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Comorbidity of Arithmetic and Reading Disorder: Basic Number Processing and Calculation in Children With Learning Impairments

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Abstract

The aim of the present study was to investigate the cognitive profiles of primary school children (age 82–133 months) on a battery of basic number processing and calculation tasks. The sample consisted of four groups matched for age and IQ: arithmetic disorder only (AD; *n* = 20), reading disorder only (RD; *n* = 40), a comorbid group (*n* = 27), and an unimpaired control group (*n* = 40). Multiple 2 (RD vs. No RD) × 2 (AD vs. No AD) factorial ANCOVAs showed that children with RD had selective impairments in counting and number transcoding efficiency. In contrast, children with AD performed poorly in most tasks, including symbolic and nonsymbolic magnitude comparisons, subitizing, number line estimation, number sets, number transcoding accuracy, and calculation. These findings provide further support that AD is characterized by multiple, heterogeneous underlying deficits. In contrast, RD is associated with specific number processing impairments only if tasks require verbal processing. Taken together, the results fully support the assumption of comorbid additivity of AD and RD.

Keywords

arithmetic disorder, reading disorder, comorbidity, numerical processing

Arithmetic disorder (AD) is a specific learning impairment for mathematical abilities. In AD, basic arithmetic operations (addition, subtraction, multiplication, and division) are impaired, which cannot be explained by low intelligence, inadequate teaching, or neurological diseases (*Diagnostic and Statistical Manual of Mental Disorders* [*DSM-5*], American Psychiatric Association, 2013; *International Classification of Diseases* [*ICD-10*], World Health Organization, 2011). Despite an increasing body of research on AD, its causal mechanisms are not yet fully understood. Obvious reasons might be the phenotypical heterogeneity of AD, although this does not necessarily imply different causal mechanisms (Rubinsten & Henik, 2009). Particularly striking is the high comorbidity of AD with reading disorder (RD), ranging up to 47 % (Moll, Bruder, Kunze, Neuhoff, & Schulte-Körne, 2014). This seemingly paradoxical high rate of co-occurrence is thought to be linked to a neurobiological cause (cf., Butterworth & Kovas, 2013; Landerl & Moll, 2010). RD is often defined as an impairment of reading fluency as well as accuracy (*DSM-5*, *ICD-10*).

In the current study, we assessed basic number processing and calculation skills in groups of children with specific learning disorders. The groups were formed by using timed measures, as impaired compared to unimpaired children seem to solve timed tasks less efficient, but at a comparable level of accuracy (cf., Moll, Göbel, & Snowling, 2015). We compared the cognitive profiles in isolated and comorbid groups of children with learning disabilities in order to differentiate between specific and shared risk factors (i.e., multiple deficit model of developmental disorders; Pennington, 2006; see also Willcutt et al., 2013). The selection of tests was based on theoretical models making strong predictions about specific mathematical dysfunctions. Comparing groups of children with AD only, RD only, AD and RD, as well as controls allowed us to describe whether AD and RD lead to additive effects or whether these learning disorders interact. To our knowledge, there are only a few studies examining this issue, none of which succeeded in clarifying this debate for various reasons: First, not all of

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them examined the four groups that are needed to describe the nature of comorbidity. Second, not all of them used adequate sample sizes and homogenous groups, considering IQ as well as age. Third, most of them did not use a sufficient number of different numeric processing tasks. Finally, a controlling working memory (WM) task has not been used in recent studies (e.g., Moll et al., 2015). All of these aspects were taken into account in the current study.

Difficulties in executing calculation procedures and remembering arithmetic facts constitute definitional measures of AD (Geary, 1993). In addition to these rather complex functions, basic numerical processing is often impaired in AD—for example, deficits in subitizing and enumeration (e.g., Reigosa-Crespo et al., 2012), magnitude comparison (e.g., Landerl, Bevan, & Butterworth, 2004; Mazzocco, Feigenson, & Halberda, 2011), number line estimation (e.g., Geary, Hoard, Nugent, & Byrd-Craven, 2008), or writing and reading numbers (transcoding; Moura et al., 2013). Apart from these domain-specific deficits in number processing, domain-general cognitive deficits in children with AD have been reported as well—that is, impairments in reading (Von Aster & Shalev, 2007) as well as in WM (Swanson & Jerman, 2006). Thus, children with AD often have very heterogeneous cognitive profiles. A recent study (Bartelet, Ansari, Vaessen, & Blomert, 2014) stressed this high variability, finding as many as six distinguishable cognitive subtypes in a large sample of children with AD.

Several neurocognitive theories of number or magnitude processing have been advanced as causal mechanisms for AD. Some authors assume that a deficit in the cognitive system for representing large numerosities, the approximate number system (ANS), is a root cause for AD (e.g., Mazzocco et al., 2011). Butterworth (2010) suggested a deficit in numerosity coding, which contains the exact quantification of sets of objects, as being mainly responsible for AD. Rousselle and Noël (2007) suggested a deficit in accessing magnitude information from symbols (e.g., visual-Arabic numbers), while they imply that the general cognitive representation of numerosity is intact in AD. All explanations assume a domain-specific deficit in number processing to be responsible for the disorder, which, regardless of its origin, is considered to represent the core cognitive deficit associated with AD.

