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META-ANALYSIS

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Cognitive Profiles of Children with Isolated and Comorbid Learning Difficulties in Reading and Math: a Meta-analysis

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Abstract

The causes underlying comorbid learning difficulties in reading (RD) and math (MD) are still a matter of debate. Based on current research, two models for the relation of the cognitive profile of isolated and combined learning difficulties (RDMD) are discussed. Regarding the "multi-deficit model", the profile of RDMD is characterized by the sum of domain-specific core deficits of RD and MD (*additivity*) as well as shared domain-general risk factors of RD and MD resulting in less severe deficits than expected under additivity (*under-additivity*). The "three independent disorders model" explains RDMD as a distinct learning disorder, showing a separate cognitive profile with distinct and/or more severe deficits, compared to the sum of RD's and MD's profiles (*over-additivity*). To evaluate these approaches, a meta-analysis including 74 studies, examining children aged 6–12, was conducted. Separate group comparisons for the three subcomponents in the cognitive profiles—reading, math, executive functions (EF)—were considered. Linear hypothesis testing revealed different results regarding the three subcomponents of the cognitive profiles of children with isolated vs. combined learning difficulties: Whereas RDMDs' deficits in reading and math represented the sum of the deficits in the isolated groups (additivity), there was some evidence that RDMDs' deficits in EF skills corresponded to under-additivity. Furthermore, group differences in math skills were more pronounced in symbolic than in non-symbolic math tasks, whereas in reading, group differences were larger in phonological processing and reading than in rapid automatized naming and language skills. Results are discussed in terms of intervention options for RDMD.

Keywords Learning difficulties · Reading skills · Math skills · Comorbidity

Nurit Viesel-Nordmeyer and Julia Reuber contributed equally to this work.

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Introduction

Even though learning difficulties (LD) in reading (RD) and math (MD) often co-occur (11–70%; e.g., Moll et al., 2019; Willcutt et al., 2019), the reason for their comorbidity (RDMD) is not yet fully understood. Two main explanatory approaches for the comorbidity of RD and MD—the "multi-deficit model" vs. the "three independent disorders model"—shape the current research debate (e.g., McGrath et al., 2019). The "multi-deficit model" (e.g., McGrath et al., 2019; Pennington, 2006) explains learning disorders by complex interactions between core deficits (specific for a particular disorder) as well as other risk factors that are shared between disorders. Specifically, domain-specific core deficits underlying RD (e.g., phonological processing) and MD (e.g., numerosity and magnitude processing) sum up, resulting in an so-called "*additive*" *profile* in children with RDMD (e.g., Kißler et al., 2020; Peters et al., 2020; Wilson et al., 2015). Additionally, deficits in domain-general cognitive processes (e.g., memory skills, attention; cf. Moll, 2022; Prado, 2018) have been reported for both disorders and seem to be shared between RD and MD. Consequently, deficits in domain-general cognitive processes in RDMD's profile are reffered to as "*under-additive*." "*Under-additivity*" means that the deficits in the cognitive profile of RDMD are smaller than the sum of isolated RDs' and MDs' deficits (e.g., Landerl et al., 2009). In contrast, the three independent disorders model regards isolated RD or MD as well as comorbid RDMD as separate disorders characterized by a unique cognitive profile (e.g., Skeide et al., 2018). In this view, compared to isolated RD or MD, the cognitive profile of RDMD is characterized by qualitatively distinct and/or more deficits in reading and math skills as well as in domain-general cognitive processes. Consequently, in the three independent disorders model, the core and domain-general deficits in RDMD are larger than the sum of the deficits observed in isolated RDs' or MDs' profile ("*over-additivity*") (e.g., Landerl et al., 2009).

Since it can be assumed that a better understanding of the underlying causes of RDMD could help designing a more targeted support of these doubly disadvantaged children (e.g., McGrath et al., 2019; Moll et al., 2019), the main goal of our meta-analysis was to clarify the actual distribution of domain-specific core deficits and domain-general deficits in RDMD's cognitive profile. Building on recent research, we define domain-general deficits as proposed potential risk factors under the broad umbrella of executive functions (EF) seen as relevant for developing isolated or combined LD (e.g., Peng & Fuchs, 2014; Schuchardt & Mähler, 2016; Watson, 2016). To specify, core domain-general risk factors of LD (cf. Moll, 2022) like memory skills, inhibition, shifting or updating, processing speed, and attention are included in our used definition of EF.

