comorbid group performed significantly worse than children with RD or MD in the majority of tasks. The only exception was the symbolic number comparison (large distance) task where the difference between the comorbid and the single deficit groups did not reach significance; however, inspection of the means revealed a tendency for poorer performance in the comorbid group compared to the single deficit groups.

**Association between cognitive skills and speeded verbal number tasks in RD versus MD**

To further investigate whether difficulties in speeded verbal number tasks in children with RD are due to difficulties in phonological skills, in particular in efficient (visual-) verbal access, we ran a series of univariate ANCOVAs comparing performance on all timed verbal number tasks (verbal counting, dot counting and number comparison) and the two timed calculation tasks (efficiency for addition and subtraction) in children with RD and typically developing children after controlling for differences in phonological skills (RAN and PA). The results revealed that once phonological skills were controlled, the RD and the TD groups no longer differed from each other. In contrast, controlling for phonological skills did not affect the significant difference between children with MD and typically developing children (all *p*s < .05). Interestingly, the pattern was reversed when controlling for ANS (indexed by non-symbolic number comparison): children with RD and typically developing children still differed on all three verbal number tasks and on the two calculation tasks, whereas the group difference between children with MD and typically developing children was no longer significant for dot counting and number comparison (not verbal counting) once differences in the ANS were controlled. For calculation, the group difference between MD and TD stayed significant after controlling for ANS.

**Discussion**

This study investigated cognitive profiles in children with RD, MD, RD+MD and typically developing children (TD). Number skills were assessed with tasks tapping to varying extents the three number codes: the verbal code, the visual code and the analogue magnitude system (ANS). Our design allowed us to directly examine how number processing for the different number codes is related to mathematical and reading ability. Our results clearly indicate that factors underlying numerical difficulties in children with RD are distinct from the factors underlying numerical difficulties in children with MD.

In line with previous research, *children with RD* were impaired in phoneme awareness and in RAN but not in simple RT (Bonifacci & Snowling, 2008). Although they had no difficulty with either the non-symbolic number comparison or in positioning numbers on the numberline, they performed poorly on all tasks tapping verbal number skills. Their difficulties were particularly marked when required to transcode numbers. Together these findings support our first hypothesis that children with RD experience deficits in numerical tasks tapping verbal skills, but are unimpaired in their approximate number sense. These findings are consistent with the view that individuals with RD have a language processing impairment which affects the use of the verbal number code (Boets & De Smedt, 2010; De Smedt & Boets, 2010; Göbel & Snowling, 2010; Simmons & Singleton, 2006, 2009). This interpretation is further supported by the finding that, for calculation, children with RD made fewer errors on the subtraction subtest than children with MD/RD+MD. Within the Triple Code Model, Dehaene and Cohen (1997) proposed that addition and multiplication call more strongly upon the verbal code than subtraction; verbal representations are then expected to trigger fact retrieval. Subtraction in contrast depends more strongly upon an abstract semantic representation of numerical quantity (i.e. the ANS) than addition and multiplication. In line with this theory, phonological suppression affects multiplication but not subtraction performance (Lee & Kang, 2002), highlighting the different extent to which multiplication/addition and subtraction draw upon the verbal code, at least in adults.

A difficulty with visual-verbal access could plausibly explain a number of the deficits observed in the RD group. If, as has been argued, RAN is a measure of efficient visual-verbal access (e.g. Lervåg & Hulme, 2009; Moll, Fussenegger, Willburger, & Landerl, 2009), then it suggests that children with RD are impaired in symbolic number comparison because of deficits in visual-verbal access. This interpretation receives some support from the findings that after controlling for phonological skills (a composite of RAN and phoneme awareness) the group difference on visual-verbal number tasks between children with RD and TD children vanished, whereas the group difference between children with MD and TD children remained significant.

More generally, we propose that inefficient number processing (as revealed by slowness in speeded verbal number tasks) can arise for at least two different reasons: for children with RD, the longer RTs in verbal number tasks reflect deficits in access to phonological codes (i.e. visual-verbal access), whereas for children with MD, longer RTs reflect deficits in processing numerical information (e.g. processing numerosities in the symbolic number comparison task).

In contrast to the pattern observed for RD, *children with MD* were impaired not only on the verbal number tasks but also on the non-verbal measures (number line and non-symbolic number comparison). Moreover, and in line with our predictions that a deficit in number processing is the core deficit underlying MD (hypothesis 2), the effect sizes for verbal number tasks for children with mathematics difficulties were generally larger than for those with reading difficulties (mean effect size ŋ2 = .17 versus ŋ2 = .08).