In addition to domain-specific deficits in number processing, it has been suggested that domain-general risk factors affect mathematics skills as well. Several developmental models underscore the importance of language skills in mathematical development. For example, Von Aster and Shalev (2007) assume that children whose core system of number processing (i.e., the ANS) is intact may nevertheless develop problems in verbal number tasks (e.g., counting and fact retrieval) if language impairments or RD are present. In these cases, the mapping between nonsymbolic numerosities (e.g., three dots) and corresponding linguistic symbolizations (e.g., “three”) is perturbed, leading to difficulties in counting strategies, arithmetic, and storage of mathematical facts. Göbel, Watson, Lervåg, and Hulme (2014) found that mapping numbers to their verbal codes was crucial in predicting mathematical ability in early elementary school. Krajewski and Schneider (2009) reported that phonological awareness is an important predictor of mastering number words and the number word sequence.

Further stressing the importance of early language skills in mathematics achievement, LeFevre et al. (2010) found that linguistic skills (vocabulary, phonological awareness) in preschool had the highest predictive power for mathematical achievement in third grade, even compared to preschool quantitative skills or visuospatial attention. Based on these results, it can be hypothesized that the development of mathematical knowledge is affected both by language and quantitative skills. Children with both AD and RD (AD/RD) will therefore show marked difficulties in all number tasks, whereas children with RD will show specific difficulties in mathematical tasks that rely heavily on language skills (e.g., counting, transcoding numbers, word problems).

In line with the notion that some risk factors are shared between AD and RD, their comorbidity rate is high, with estimates ranging from 17% to 70% of children with AD showing reading problems (e.g., Gross-Tsur, Manor, & Shalev, 1996; Von Aster et al., 2007). Most studies find that the difficulties of children with AD/RD largely represent an additive combination of deficits in children with RD and those in children with AD (e.g., Cirino, Fuchs, Elias, Powell, & Schumacher, 2015; Landerl et al., 2004; Landerl, Fussenegger, Moll, & Willburger, 2009; Moll et al., 2015). This additivity supports the notion that AD and RD are not caused by the same core deficit, in which case underadditivity would have been expected (Landerl et al., 2009). In line with this argument, the recent neurobiological literature points to relatively distinct neuronal circuits involved in AD and RD (Ashkenazi, Black, Abrams, Hoeft, & Menon, 2013), although some areas of the brain—for example, the left angular gyrus—are recruited in both calculation and reading (Dehaene, Piazza, Pinel, & Cohen, 2003). Generally, RD seems to aggravate rather than cause AD (Cirino et al., 2015). However, the fact that AD and RD may be regarded as largely additive in explaining cognitive profiles of children with AD/RD neither implies that AD and AD/RD profiles in numerical processing and calculation fully overlap nor that additivity fully holds across the entire spectrum of mathematical skills. This might explain why empirical evidence is unclear with respect to differences between AD and AD/RD groups.

Although many studies fail to find differing profiles between these groups in numerical processing and calculation (e.g., Andersson, 2008; Landerl et al., 2004, 2009; Rousselle & Noël, 2007), other studies find such differences. For example, Chan and Ho (2010) reported substantial differences between AD and AD/RD groups on measures of fact retrieval and number sense, whereas Geary, Hamson, and Hoard (2000) found differences between these two groups on a symbolic magnitude comparison task. More recently, a study by Moll et al. (2015) found that an AD/RD group showed a tendency of being slower in the subitizing range compared to an AD group. In the counting range, all three deficit groups were similarly impaired. To summarize, it remains unclear to which degree deficits in number processing of children with AD/RD are aggravated, compared to children with AD. Thus, this state of the literature calls for more research and replication of earlier findings. Despite the large body of evidence supporting additivity of AD and RD, the results of a recent study by Moll et al. (2015) also point to difficulties in number processing associated with RD only. Children with RD generally have deficits in accessing phonological codes (Vellutino, Fletcher, Snowling, & Scanlon, 2004). As a consequence, performance on number processing tasks requiring verbal procedures like counting should be affected, which is also suggested by the developmental model of Von Aster and Shalev (2007) (see also Van der Sluis, de Jong, & van der Leij, 2004).

Likewise, Simmons and Singleton (2008) suggested in their review that children with RD are likely to be impaired in solving mathematical tasks tapping the verbal code, which is one of the three systems for processing numbers in the Triple Code Model (Dehaene, 1992). Indeed, the results of Moll et al. (2015) showed that RD selectively impairs performance on such tasks (e.g., counting, transcoding). In addition, RD also seemed to interfere with symbolic magnitude comparisons. A possible explanation was that impaired visual-verbal access and naming speed deficits in children with RD (e.g., Willburger, Fussenegger, Moll, Wood, & Landerl, 2008) may result in deficient number symbol processing. However, the majority of studies did not find deficits in symbolic number processing in RD children (e.g., Landerl et al., 2004; Landerl et al., 2009). Thus, this result requires further confirmation.

The purpose of the present study was to investigate differences in basic number processing and calculation skills in groups of children with AD, RD, AD/RD, and an unimpaired control group (C). AD and RD were regarded as separate factors in all statistical analyses. Our analyses allowed us to ask whether children with AD show deficits in tasks tapping all modules of number processing (Dehaene, 1992): the analogue magnitude representation or ANS (e.g., dot magnitude comparison, number line estimation; Mazzocco et al., 2011), the verbal code (e.g., counting, transcoding; Rousselle & Noël, 2007), and Arabic number processing (e.g., calculation, symbolic magnitude comparison; Butterworth, 2010).