Finally, we conducted separate analyses for studies' reading, math, and EF outcomes to detect whether children with RDMD show an additive or an interactive (under- or over-additivity) profile of isolated RD and MD. With respect to recent studies (e.g., Compton et al., 2012; Moll et al., 2019; Peters et al., 2020), a broad range of moderators for isolated and combined RD and MD was analyzed to investigate their role in describing heterogeneity of results. To the best of our knowledge, to date, only one meta-analysis examined whether the multi-deficit or cognitive subtype model for RD was supported (Peng et al., 2022). In this meta-analysis, domain-general skills were analyzed in a slightly more differentiated manner than here. However, Peng et al. (2022) only examined children with RD besides typical achievers (here C), whereas the current study additionally takes MD as well as RDMD into account.

Explanatory Values for Co-occurring Learning Difficulties in Reading and Math

According to diagnostic guidelines (DSM-5; American Psychiatric Association, 2013; ICD 10; World Health Organization, 1992) and recent research on LD, isolated RD appears to be primarily caused by deficits in phonological processing, leading to problems in spelling, word recognition, and reading comprehension. In contrast, isolated MD seems to be mainly based on deficient processing of numbers and magnitude (e.g., Compton et al., 2012; Landerl et al., 2009). Besides these core deficits, both RD and MD have been associated with shared domain-general skills, which are proposed as potential risk factor developing isolated or combined LD. To specify, key domain–general skills in the development of LD are memory skills (phonological and visual working memory), inhibition, shifting or updating (main executive function skills), processing speed, and attention, as well as general language skills (cf., Moll, 2022). The key role of these domain-general skills can be explained by their importance for an adequate development of both, reading and math skills (e.g., Moll, 2022; Peng & Fuchs, 2014; Peng et al., 2020). In the current study, most of these skills were comprised under the term EF, with the exception of general language skills as well as verbal processing speed (RAN), which were placed among the reading-related skills.

Despite high prevalence rates of co-occurring RD and MD ranging from 11 to 70% (e.g., Gross-Tur et al., 1996; Landerl & Moll, 2010; Moll et al., 2019; Willcutt et al., 2019), the composition of the cognitive profile of RDMD and the underlying causes are not yet fully understood. Particularly, the specific role of core deficits associated with RD or MD, as well as the role of domain-general deficits in EF for the cognitive profile of comorbid RDMD, has not been clarified. The latter can be traced back to the lack of available studies with adequate sample size considering children with isolated and combined RD and MD. However, a better understanding of comorbidity can be considered promising for a suitable promotion and prevention of RDMD (e.g., McGrath et al., 2019; Moll et al., 2019).

Based on a comprehensive research review of neuro-cognitive findings, Ashkenazi and colleagues (2013) suggested three possible explanations for the frequent co-occurrence of RD and MD. We describe these below, adding the "cognitive subtype" hypothesis (e.g., Rucklidge & Tannock, 2002) to complete the aforementioned review.

The Under-Additivity Hypothesis ("Shared Risk Factor")

The under-additivity or "shared risk factor" hypothesis is based on two lines of research. According to this view, co-occurring LD in reading and math are caused by common deficits in domain-general skills, which are necessary to process information adequately in both learning domains (reading and math). In line with this view, a number of studies have found deficits of children with isolated or combined LD in EF like inhibition, shifting, or specific working memory components (e.g., Peng & Fuchs, 2014; van der Sluis et al., 2004). Evidence for the shared risk factor hypothesis has also been reported in a comprehensive research review of neuro-cognitive studies (c.f. Prado, 2018). Furthermore, the shared risk factor hypothesis is in line with the assumptions of recent multi-deficit model approaches (e.g., McGrath et al., 2019; Pennington, 2006), that explain learning disorders by complex interactions between core deficits (disorder specific risk factors) as well as risk factors that are shared between disorders (domain-general risk factors). In addition to shared risk factors in domain-general processes, verbal or phonological processing deficits, which have originally been conceptualized as a domain-specific core deficit of RD, are discussed as cause for the comorbidity between RD and MD. The association between verbal respectively language risk factors and mathematics is based on the idea of a number representation in three different codes (c.f. Triple-Code Model (TCM); Dehaene, 1992), a verbal code ("one, two, three"), a visual-Arabic code ("1, 2, 3"), and a magnitude code (" •, ••, •••"). Impairments in language skills have been shown to affect the verbal code leading to problems in verbal math tasks, such as counting and fact retrieval (c.f. Prado, 2018). However, with regard to the evidence of an explanatory value of verbal processes for RDMD, results of individual studies differ. Slot and colleagues (2016) detected underlying deficits in phonological processing as shared risk factors for RD and MD, while taking further cognitive skills like number sense and EF into account. Furthermore, Moll and colleagues (2015a) found that cognitive deficits in children with RDMD in performing verbal number processing tasks (e.g., fact retrieval, counting, transcoding) could lead back to problems in both numerosity and phonological processing. Finally, a large neuroscientific study (Viesel-Nordmeyer & Prado, 2023) revealed associations between children's and adolescents' arithmetic skills and their grey matter volume (GMV) in brain areas related to verbal processing (cf. Dehaene, 1992).