The finding that (visual-)verbal as well as non-verbal number skills were impaired in children with MD suggests that they have difficulties with all number codes (verbal, visual-verbal and non-verbal). Together the findings are consistent with the view proposed by Piazza et al. (2010) that a deficit in the preverbal number system (ANS) is at the core of MD. Taking a developmental perspective, this specific deficit in understanding the basic concepts of numerosities could lead to a range of difficulties in acquiring arithmetic and other mathematical skills. However, current results cannot exclude the possibility of an early deficit in processing numerical symbols leading to a later deficit in processing non-symbolic numerosities (Noël & Rousselle, 2011). Our results show clearly that all number codes are affected but our results are neutral with respect to the potential underlying causes and developmental changes. Furthermore, we cannot exclude from our data that there might be a subgroup of children with MD that primarily show an access deficit (Noël & Rousselle, 2011).

A new finding of our study is that children with MD have deficits in verbal number tasks although they performed within the typical range on tasks of phoneme awareness and RAN. Given this, we propose that a problem with basic number concepts has a downstream effect on the ability to learn the mappings between symbols and numerosities (as required by the Arabic code) and on the acquisition of the verbal number facts that underpin counting and calculation. In addition, our finding of more selective numerical deficits in RD underlines the need for proficient verbal skills if mathematical development is to proceed normally.

Further evidence for the separate underlying causes of poor performance in number tasks for children with RD versus children with MD comes from performance on the dot counting task. Here *children with RD* showed longer RTs than TD children although they did not differ in accuracy. The increased RTs can be interpreted as indicating a deficit in accessing the verbal code when counting dots, whereas the high accuracy of the RD group reflects their intact number system. Furthermore, children with RD were not impaired in the subitizing range (1-3 dots) where no counting is required and demands on sequential verbal access are reduced. In contrast, *children with MD* showed not only increased RTs, but also marked deficits in accuracy when counting dots.

 Our design allowed us to investigate whether the profiles of number skills in children with *comorbid reading and mathematics deficits (RD+MD)* reflect the sum of the two single deficit groups or rather show an interactive pattern. We predicted that the cognitive deficits associated with RD and MD are domain-specific. As a result children with comorbid RD+MD should show an additive profile of impairments reflecting the sum of the two single deficit groups (hypothesis 3). With respect to their cognitive profile, the RD+MD group did not differ from the single deficit groups in mathematics and literacy skills used for classification, but showed poorer performance than the RD group in some language measures (PA and VIQ). In line with our prediction, the interactions of RD by MD were not significant, indicating an additive profile of number skills of the two single disorders; however an exception was the three-way interaction RD by MD by condition in the dot counting task, indicating that in the subitizing range it was the comorbid group that scored more poorly (longer RTs) whereas the other three groups did not differ from each other. Previous findings have suggested that children with MD, in contrast to control children, appeared to be counting rather than subitizing in a dot-matching task (Koontz & Berch, 1996). Several recent studies have replicated this earlier finding and shown that children with MD often have deficits in subitizing in the range of 1-3 dots (e.g., Schleifer & Landerl, 2011; Moeller et al., 2009; Bruandet, Molko, Cohen, & Dehaene, 2004). However, the exact nature of the subitizing deficit in children with MD is debated, and additional risk factors might play a role in explaining poor performance in subitizing.

In conclusion, the present study shows that children with RD have selective deficits in number tasks relying on the verbal system or on tasks requiring efficient visual-verbal access, but are unimpaired in tasks calling upon the ANS. In contrast, children with MD show deficits in a wide range of number tasks, reflecting, we propose, a developmental deficit in processing numerosities. In line with this interpretation, deficits in number tasks were more pronounced in the MD group compared to children with RD only. Together the findings suggest that the same behavioural phenotype (i.e., an impairment of number skills) might be associated with different cognitive risk factors: a deficit in accessing verbal codes from symbolic stimuli in the case of RD and a deficit in processing numerosities in the case of MD. The comorbid group showed an additive pattern: the deficits found were those expected from deficits in the RD and MD groups. These findings speak against the view that the same cognitive core deficits are underlying RD and MD (underadditivity) or that the comorbid group (RD+MD) constitutes a separate disorder (overadditivity).