We hypothesized that, in contrast to children with AD, children with RD should not display weaknesses in tasks tapping the ANS. However, we assumed that the phonological processing deficits in children with RD would result in deficits in number processing tasks tapping the verbal code substantially (Simmons & Singleton, 2009) as well as in tasks mapping the verbal code and Arabic number processing (i.e., transcoding heard numbers into Arabic digits). Regarding the interplay of RD and AD, we hypothesized that the profile of children with AD/RD should additively result from the profiles of children with AD and RD. Statistically, this corresponds to a lack of interaction between AD and RD factors in explaining single task performance given sufficient statistical power. Assuming an additivity of effects, comorbid children would be expected to show deficits in both cognitive domains. Their deficits should correspond to the sum of those in the two single deficit groups (AD plus RD). In contrast, underadditivity would indicate a shared cognitive deficit underlying AD and RD (cf., Moll et al., 2015). In that case, the group of children with AD/RD should be less impaired compared to the sum of the single-deficit groups (interaction between AD and RD). According to recent multiple deficits models (e.g., Pennington, 2006), the disorders could then be reduced to a common cause or a single deficit (e.g., Ashkenazi et al., 2013). Another possible characterization of effects might be overadditivity: The comorbid group would be assumed to be more impaired than the sum of the two single deficit groups. In that case, the comorbid group represents separate impairments associated with additional risk factors that are distinct from those of the single-deficit groups.

We chose to adopt the Triple Code Model by Dehaene (1992) as a theoretical framework, as it is one of the most well-established models to describe the processing of numbers. Other existing models (e.g., Case & Okamoto, 1996) that are more suited for children might not explain number processing as detailed as the Triple Code Model. A first attempt to more comprehensively explain number processing in children is the developmental model by Von Aster and Shalev (2007) that is largely based on the work by Dehaene (1992) but also takes into account the development of the capacity of WM. As mentioned, domain-general cognitive deficits in children with AD have been reported as well—that is, impairments in WM (Swanson & Jerman, 2006). According to Von Aster and Shalev (2007), first, the core system of magnitude enables children to understand the basic meaning of numbers. Second, the verbal and the Arabic number system are both preconditionally needed to develop a mental number line. In their model, the increasing capacity of WM is assumed to be related to the development of numerical cognition and, therefore, mostly important for procedural tasks in older children. This is also in line with the results of a current study by Sowinski et al. (2015), underlining that WM seems to be involved in some (e.g., backward counting) but not all mathematical

Table 1. Study Participant Details.

Details	Control group *M*	*SD*	*n*	Arithmetic disorder group *M*	*SD*	*n*	Reading disorder group *M*	*SD*	*n*	Comorbid group *M*	*SD*	*n*	F (*df*)[a]
n (boys)			40 (9)			20 (6)			40 (14)			27 (10)	χ^2 (*df*) = 2.13 (3)
n for Grades 2/3/4			4/28/8			2/12/6			9/28/3			6/14/7	χ^2 (*df*) = 8.83 (6)
Age, in months	111.58_a	8.95		112.58_a	8.97		109.79_a	9.82		108.13_a	11.08		0.98 (3, 114)
HRT	102.70_a	6.67		79.83_b	5.23		101.73_a	6.50		78.94_b	4.91		140.83 (3, 123)***
CFT[b]	100.49_a	9.62		100.98_a	11.10		100.76_a	9.05		100.30_a	11.70		0.02 (3, 123)
SLS 1–4	100.00_a	7.22		99.15_a	7.39		78.00_b	5.52		76.33_b	6.39		122.82 (2, 123)***

Note. CFT = Culture Fair Test (IQ); HRT = Heidelberger Rechentest (calculation); SLS 1–4 = Salzburger Lesescreening (reading). All test scores are standard scores. Means with the same subscripts do not differ significantly from each other (least significant difference method).
[a]Except where otherwise noted. [b]*Intelligence Scale 1–Revision* (CFT 1-R) was used for Grades 2 and 3, and *Intelligence Scale 2–Revision* (CFT 20-R) was used for Grade 4.
***$p < .001$.

operations. Therefore, we will control the influence of WM with a task tapping aspects of the central-executive and the visuo-spatial sketchpad.

Method

Participants

All participants ($N = 127$) were primary school children (Grades 2–4). We decided to examine children in this age range as it represents a sensitive developmental phase for mathematical competencies. Four groups of children were selected, based on standard scores of reading, math, and IQ measures: AD ($n = 20$; IQ ≥ 85, reading ≥ 90, math ≤ 85), RD ($n = 40$; IQ ≥ 85, reading ≤ 85, math ≥ 90), AD/RD ($n = 27$; IQ ≥ 85, reading ≤ 85, math ≤ 85), and C ($n = 40$; IQ ≥ 85, reading ≥ 90, math ≥ 90). Exclusion criteria for all children were ADHD, neurological diseases, or German as second language. As can be seen from Table 1, groups were carefully matched on age and IQ. Age information was missing for nine children.