The Additivity Hypothesis

Several studies suggest that comorbidity of RD and MD is characterized by an additive combination of risk factors (e.g., Kißler et al., 2020; Landerl et al., 2009; Moll et al., 2015a; Schuchardt et al., 2008). To statistically test additivity versus under- or over-additivity for the cognitive profile of RDMD, a statistically significant interaction of RD and MD factors (e.g., in an analysis of variance or ANOVA) must be absent (additivity) or present (under- or over-additivity). Recent studies focusing on this issue have frequently provided evidence for the additivity of the examined skills based on the absence of an RD by MD interaction in ANOVA results. This was reported for math-related skills such as symbolic magnitude comparisons, number line (Landerl et al., 2009) or number processing (Raddatz et al., 2017), for literacy and language skills such as reading fluency or vocabulary (Peters et al., 2020), and for EF skills including all three components of working memory (Moll et al., 2015a;

Schuchardt et al., 2008), inhibition (De Weerdt et al., 2013a) and spatial visualization (e.g., Peters et al., 2020).

Furthermore, in a recent study (Kißler et al., 2020) using Bayesian methods for a better interpretation of significant and non-significant interaction effects, the additivity of cognitive profiles in children with RDMD could be confirmed. Specifically, additivity in the cognitive profile of comorbid RDMD could be validated for various children's math skills (e.g., symbolic magnitude comparisons, number line, counting), for measurements of literacy related skills (i.e., RAN), and for alertness as well as for all three working memory components (cf. Baddeley, 2012). However, some studies found small but significant interactive patterns between RD and MD. For example, Dirks and colleagues (2008) showed an interaction of RD and MD in reading comprehension, and de Weerdt and colleagues (2013b) reported an interaction of RD and MD in the central executive.

The Over-Additivity Hypothesis ("Cognitive Subtype")

According to the "cognitive subtype" hypothesis (c.f. Rucklidge & Tannock, 2002) or the "three independent disorders model" (Neale & Kendler, 1995), RDMD represents a separate disorder group with a cognitive profile that is distinct from the profile of the isolated RD and MD groups. According to this view, RDMD is characterized by a more impaired cognitive profile compared to the deficit profiles of isolated RD and MD ("over-additivity"). Interestingly, the hypothesis of RDMD as a separate disorder group is also suggested by the ICD-10, where RDMD is listed as a distinct diagnostic category. Moreover, distinct multimodal neural signatures associated with RDMD compared to isolated RD and MD were found using fMRI (Skeide et al., 2018), supporting the assumption of a qualitatively different disorder subtype.

Aims of the Current Review

In the current meta-analytic review, we strive to answer the question whether domain-specific core deficits as well as domain-general cognitive deficits in RD and MD lead to additive effects or interact (under-additivity or over-additivity; e.g., Landerl et al., 2009) in the cognitive profile of RDMD. Specifically, our goal is to investigate whether the multi-deficit model (additivity of the core deficits, under-additivity of EF) or the three independent disorder model (over-additivity of deficits) better explains the cognitive profile in children with RDMD. Power analyses showed that taking adequate statistical power of 0.80 into account, an interaction effect of medium size (Cohen's $f = 0.25$ or $d = 0.50$) can be detected in 2 (RD vs. no RD) $\times$ 2 (MD vs. no MD) factorial ANOVAs with a sample size of $N = 128$ (Faul et al., 2007). A small interaction effect (Cohen's $f = 0.10$ or $d = 0.20$) would require a sample size of $N = 787$, which in turn would require screening around 10,000 children given the standard prevalence rates. Such an enterprise requires large multicenter studies. Performing a meta-analysis is an appropriate alternative to investigate whether small interaction effects of RD x MD actually occur in the current literature.

In line with the multi-deficits model, we hypothesized an additive profile of RDMD in the domain-specific core deficits of the isolated LD groups (e.g., phonological processing of RD; numerosity processing of MD) as well as an under-additivity in domain-general EF (cf. Dehaene, 1992). Thus, we did not assume any interaction between RD and MD in reading-related skills (e.g., Kißler et al., 2020; Peters et al., 2020) or math-related skills (e.g., De Weerdt et al., 2013a; Kißler et al., 2020; Landerl et al., 2009; Peters et al., 2020; Raddatz et al., 2017) but in EF (e.g., De Weerdt et al., 2013b). To the best of our knowledge, to date, no meta-analysis has been published that examines the multi-deficit model of comorbid RDMD in relation to the cognitive profiles of isolated RD and MD and a control group (C). Specifically, we are unware of any meta-analyses clarifying the cognitive profile of the core deficits in isolated RD and MD in comparison to the cognitive profile of RDMD ("additivity", "over-additivity" or "under-additivity") with respect to reading and math skills and domain general skills. In addition, concerning subcomponents of math, reading, and EF, our hypotheses regarding performance differences were as follows.