Our findings also have practical implications: In contrast to some previous studies (Andersson, 2008; Landerl et al., 2004, 2009) the current investigation has documented mathematical difficulties in children with RD-only. Those difficulties were milder than in children with MD or RD+MD, but they affected several mathematical tasks and constitute significant impairments which disadvantage children with RD in their mathematical development and learning. However, it is important to note that the mathematical difficulties in RD are associated with a different cognitive profile than those observed in MD. It will therefore be important to develop intervention programmes separately for children with RD and MD. Interventions targeting language and phonological skills might impact positively on verbal number skills such as transcribing numbers in children with RD but are not expected to improve number skills in children with MD. Our findings that the comorbid group showed an additive pattern reflecting the sum of the single deficit groups rather than a distinct cognitive profile further indicates that the comorbid group can benefit from intervention programmes for both RD and MD and ideally should receive literacy as well as numeracy interventions in order to improve both skills and to target the different cognitive deficits underlying deficits in number processing.

Future studies will have to replicate these findings within more restricted age ranges. Furthermore, longitudinal studies are needed in order to assess developmental changes in numerical processing and calculation skills in children with RD, MD and comorbid deficits.

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Footnotes

1. An additional analysis investigating group differences separately for the two RAN conditions (letters and digits) showed that children with MD did not differ significantly from TD children in either condition (*p*s > .05), but performed significantly better than the two groups with literacy difficulties on both, letter and digit naming (*p*s < .01 and < .05, respectively).
2. The analysis was re-run with FIQ as additional covariate. FIQ was not significant in any of the number processing tasks with exception of the numberline task, *F* (1, 82) = 10.40, *p* < .01, ŋ2 = .11, and the calculation efficiency, *F* (1, 83) = 7.05, *p* < .05, ŋ2 = .08. The overall pattern of results of the two tasks did not change with FIQ as covariate.

Table 1

*Means (standard deviations) for descriptive measures for the four groups.*

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Task | RD | MD | RD+MD | TD | *F* |
| Age [months] | 106.9 (21.9) a | 112.8 (21.3) a | 117.1 (21.8) a | 107.5 (17.9) a |  1.19 |
| Literacy composite 1 |  86.1 (9.6) b |  99.5 (7.1) a |  79.0 (8.8) b | 106.1 (11.1) a  | 38.73 \*\*\* |
| Numerical operations 1 |  99.7 (11.2) a |  80.6 (4.4) b |  71.7 (8.1) b | 107.8 (15.0) a | 49.33 \*\*\* |
| Verbal IQ | 115.5 (14.9) a, b | 105.0 (14.2) b, c |  98.6 (14.8) c | 123.9 (13.1) a | 14.89 \*\*\* |
| Performance IQ | 107.8 (12.4) a |  94.7 (9.8) b |  92.3 (9.6) b | 111.4 (16.2) a | 12.01 \*\*\* |
| Full IQ | 112.7 (10.9) a |  99.6 (9.8) b |  95.0 (12.3) b | 120.3 (14.5) a | 20.67 \*\*\* |
| PA [% corr] 2 |  60.3 (20.5) b |  80.2 (20.5) a |  45.9 (20.8) b |  88.7 (20.5) a | 18.75 \*\*\* |
| RAN [items corr/sec.] 2 |  1.64 (0.39) b,c |  2.08 (0.39) a |  1.53 (0.40) c |  1.92 (0.40) a,b |  7.53 \*\*\* |
| RT 2 | 382.0 (73.8) a | 368.0 (73.8) a | 420.0 (74.5) a | 379.3 (74.1) a |  1.76 |

*Notes:* 1 standard scores; 2 age-adjusted means; \*\*\**p*<.001

Means with the same subscripts don’t differ significantly from each other (Sidak adjustment).Table 2

*Age adjusted means (standard deviations) of number processing skills for the four groups and main effects of mathematics and literacy*