Tasks and Procedures

Participants were tested at two group sessions in a quiet room in their schools by one of the authors or by trained research assistants. General intelligence of children from Grades 2 to 3 was measured using three subtests of the *Intelligence Scale 1–Revision* (CFT 1-R; Weiß & Osterland, 2012): Series Completion, Classification, and Matrices (test–retest reliability $r_{tt} = 0.95$). Children from Grade 4 were examined using four subtests of the *Intelligence Scale 2–Revision* (CFT 20-R; Weiß, 2008): Series Completion, Classification, Matrices, and Topologies ($r_{tt} = 0.80$). Mathematical abilities were assessed using four subtests of the Arithmetic Operations of the *Heidelberger Numeracy Test* (HRT 1-4; Haffner, Baro, Parzer, & Resch, 2005): Addition, Subtraction, Greater/Less-Comparison, and Placeholder Tasks ($r_{tt} = 0.93$). All subtests had a time limit of 2 min and increased in difficulty. In the Addition and Subtraction subtests, children had to solve as many addition/subtraction problems as possible, which were increasing gradually in difficulty (e.g., 12 + 7 = _). In the Greater/Less-Comparison subtest, children had to compare two Arabic numbers and decide which number was larger. In the Placeholder subtest, children had to find the missing number in simple equations (e.g., _ + 4 = 10). The test score was calculated as the total number of correctly solved tasks in the four subtests. Literacy skills were assessed using the *Salzburger Reading Screening* (SLS 1–4; Mayringer & Wimmer, 2003). Children had to read simple sentences (e.g., "Cherries can talk") and then decide whether they were right or wrong by marking either a check mark or a cross that were printed besides each sentence (parallel-forms reliability = 0.90). The test score was calculated as the total number of correctly marked sentences within 3 min. The HRT 1–4 and the SLS 1–4 were used for group classification in the current study. All other tasks were computer-administered.

We reported test–retest reliability for all self-developed tasks from a different sample that processes the tasks twice in an interval of 2 weeks. First, children were given a computer-based reaction time (RT) test. The computer screen was divided by a white line. In each trial, children were shown a white square in different areas of the screen. As quickly as possible, they had to press either the left or the right key on a computer keyboard to indicate the side of the screen on which the white square had appeared. Overall, five practice trials and 20 test trials were used. All items were preceded by an interstimulus interval of randomly varying length (500 ms, 1,000 ms, or 1,500 ms), in which only the white line was visible. Maximum testing time was 2 min. The median of RTs, averaged over all correct answers, as well as the total score of correct answers were used for further analysis.

Tasks Tapping the ANS

Panamath. Children were administered the Panamath test as a dot magnitude comparison task (cf., Halberda, Mazzocco, & Feigenson, 2008). They were shown two sets of dots (yellow and blue) next to each other on the screen and had to decide as fast as possible without counting which of them was larger. Children had to use the computer keyboard for their answers. They were given a total of 48 items with four ratios between the two sets: 1.2, 1.4, 1.6, and 2.6 (12 items each). The number of dots ranged from 5 to 21. The median of RTs, averaged over all correct answers, and the total score of correct answers were calculated. Individual's total score was used in addition to RTs because it is normally distributed and shows high test–retest reliability (Inglis & Gilmore, 2014).

Number line task. In the number line task, children had to locate a presented number on a number line using the computer mouse (r_{tt} = 0.68). The presented number line was unscaled, except for the endpoints 0 and 100 (cf., Siegler & Booth, 2004). They were given two practice items (numbers 0 and 100) and 23 test items. Items were displayed in random order, with three items each out of the lowest three decades (1–10, 11–20, 21–30) as well as two out of the higher ones. The items were preceded by a fixation cross lasting 500 ms. Maximum testing time was 5 min. The test score was the average deviation of the given answers from the presented numbers.

Tasks Tapping Verbal Code and Arabic Number Processing

Dot-enumeration task. In the dot-enumeration task, which is only tapping the verbal code, a number of black dots (1–9) appeared on the screen. Children had to count the dots as quickly as possible. They used the number keys on the keyboard to provide their answer. Overall, children were given four practice trials and 18 test trials. Each dot number was randomly presented twice but never repeated in two consecutive trials. The items were preceded by a fixation cross lasting 500 ms. Maximum testing time was 4 min. The median of RTs, averaged over all correct answers, and the total score of correct answers were separately calculated for the subitizing range (1–3) and the counting range (4–9).

Transcoding task. The transcoding tasks tap both the verbal code as well as Arabic number processing (Cronbach's α = 0.70). Children heard number words by headphone and had to type them as Arabic digits using the computer keyboard. They were given two examples and eight test items. If they were not sure which number word they had heard, they were able to listen to it one more time. The first four test items were shared across grades, the subsequent four were adjusted to the number range dealt with in each grade. The items were presented along with a fixation cross. Maximum testing time was 3.5 min. The median of RTs, averaged over all correct answers, and the total score of correct answers were calculated.

Calculation tasks. Children were given three examples and nine addition, nine subtraction, and four multiplication tasks (Cronbach's α = 0.80). The minority were fact retrieval (e.g., 1 + 6 = X), whereas the majority were more difficult calculation tasks (e.g., 231 – 17 = X). Children had to solve the equation by entering the correct result using the computer keyboard. Again, test items were partly identical across grades and partly adjusted with respect to the children's grade. The items were preceded by a fixation cross lasting 500 ms. Maximum testing time was 6 min. The median of RTs, averaged over all correct answers, and the total score of correct answers were calculated.

Magnitude comparison tasks. In the magnitude comparison tasks (symbolic and mixed), two one-digit Arabic numbers were shown on the screen, one left and one right. Children had to compare the numbers and decide which of them was numerically larger. Again, they used the computer keyboard for their answers. Children were given three practice trials and 24 test trials. After that, another 24 trials followed: Here, they had to compare an Arabic number with a numerosity of dots (cf., Defever, De Smedt, & Reynvoet, 2013). Numerical distances between the two stimuli (small: 1, 2, 3; large: 4, 5, 6) were equally distributed, following a balanced design with each difference between one and six appearing four times. The items were preceded by a fixation cross lasting 500 ms. Maximum testing time was 5 min. The median of RTs, averaged over all correct answers, and the total score of correct answers were calculated for analysis.