Math Tasks Based on the triple-code model by Dehaene (1992), numbers can be processed in three modules pertaining to different number representation forms: analogue magnitudes, verbal code, and Arabic number form. Building on recent research, we assumed that children with MD show deficits in tasks tapping all modules of number processing (e.g., Moll et al., 2015a) as well as in the verbal code (e.g., Viesel-Nordmeyer & Prado, 2023). Furthermore, we hypothesized that children with RD exhibit deficits in number processing tasks tapping the verbal code (cf. Prado, 2018) as well as in tasks mapping the verbal *and* the Arabic code (e.g., von Aster & Shalev, 2007; cf. Prado, 2018).

Reading Tasks We assumed that children with MD show no deficits in reading-related tasks (e.g., Moll et al., 2015a), whereas children with RD present deficits in all reading-related tasks (Moll et al., 2015a). These assumptions would support the original classification of the isolated RD and MD with regard to the domain-specific core deficits in LD.

Executive Functions Tasks Based on the reported literature (e.g., Peng & Fuchs, 2014), we assumed that children with MD are impaired in inhibition, shifting, and visuospatial updating as well as in the visuospatial and verbal working memory tasks. Furthermore, we presumed that children with RD are not impaired in the visuospatial sketchpad tasks, but in some attention-related EF tasks (e.g., inhibition, shifting), as they often show subclinical attention problems without fulfilling diagnostic criteria. Furthermore, we assumed children with RD to be impaired in verbal working memory tasks (e.g., Peng et al., 2013), like verbal updating or phonological loop.

Method

Inclusion Criteria

With respect to our research question, the following inclusion criteria (Fig. 1) were mandatory for the literature search described below: Only studies that comprised at least one group of children with isolated RD or MD and a group with comorbid RDMD were taken into account. In the included studies, RD was defined by impaired skills in word reading accuracy (33.8%), word reading fluency (25.4%), both (21.1%), reading comprehension (7.0%), mixed (11.3%; including all four), or spelling (1.4%). MD was defined by impaired skills in arithmetic (59.2%) or mix math skills (40.8%; including word problems and geometry). The following cut-off criteria (percentile ranks: PR) to classify LD groups were used: RD: PR 1–10: 11.9%; PR 11–25: 52.4%; PR > 25: 35.7%; MD: PR 1–10: 10.7%; PR 11–25: 57.1%; PR > 25: 32.1%; RDMD: PR 1–10: 10.3%; PR 11–25: 62.1%; PR > 25: 27.6%. Studies with (8.1%) and without (91.9%) IQ discrepancy criterion were considered. Furthermore, studies had to focus on outcomes of math, reading, or executive functions. Finally, we decided for an age span limit from 6 to 12 years, the age span where LD mostly become visible.

Literature Search

Studies included in the meta-analysis were identified in three steps. First, studies were identified conducting electronic literature search based on the following search term (dyscalcul* OR acalcul* OR "math* disabilit*" OR "math* difficult" OR "arithmetic difficult*" OR "arithmetic disabilit*") AND (dyslex* OR "read* difficult*" OR "read* disabilit*") AND (comorbid* OR "learn* disorder" OR "learn* disabilit*" OR "learn* difficult*") using the platform EBSCOHOST, which resulted in $n = 491$ hits. To complement the search process, we applied the search term (Mathematics AND Reading AND Learning (disabilities OR difficulties OR disorders)) using the database ERIC, resulting in $n = 216$ hits. In a second step, the abstracts and if necessary the full-texts were screened to identify whether studies fulfilled the inclusion criteria defined above. Thereby, three additional studies which were not included in the EBSCOHOST search hits could be added from the ERIC search hits. Both step 1 and step 2 were carried out by the two first authors. One of the first authors identified an additional study within the publication time until 2014 (agreement rate: 98.2%).To standardize the meta-analytic sample, papers including different samples ($n = 2$) and time points ($n = 6$) had to be split. Finally, 72 studies fulfilling the inclusion criteria could be included. Eventually, grey literature was gathered sending e-mails to scientists in the research field of interest via mailing lists. This procedure helped to expand our sample by two further studies ($n = 74$). Third, all references of the papers included were screened to find studies not identified before. Another added study completed our sample, resulting in a total of 75 studies. However, one of the identified studies had to be sorted out during the coding

Fig. 1 PRISMA diagram showing the selection process of studies for the systematic search ▸

procedure, because the outcome measure could not be assigned to one of the outcome variables of interest. Consequently, the final sample represents 74 studies from 15 countries published between 1985 and 2020.