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Task | RD | MD | RD+MD | TD | Maths effectF (ŋ2) | Literacy effectF (ŋ2) |
| Verbal counting | 16.75 (4.54) b | 14.47 (4.53) b,c  | 13.40 (4.58) c  | 21.69 (4.57) a  | 25.22 (.25) \*\*\* |  8.18 (.10) \*\* |
| Dot Counting Acc [% corr] 1 |  |  |  |  | ̶ | ̶ |
|  subitizing counting | 100.00 (0.00) a96.38 (12.37) a | 100.00 (0.00) a86.49 (12.33) b | 100.00 (0.00) a83.78 (12.47) b | 100.00 (0.00) a96.01 (12.39) a | 16.38 (.16) \*\*\* |  0.19 (.00) |
| Dot Counting RT [ms] |  |  |  |  |  4.01 (.05) \* |  4.77 (.05) \* |
|  subitizing  | 1021 (319.41) a | 989 (318.30) a | 1125 (321.69) (a) | 957 (319.05) a |  |  |
|  counting  | 3244 (741.00) b | 3246 (739.27) b | 3318 (747.12) b | 2629 (741.05) a |  |  |
| Number identification [10] |  7.80 (2.43) b | 6.14 (2.43) (b),c | 5.06 (2.46) c  | 9.56 (2.44) a | 29.73 (.28) \*\*\* | 6.33 (.08) \* |
| Transcoding numbers [30] |  26.79 (3.39) b | 26.70 (3.37) b | 23.32 (3.44) c | 29.82 (3.38) a | 17.75 (.19) \*\*\* |  16.91 (.18) \*\*\* |
| Calculation accuracy  |  |  |  |  | 14.46 (.15) \*\*\* |  7.40 (.08) \*\* |
|  addition |  96.33 (13.52) a | 94.66 (13.48) a | 84.06 (13.64) b | 99.79 (13.52) a |  |  |
|  subtraction | 91.74 (17.87) a,b | 86.34 (17.85) b | 73.29 (18.05) c | 98.17 (17.88) a |  |  |
| Calculation efficiency |  |  |  |  | 22.04 (.21) \*\*\* | 6.14 (.07) \* |
|  addition |  0.30 (0.09) b | 0.26 (0.08) b | 0.22 (0.09) c | 0.37 (0.11) a |  |  |
|  subtraction |  0.21 (0.09) (b) | 0.16 (0.08) c | 0.15 (0.09) c | 0.27 (0.11) a |  |  |

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Symbolic NC |  |  |  |  | 5.22 (.06) \* | 6.01 (.07) \* |
|  RT [ms] small distance |  1277 (306.57) (a),b | 1286 (305.93)(a)b | 1453 (309.05) b | 1117 (306.60) a |  |  |
|  RT [ms] large distance  |  1114 (247.92) b | 1090 (247.39) a,b | 1189 (249.76) b | 968 (247.77) a |  |  |
|  Regression slopes  | -59.36 (42.39) a,b | -61.66 (42.30) a,b | -77.47 (42.76) b | -49.65 (42.43) a |  |  |
| Numberline |  |  |  |  | 27.51 (.25) \*\*\* | 0.68 (.01) |
|  Deviance 0 to 100 | 41.42 (29.01) a | 62.12 (28.90) b | 64.55 (29.49) b | 29.75 (29.02) a |  |  |
|  Deviance 0 to 1000 | 76.77 (51.14) a | 129.19 (50.96) b | 117.15 (51.97) b | 52.22 (51.19) a |  |  |
| Nonsymbolic NC |  |  |  |  | 18.10 (.18) \*\*\* | 0.70 (.01) |
|  Small distance [max.12] | 9.96 (1.37) a | 9.05 (1.36) b | 8.61 (1.39) b | 9.94 (1.36) a |  |  |
|  Large distance [max.12] | 11.10 (1.05) a | 10.37 (1.07) b | 10.31 (1.09) b | 11.41 (1.07) a |  |  |

Note: \* *p* < .05; \*\* *p* < .01; \*\*\* *p* < .001

Means with the same subscripts don’t differ significantly from each other (LSD method). Marginal results are indicated by brackets.

1 Condition effect not calculated due to ceiling effects in the subitizing range

**Appendix**

Table A

*Summary of the results from the ANCOVAs*

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Dependant variable | Effect of maths | Effect of literacy | Effect of condition | Interactionmaths x lit | Interactioncond x group |
| Verbal Counting | ++ | + | NA | (+) | NA |
| Dot Counting Acc 1 | ++ | ̶ | NA | ̶ | NA |
| Dot Counting RT | + | + | ++ | ̶ | cond x lit x maths |
| Number Identification | ++ | + | NA | ̶ | NA |
| Transcoding numbers | ++ | ++ | NA | ̶ | NA |
| Calculation Acc | ++ | + | + | ̶ | cond x maths |
| Calculation efficiency | ++ | + | ̶ | ̶ | ̶ |
| Symbolic NC | + | + | ++ | ̶ | cond x maths |
| Numberline | ++ | ̶ | ++ | ̶ | cond x maths |
| Nonsymbolic NC  | ++ | ̶ | (+) | ̶ | ̶ |

*Note:* ─ no significant effect; (+) marginally significant effect; + significant effect *F* = 4-10, *p* < .05; ++ highly significant effect *F* > 14, *p* < .001.

1 Condition effect not calculated due to ceiling effects in the subitizing range



[A]



[B]

*Figure A*

Mean RT (A) and accuracy (B) for 1 to 7 dots in the Dot counting task for the four groups.