Further Tasks

Number sets. The number sets task was inspired by Geary, Bailey, and Hoard (2009), but contrary to their work, we used a single trial format (r_{tt} = 0.78). Children had to compare an Arabic number at the top of the screen (target) with a number set at the bottom of the screen. The number set was composed of two numbers, two numerosities of geometric symbols, or a mixed set with one digit and one numerosity of geometric figures. Children had to decide whether the target number at the top of the screen matched the numerosity of the total number set shown at the bottom of the screen or not (e.g., target = 5, Set 3 + two geometric figures). Again, they had to use the computer keyboard for their answers. Children were given four examples and 140 test items: In 70 trials, the number at the top of the screen was five and in another 70 the number was nine (90 s each). The items were preceded by a fixation cross lasting 500 ms. Maximum testing time was 5 min. The test score was calculated by subtracting the sum of false alarms from the sum of hits.

WM task. The WM task matrix span taps aspects of the central-executive and the visuo-spatial sketchpad (r_{tt} = 0.61). The children had to remember a pattern of dots within a matrix. After 5 s, the points disappeared and one row or column of the matrix was colored yellow. Children had to decide if one of the points had been in the colored row or column before or not. After that, they had to reproduce the pattern shown initially within an empty matrix, using a computer mouse. Children were given two practice items and up to 16 test items. The size of the matrix and the number of dots increased with each trial, from a six-cell matrix with two dots up to a 56-cell matrix with nine dots. Processing time for each item was unlimited, but total test time for the main trials was limited to 5 min. If children failed to reproduce three successively presented patterns, the task was terminated. The items were preceded by a fixation cross lasting 500 ms. The test score was calculated as the number of correctly reproduced patterns.

Multiple 2 × 2 factorial ANCOVAs were conducted with the between-subject factors arithmetic and reading, as this approach allowed us to make direct statements about the additivity of the learning disabilities. In this context, two-way interactions between the two group factors [([C – AD] + [C – RD])] – (C – AD/RD)] are of special interest, indicating an interactive, nonadditive pattern. To directly compare the performance in the four groups, post hoc comparisons between groups were conducted. For experimental tasks with more than one condition, an additional within-subject factor was computed. We controlled for gender and grade as well as for additional factors, depending on the different tasks (e.g., simple RT). Due to missing age data, the sample consisted of N = 118 in some analyses.

Results

Our results can be summarized as follows: We expected an AD effect for all measures and found such an effect for dot magnitude comparison, number line, dot-enumeration, transcoding, calculation, symbolic number comparison, and number sets, but not for mixed number comparison. Furthermore, we expected an RD effect for dot-enumeration (counting only), transcoding, and number sets and found such an effect for counting and number sets but only a marginal effect for transcoding. As expected, we did not find a two-way interaction of Arithmetic × Reading (all Fs < 2.63, all ps > .10). Group means and standard deviations for all tasks are reported in Table 2, along with the main effects of arithmetic and reading as well as the effect sizes (Cohen's d). Results from the post hoc group comparisons are indicated by subscripts.

Only RTs for correct responses were considered. RTs < 200 ms and 3 SD above the participant's average were discarded. In the simple RT test, only a main effect of arithmetic occurred with respect to RTs. Except for the control group and the AD/RD group, the groups did not differ significantly in simple RTs. Therefore, we controlled for simple RTs in speeded tasks, which did not substantially change the results. For technical reasons, data for the dot magnitude comparison task (Panamath) were only available for n = 78 children. We therefore conducted multiple imputation ANOVAs (cf., van Ginkel & Kroonenberg, 2014) pooling analysis results over 10 imputed data sets, using all basic numerical tasks as well as demographic variables (age, gender, IQ) as covariates. Results from multiple imputation ANOVAs did not provide different results from those obtained from analyzing incomplete data; we therefore report the latter only. Regarding accuracy, a marginal main effect of arithmetic occurred, with and without covariates.

In terms of RTs, a main effect of arithmetic was found without covariates. When we controlled for covariates, the effect vanished (see Table 2). In the dot-enumeration task, the number of dots was divided into two conditions, subitizing (1–3) and counting (4–9). We found a strong main effect of condition, $F(1, 123) = 1{,}311.25$, $p < .001$, with longer RTs in the counting compared to the subitizing range. These main effects were complemented by a two-way interaction of Condition × Arithmetic, $F(1, 123) = 6.13$, $p < .05$, as well as by a two-way interaction of Condition × Reading, $F(1, 123) = 14.08$, $p < .001$, indicating higher RTs for AD/RD mostly in the counting range. The three-way interaction of Condition × Arithmetic × Reading was not significant, $F(1, 123) = 0.95$, $p = .332$.