Coding Procedure

The 74 studies were double coded by one of the two first authors and one trained graduate student. This is described in the following subsection. After coding, and interrater reliability of $\kappa = 0.95$ was computed averaged over categories (sample specific: $\kappa = 0.88$; range 0.03–1.00; task specific: $\kappa = 0.97$; range: 0.04–1.00). Eventually, all disagreements could be solved by consulting the original article or in discussion.

Meta-analytic Procedure

The standardized mean difference effect size used was Hedges' *g* (Hedges, 1981). Because many effect sizes were clustered within studies, we utilized a three-level meta-analytic approach (Konstantopoulos, 2011). This statistical procedure splits the total variance into sampling variance and two sources of true variance: between-study variance, based on the variability between studies, and within-study variance, based on the variability of effect sizes within studies. By taking the within-study dependencies into account, unbiased estimates of standard errors can be obtained. We used a restricted maximum likelihood estimator (REML) to avoid bias in variance estimates (Viechtbauer, 2005). All analyses were conducted in R (R Core Team, 2021), using the *metafor* (Viechtbauer, 2010) and *dmetar* (Harrer et al., 2020) packages.

In order to investigate heterogeneity of effect sizes, we conducted moderator analyses. Moderators were grouped as sample-specific or task-specific moderators. Separate analyses were calculated for each of the possible moderators (cf. Table 1).

Sample-specific moderators were year of publication and mean age of children in a study, as well as all aspects of heterogeneity of LD between studies (e.g., Fischbach et al., 2013) like fulfillment of IQ discrepancy criterion, IQ difference between the respective LD or control groups, and percentile rank in diagnosis. Moreover, since comorbidity rates between ADHD and LD in reading and math are high (e.g., Czamara et al., 2013), we considered whether studies excluded children with ADHD. Finally, we included differences in socio-economic status (SES) between groups, which is also discussed as a risk factor for diagnosing LD (e.g., Blair and Scott, 2002) .

Task-specific moderators included screening tests of LD and the observed outcome variables (tasks) of included studies. Since the content of the math screening was quite uniform, we only distinguished between arithmetic or mixed tests (e.g., parallel consideration of arithmetic, geometry, and word problems). Given that the reliability of speeded math tests is critically discussed (e.g., Lonnemann &

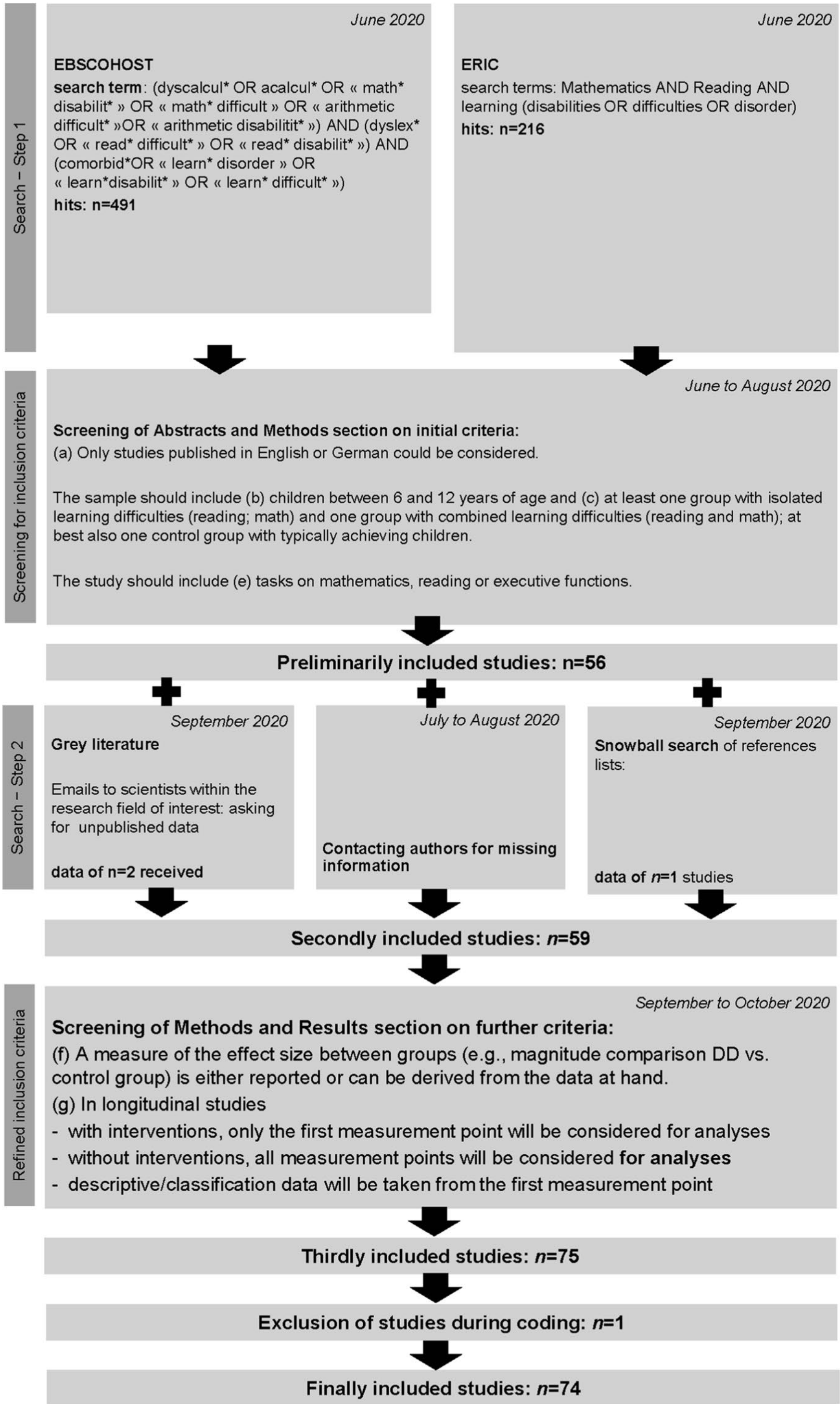
Search – Step 1
June 2020
EBSCOHOST
search term: (dyscalcul* OR acalcul* OR « math* disabilit* » OR « math* difficult » OR « arithmetic difficult* »OR « arithmetic disabilitit* ») AND (dyslex* OR « read* difficult* » OR « read* disabilit* ») AND (comorbid*OR « learn* disorder » OR « learn*disabilit* » OR « learn* difficult* »)
hits: n=491
June 2020
ERIC
search terms: Mathematics AND Reading AND learning (disabilities OR difficulties OR disorder)
hits: n=216
Screening for inclusion criteria
June to August 2020
Screening of Abstracts and Methods section on initial criteria:
(a) Only studies published in English or German could be considered.
The sample should include (b) children between 6 and 12 years of age and (c) at least one group with isolated learning difficulties (reading; math) and one group with combined learning difficulties (reading and math); at best also one control group with typically achieving children.
The study should include (e) tasks on mathematics, reading or executive functions.
Preliminarily included studies: n=56
Search – Step 2
September 2020
Grey literature
Emails to scientists within the research field of interest: asking for unpublished data
data of n=2 received
July to August 2020
Contacting authors for missing information
September 2020
Snowball search of references lists:
data of n=1 studies
Secondly included studies: n=59
Refined inclusion criteria
September to October 2020
Screening of Methods and Results section on further criteria:
(f) A measure of the effect size between groups (e.g., magnitude comparison DD vs. control group) is either reported or can be derived from the data at hand.
(g) In longitudinal studies
- with interventions, only the first measurement point will be considered for analyses
- without interventions, all measurement points will be considered for analyses
- descriptive/classification data will be taken from the first measurement point
Thirdly included studies: n=75
Exclusion of studies during coding: n=1
Finally included studies: n=74

Table 1 Coding criteria for moderators and operational definitions

Moderator	Levels and operational definitions
Sample-specific moderators	
Year of publication	We coded the paper's year of publication
Age	We coded the mean age of the sample (in months)
IQ discrepancy criterion	We coded whether the IQ discrepancy criterion was used
IQ difference	We computed if there is a IQ difference between the different LD groups
Classification percentile rank	We used three categories to code the percentile rank which was used categorizing LD children: 1 = percentile rank ≤ 10 2 = percentile rank 11–25 3 = percentile rank > 25
Controlling for ADHD	We coded whether the existence of ADHD was controlled or if children with ADHD were excluded
Socio-economic status	We coded group values of the socio-economic status (SES) and computed for available group differences in SES
Task-specific moderators	
Math screening content	We determined the math screening content: a) Arithmetic (basic arithmetic operations) b) Mixed (word problems, geometry, etc.) Further, we included the related test values of the groups
Math screening type	We added which type of math screening was used: a) Power test b) Speed test (strict time test) c) Time limit test (focus on accuracy with time limitation) d) mixed
Math outcome/tasks	With respect to the Triple-Code Model (cf., Dehane, 1992), we coded the content of math outcome/tasks and included the related groups values: a) Non-symbolic approximate magnitude processing (e.g., non-symbolic comparison of quantities, rollover, number line estimation) b) Symbolic verbal-auditory processing (e.g., number words, counting, factual knowledge, transcoding) c) Symbolic visual processing (e.g., operations with multi-digit numbers, calculation, symbolic comparison of numbers)
Reading screening content	We coded the reading screening content: a) Word reading accuracy b) Word reading fluency c) Word reading accuracy and fluency d) Reading comprehension Furthermore, we included the related test values of the groups
Reading outcome/tasks	We coded the content of reading outcome/tasks and included the related group values: a) Rapid automatized naming (RAN; figures, colors; objects, mixed) b) Phonological processing c) Language skills (e.g., syntax awareness; articulation speed) d) Reading (accuracy, fluency, comprehension, mixed)