The analysis of the distance effect, as an indication of precise number representation, was of key interest in all magnitude comparison tasks (cf., Holloway & Ansari, 2009). Distances in symbolic and mixed magnitude comparisons were divided into two categories: small distances (1–3) and large distances (4–6). We additionally controlled for the total scores of correct answers of large and small distances. In the symbolic magnitude comparison task, no effect was found for distance, $F(1, 118) = 1.08$, $p = .302$. A significant two-way interaction of Distance × Arithmetic occurred, $F(1, 118) = 7.92$, $p < .01$, indicating higher RTs for both children with AD and AD/RD in small distances. The three-way interaction of Distance × Arithmetic × Reading was not significant, $F(1, 118) = 0.00$, $p = .996$. According to the mixed magnitude comparison task, only a significant main effect of distance occurred, $F(1, 123) = 125.94$, $p < .001$, indicating higher RTs in small distances. There were neither significant two-way nor three-way interactions, $F(1, 123) = .06$, $p = .804$; $F(1, 123) = .01$, $p = .937$; and $F(1, 123) = .31$, $p = .577$.

Discussion

The aim of the present study was to investigate differences in basic number processing and calculation skills in groups of children with AD, RD, AD/RD, and an unimpaired

Table 2. Number Processing, Calculation, and Working Memory Means (Standard Deviations) for the Four Groups and Main Effects of Arithmetic and Reading.

Task	Control group	Arithmetic disorder group	Reading disorder group	Comorbid group	Arithmetic effect F^a (*d*)	Reading effect F^a (*d*)	Interaction effect AD × RD F^a
Simple Reaction Time (SRT)							
Accuracy	$19.35\ (0.86)_{a}$	$19.50\ (0.83)_{a}$	$19.43\ (0.78)_{a}$	$19.52\ (0.70)_{a}$	0.68 (.02)	0.10 (.01)	0.04
RT	$543.24\ (133.42)_{a,b}$	$630.00\ (214.94)_{(a),b,d}$	$610.81\ (201.42)_{b,c}$	$684.85\ (305.81)_{(c),d}$	4.16 (.32)*	2.41 (.22)	0.03
Dot magnitude comparison[b]							
Accuracy [% corr]	$87.06\ (9.52)_{a,b}$	$81.87\ (19.44)_{a}$	$91.56\ (5.27)_{(b),c}$	$86.61\ (10.57)_{a,(c)}$	4.01 (.33)*	3.34 (.00)†	0.00
RT	$871.31\ (159.96)_{a}$	$1{,}155.90\ (708.31)_{a,b}$	$952.85\ (280.98)_{a,c}$	$1{,}235.31\ (902.81)_{b,(c)}$	2.36 (.51)	0.01 (.16)	0.00
Number line average deviation	$8.28\ (5.25)_{a,b}$	$9.08\ (6.01)_{a,c}$	$8.44\ (5.60)_{a}$	$10.70\ (6.31)_{(b),c}$	5.36 (.17)*	0.01 (.07)	0.90
Dot-enumeration RT[b]					10.38 (.46)**	14.16 (.44)***	0.26
Subitizing	$1{,}542.25\ (228.75)_{a}$	$1{,}687.63\ (271.85)_{b,c}$	$1{,}657.94\ (287.24)_{a,c}$	$1{,}775.37\ (314.24)_{b}$			
Counting	$3{,}406.70\ (621.08)_{a}$	$3{,}733.00\ (610.23)_{(a),b}$	$3{,}857.06\ (791.40)_{b}$	$4{,}390.13\ (975.39)_{c}$			
Transcoding							
Accuracy	$7.55\ (0.68)_{a}$	$7.10\ (1.33)_{a,b}$	$7.45\ (1.12)_{a}$	$6.63\ (1.96)_{b}$	7.25 (.10)**	1.46 (.03)	0.62
RT	$2{,}708.60\ (1{,}316.19)_{a}$	$2{,}926.75\ (1{,}159.92)_{a}$	$2{,}899.38\ (1{,}206.86)_{a}$	$4{,}010.48\ (2{,}134.11)_{b}$	3.53 (.40)†	3.81 (.26)†	2.23
Calculation accuracy							
Addition	$5.78\ (1.27)_{a,b}$	$5.25\ (1.83)_{a,c}$	$5.83\ (1.17)_{b}$	$4.78\ (1.65)_{c}$	8.83 (.12)**	0.64 (.02)	0.98
Subtraction	$4.68\ (1.58)_{a}$	$3.35\ (1.56)_{b}$	$4.00\ (1.63)_{a}$	$3.00\ (1.90)_{b}$	21.36 (.17)***	1.22 (.08)	0.19
Multiplication	$3.47\ (0.69)_{a}$	$3.00\ (1.21)_{c}$	$3.20\ (1.04)_{a,c}$	$2.26\ (1.40)_{b}$	19.14 (.11)***	3.68 (.06)†	2.08
Calculation RT							
Addition	$1{,}904.61\ (1{,}134.76)_{a}$	$2{,}315.13\ (1{,}172.48)_{a}$	$2{,}176.39\ (1{,}123.92)_{a}$	$2{,}200.43\ (1{,}439.06)_{a}$	0.93 (.14)	0.12 (.09)	0.73
Subtraction	$2{,}083.42\ (1{,}670.76)_{a,b}$	$1{,}829.32\ (880.46)_{a,b}$	$1{,}748.28\ (772.47)_{b,c}$	$2{,}562.56\ (3{,}044.97)_{b,(c)}$	0.70 (.15)	0.36 (.02)	2.62
Multiplication	$1{,}359.45\ (499.37)_{a,b}$	$1{,}527.25\ (598.25)_{a,c}$	$1{,}620.32\ (750.63)_{a,c}$	$1{,}730.35\ (1{,}243.37)_{(b),c}$	0.87 (.15)	2.43 (.23)	0.04
Symbolic number comparison [b]					13.50 (.54)***	0.66 (.25)	0.00
RT small distance	$963.19\ (155.99)_{a}$	$1{,}135.28\ (194.87)_{b}$	$1{,}051.08\ (240.09)_{a}$	$1{,}199.46\ (234.28)_{b}$			
RT large distance	$895.55\ (142.68)_{a}$	$1{,}005.73\ (197.00)_{b,(c)}$	$950.44\ (209.26)_{a,c}$	$1{,}043.06\ (193.91)_{b}$			
Mixed NC^{SRT}					0.57 (.10)	0.08 (.07)	0.67
RT small distance	$2{,}164.09\ (799.65)_{a}$	$2{,}395.75\ (860.64)_{a}$	$2{,}331.93\ (972.15)_{a}$	$2{,}303.48\ (1{,}015.16)_{a}$			
RT large distance	$1{,}461.79\ (402.77)_{a}$	$1{,}583.68\ (342.78)_{a}$	$1{,}542.83\ (461.06)_{a}$	$1{,}556.61\ (405.29)_{a}$			
Number sets[b]	$18.68\ (5.24)_{a}$	$15.55\ (6.18)_{c,b}$	$16.25\ (6.39)_{a,c}$	$11.93\ (5.84)_{(b)}$	11.65 (.40)**	7.68 (.26)**	0.30
Matrix span accuracy	$3.60\ (1.45)_{a,b}$	$3.65\ (1.76)_{a,d}$	$3.40\ (1.58)_{a,c}$	$2.85\ (1.56)_{(b),(c),d}$	1.49 (.04)	1.98 (.05)	1.25