Table 1 (continued)

Moderator	Levels and operational definitions
Executive function outcome/tasks	We coded the content of executive function outcomes and included the related group values: a) Inhibition, shifting, and updating b) Working memory (phonological loop, visuospatial sketchpad, central executive) c) Nonverbal processing speed d) Attention

Hasselhorn, 2019), we also coded whether math screening tests were power tests, speed tests, or time-limit tests. For the screening tests of reading, we coded whether they assessed accuracy, fluency, a combination of both, or reading comprehension. In contrast to the math screening tests, we assumed a higher diversity for math outcomes (tasks). Thus, we decided coding math outcome variables classifying with respect to the triple-code model (Dehaene, 1992). We distinguished between non-symbolic approximate magnitude, symbolic verbal-auditory, or symbolic visual processing. The type of reading-related outcome was coded as measuring RAN, phonological processing, language skills (e.g., syntax awareness, articulation speed), or reading skills (accuracy, speed, comprehension). EF were coded considering a common taxonomy for children with LD (Gilmore & Cragg, 2018; Moll, 2022): core executive functions (inhibition, shifting, updating), working memory (phonological loop, visuospatial sketchpad), processing speed, and alertness.

In order to investigate whether the cognitive profile of the comorbid RDMD group resulted additively from the cognitive profile of the isolated LD groups (additivity) or whether the comorbid RDMD group profile deviated from the sum of the isolated LD profiles (under-additivity, over-additivity), the assumption of additivity was translated into a linear hypothesis. For this procedure, three terms or effect sizes were needed: g_1 $(C-RD)$, g_2 $(C-MD)$, and g_3 $(C-RDMD)$. The following linear hypothesis representing additivity was investigated meta-analyticly:

$$g_{Add} = g_1 + g_2 - g_3 = [(C - RD) + (C - MD)] - (C - RDMD) = 0$$

Since the effect size g_3 was subtracted from the term $g_1 + g_2$, a negative value would represent over-additivity (RDMD group is more impaired than expected based on isolated LD groups), whereas a positive value would represent under-additivity (RDMD group is less impaired than expected based on isolated LD groups). In contrast, additivity corresponds to a sum of 0. To compare effect sizes across categories, we conducted moderator analyses based on Tukey's HSD test (Hays, 1994). All tests of statistical significance and p-values were Bonferroni-Holm-corrected (Holm, 1979).

Funnel plots using the trim and fill method (e.g., Duval & Tweedie, 2000) and multivariate meta-regressions with standard errors of effect sizes as moderator (Egger-type tests; cf. Rodgers & Pustejovsky, 2020) were used to check for publication bias. Furthermore, we computed Cook's distance (Cook & Weisberg, 1982) for all group differences in math, reading, and EF outcomes. With this procedure, outliers based on a threshold of 2 standard deviations (*SD*) were identified and excluded from further analysis (cf. Viechtbauer & Cheung, 2010). This yielded the following exclusion of studies: for analyses of math outcomes, we excluded two studies for *C-MD* as well as one study each for *C-RD* and *C-RDMD*. For reading outcomes, one study each for *C-MD* and *C-RD* and two for *C-RDMD* were removed. For executive function outcomes, one study for *C-MD*, two for *C-RD*, and four studies for *C-RDMD* were excluded.

Results

The 74 studies included in our meta-analysis comprised 11,588 individuals (female = 51.8%) with and without LD. Overall, 74 RDMD groups (mean $n = 34.0$; female = 48.3%), 52 RD groups (mean $n = 30.1$, female = 43.5%), 70 MD groups (mean $n = 32.4$, female = 57.4%), and 66 C groups (mean $n = 80.6$, female = 52.6%) were considered. Heterogeneity and publication bias analysis will be provided in the following section. Subsequently, findings for overall and moderator effects for the three subcomponents of interest (i.e., math, reading, and EF skills) will be reported. Finally, results of the linear hypothesis for the assumed additivity will be shown under consideration of possible moderators.