Note. Means with the same subscripts do not differ significantly from each other (LSD method). Marginal results are indicated by parentheses. Cohen's *d* values are raw scores respectively absolute values. The ranges of our scales allowed for an adequate distribution of means. We tested for normality distribution and used the Welch test in case of unequal variances. We found neither a small number of individuals that drove the results nor any ceiling effects.

[a]*F* values are adjusted for covariates. [b]We also controlled for SRT.

†$p < .10$. *$p < .05$. **$p < .01$. ***$p < .001$.

control group. Time-based measure was a reliable criterion to identify children with learning disorders (see also Moll et al., 2015). Our design allowed us to directly ask how number processing was related to mathematical and reading ability. Summarizing the results briefly, children with AD displayed impairments in various tasks related to number processing, whereas children with RD were only impaired in tasks requiring verbal skills and Arabic number processing. Furthermore, the results fully support the assumption of comorbid additivity of AD and RD. In the following, we will address these issues in detail.

Children with RD performed poorly in the counting task, which is assumed to tap the verbal code of the Triple Code Model by Dehaene (1992). As demonstrated repeatedly in children with RD (e.g., Vellutino et al., 2004), deficits in accessing phonological codes are associated with a poor performance on number processing tasks requiring verbal procedures. Therefore, their performance in the counting task is affected, an assumption that is also made by the developmental model of Von Aster and Shalev (2007). In the counting task, children had to press the appropriate digit key on a computer keyboard. Therefore, this task might both tap the verbal code as well as Arabic number processing, as it is assumed to be the case in the transcoding task. In line with our assumptions, children with RD performed less efficiently compared to the control group and at the same level as the AD group in this task. This poor performance of children with RD was underlined by a main effect of reading, but post hoc comparisons indicated that only children with AD/RD showed significantly higher RTs compared to all the other groups.

With respect to tasks substantially tapping Arabic number processing, children with RD performed on the same level as the control group. By contrast, Moll et al. (2015) found that children with RD perform poorly in a symbolic magnitude comparison task. They assumed a visual–verbal access and naming speed deficit in children with RD to be causing these deficits. The pattern of results of the number sets task, which also taps the Arabic number processing, could underline these assumptions. However, most studies (e.g., Landerl et al., 2004; Landerl et al., 2009) did not find children with RD to perform poorly in such tasks. Furthermore, children with RD were not impaired in the mixed number comparison task. As expected, children with RD showed no impairments in the ANS, as they performed similarly to the control group in the number line estimation task and partially even better in the dot magnitude comparison task. Furthermore, children with RD made fewer errors on the Subtraction subtest than children with AD or AD/RD.

Our calculation task did not allow us to determine whether children with RD display deficits in fact retrieval (e.g., De Smedt & Boets, 2010), as the majority of items did not require fact retrieval but rather mental calculation. This underlines the assumptions made by the Triple Code Model (Dehaene, 1992), where subtraction is assumed to rely less upon the verbal code than addition and multiplication. Verbal representations are assumed to trigger fact retrieval, as in addition and multiplication tasks. In contrast, subtraction depends more strongly on abstract semantic representation of numerical quantity, as it is postulated in the ANS theory. Problems that may arise from these different dependencies may affect the processing of multiplication and addition rather than subtraction tasks in children with RD. All in all, the results support our hypothesis that children with RD do not display weaknesses in tasks tapping the ANS. The phonological processing deficits (cf., Simmons & Singleton, 2009) in our sample of children with RD result in problems with number processing tasks related to the verbal code as well as Arabic number processing.

In contrast to the RD children, children with AD performed poorly on both the verbal and nonverbal tasks. These children seem to be impaired in all three modules of the Triple Code Model (Dehaene, 1992). In agreement with our assumptions, children with AD had difficulties with counting, as they showed longer RTs compared to the control group. Similar to children with RD, children with AD did not make significantly more transcoding errors compared to the control group. However, they showed difficulties in the symbolic magnitude comparison and the calculation tasks, which are associated with Arabic number processing. Further results that underline the substantial deficits of children with AD in Arabic number processing came from the number sets task: Children with AD performed more poorly compared to the control group in this task.

In contrast to other authors (Defever et al., 2013), we did not find any differences in the mixed magnitude comparison task. A number of reasons might account for these diverging results. Defever et al. (2013) required participants to indicate whether symbolic and nonsymbolic magnitudes were equal, whereas we required our study participants to indicate the larger magnitude. Furthermore, in the mixed magnitude comparison paradigm used here, only numerosities from 2 to 9 were used. It may be possible that in children with AD, the ANS is less affected in the lower numerosity range (e.g., Iuculano, Tang, Hall, & Butterworth, 2008). However, using larger numerosities that did not include the subitizing range in the dot comparison paradigm, children with AD displayed deficits in the ANS, as they were less accurate than controls. They also differed from the RD group in the number line task, with a larger mean average deviation. Overall, children with AD are impaired in various forms, as they showed multiple, heterogeneous deficits (Dowker, 2005).

There are several studies discussing clusters of different cognitive profiles of children with AD (e.g., Bartelet et al., 2014). Unfortunately, our study design does not allow us to make any reliable statements about different subtypes of children suffering from AD. Further studies, with a research design that allows for an examination of the different clusters of children with AD, are, therefore, strongly recommended.

We found neither significant two-way interactions of Arithmetic × Reading nor three-way interactions, thus indicating an additive profile of AD and RD in comorbidity. This finding speaks against the assumption of a shared cognitive deficit underlying AD/RD (underadditivity) as well as against the assumption that the comorbid group is more impaired than the sum of the two single deficit groups (overadditivity). We do not assume a single deficit in reading to be responsible for the poor performance of the AD/RD group. The AD/RD group seems to be impaired particularly in the counting and in the transcoding tasks: Here, children with AD/RD showed the longest RTs, compared to all other groups, and differed also from the AD group, suggesting that poor reading or language skills increase the deficit in these tasks. This is in line with our assumptions that these tasks strongly draw on language skills. Further research should pay particular attention to counting und transcoding tasks to identify and differentiate children suffering from AD with and without RD.

In total, our sample consisted of all four groups that are needed to describe the nature of comorbidity. The sample obtained here was large compared to several other studies examining learning disabilities and their comorbidity and, therefore, provided the conditions needed for finding a medium-strength interaction of Arithmetic × Reading with high statistical power. However, we did not find such interactions, which underlines that the impairment caused by comorbid arithmetic and RD is not characterized through over- or underadditivity. Power analyses showed that taking adequate statistical power of .80 into account, an interaction effect of medium strength (Cohen's $f = .25$) might have been detected in 2 × 2 ANOVA with a sample size of $N = 128$ (Faul, Erdfelder, Lang, & Buchner, 2007). An interaction effect of small strength (Cohen's $f = .10$) would have required a sample size of $N = 787$, which underlines the problem of underpowered studies in psychological research (e.g., Maxwell, 2004). To find such an enormous sample of children would require screening around 10,000 children given the standard prevalence rates. Such an enterprise requires multicenter studies preferably spanning several countries. We were not able to find these small effects in our sample with sufficient power. Therefore, we strongly recommend performing a meta-analysis to investigate whether small interaction effects of Arithmetic × Reading do in fact exist.

To date, there are not enough studies in this field of research to perform a meaningful meta-analysis. For that reason, primary studies examining the cognitive profiles of children with learning disabilities are needed. Moreover, in contrast to some recent work (e.g., Moll et al., 2015), our sample consisted of four very carefully matched groups regarding age and IQ. In this regard, it is important to note that group differences could not be attributed to age or intelligence. Such important differences regarding the group matching of samples need to be considered when interpreting deficits in basic number processing and calculation in children with learning disabilities. We are aware that matching the groups on IQ eliminates a source of variance that could be responsible for differences between the groups. However, as we are interested in the differences in mathematical and reading achievement scores between the disability groups, we controlled the influence of IQ as a potential confounder by matching the groups on it. Furthermore, it should be noted in particular that the importance of the present study lies in its exploration of a wide array of numerosity measures, compared to most of the existing studies that did not use a sufficient number of different numeric processing tasks. Also, none of them controlled for WM (e.g., Moll et al., 2015). Our study provided a WM control task, in which the groups did not differ significantly. One reason for this could be due to the matching on IQ, as high correlations of WM with IQ could be assumed (e.g., Fry & Hale, 2000).

Conclusions

To conclude, the aim of the present study was to investigate the cognitive profiles of primary school children suffering from AD only, RD only, comorbid AD/RD, and an unimpaired control group. Our results underline the additive effect of a comorbid AD and RD according to the impaired cognitive profiles. Children with AD are impaired in a wide range of number tasks, whereas children with RD are impaired in verbal number tasks only. Our results provide a useful basis for developing diagnostic tools and individual treatments for different learning disabilities that are tailored to their individual profiles. The high comorbidity requires more broadly testing for both core deficits resulting from AD and RD, as children with RD have been shown to perform poorly on mathematical tasks that require verbal skills. It needs to be clarified whether their problems result from their RD or if they have more severe problems that could result from a comorbid AD/RD. Also, only AD/RD children differed (marginally) from the control group in the WM task. This is important to keep in mind, as teachers need to adjust their educational support to foster the children's different ways of compensating for their deficit.

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