Heterogeneity and Publication Bias

As can be seen in Table 2, substantial heterogeneity was found for nearly all effect sizes of interest. Measures of between-study variance (I^2_b) and within-study variance (I^2_w) indicated a higher proportion of between-studies variances for math outcomes. However, in reading outcomes, between-study variance was less pronounced than within-study variance. Finally, compared to between-study variance, variability of executive function outcomes was less clearly attributable to within-study variance.

Egger-type testing (Table 3) showed evidence for publication bias in some of the group comparisons. Specifically, significant effects were found for C-RDMD in math, reading, and EF outcomes. Moreover, evidence for publication bias was also evident comparing MD and RDMD groups in reading and math outcomes. Finally, Egger-type testing indicated publication bias for group comparisons of C-MD in math as well as C-RD in executive function outcomes. Based on funnel plots (Fig. 2), evidence for publication bias could be attributed to the lack of small studies with a lower effect size than the mean. Using the trim and fill method, it became clear that all effects became smaller when taking imputed studies into account.

Overall and Moderator Effects for Mathematical Outcomes

Overall effect sizes of mathematical outcomes (Table 4) already point to an additive effect for C-RDMD (0.84), comprised of C-RD (0.27) and C-MD (0.64). These three effects differed significantly from each other (all $p < 0.01$), suggesting that the comorbid group was more strongly impaired than the MD and RD group

Table 2 Tests of heterogeneity

Effect	Test for heterogeneity		I^2_b			I^2_w		
	Q (*df*)	*p*	χ^2 (*df*)	*p*	%	χ^2 (*df*)	*p*	%
Math								
C-RD	260.37 (174)	< .001	26.28 (1)	< .001	28.58	.02 (1)	.31	6.96
C-MD	860.06 (228)	< .001	94.53 (1)	< .001	49.49	89.75 (1)	< .001	25.20
C-RDMD	1332.56 (242)	< .001	84.25 (1)	< .001	49.92	200.41 (1)	< .001	34.83
RD-RDMD	499.39 (174)	< .001	57.22 (1)	< .001	57.33	36.39 (1)	< .001	19.18
MD-RDMD	528.98 (270)	< .001	41.99 (1)	< .001	35.98	14.20 (1)	< .001	16.93
Reading								
C-RD	240.87 (87)	< .001	8.99 (1)	< .01	23.79	27.40 (1)	< .001	42
C-MD	137.65 (89)	< .001	11.97 (1)	< .001	35.34	0.00 (1)	.97	0.41
C-RDMD	360.70 (89)	< .001	3.46 (1)	.06	16.66	93.53 (1)	< .001	59.12
RD-RDMD	100.87 (98)	.40	4.57 (1)	.03	13.38	.00 (1)	1.00	0
MD-RDMD	249.15 (89)	< .001	12.64 (1)	< .001	29.4	31.38 (1)	< .001	36.18
Executive functions								
C-RD	375.75 (198)	< .001	34.68 (1)	< .001	34.17	8.33 (1)	< .01	17.62
C-MD	331.85 (213)	< .001	35.61 (1)	< .001	30.42	.03 (1)	.86	1.23
C-RDMD	692.37 (237)	< .001	102.95 (1)	< .001	45.62	15.09 (1)	<.001	17.68
RD-RDMD	284.09 (188)	< .001	29.98 (1)	< .001	23.56	1.20 (1)	.27	8.16
MD-RDMD	397.14 (240)	< .001	51.22 (1)	< .001	32.41	.17 (1)	.67	2.68

Notes. *Q*, Cochran's *Q*-statistic; I^2_b, between study variance; I^2_w, within-study variance; *RD*, reading learning difficulties; *MD*, math learning difficulties; *RDMD*, combined learning difficulties in math and reading; *C*, control

Table 3 Egger-type tests

Effect	*Est*	*p*	*LB*	*UB*
Math				
C-RD	.20	.72	−.88	1.27
C-MD	3.36	<.001	1.91	4.80
C-RDMD	2.86	<.001	1.63	4.19
RD-RDMD	2.41	<.001	1.00	3.81
MD-RDMD	.43	.33	−.44	1.30
Reading				
C-RD	.81	.39	−1.03	2.65
C-MD	.19	.79	−1.22	1.61
C-RDMD	3.24	<.01	1.01	5.47
RD-RDMD	−.14	.80	−1.23	.95
MD-RDMD	2.71	<.01	.71	4.70
Executive functions				
C-RD	2.04	<.01	.56	3.52
C-MD	.87	.06	−.04	1.78
C-RDMD	4.39	<.001	2.81	5.97
RD-RDMD	.45	.51	−.88	1.78
MD-RDMD	2.05	<.001	.94	3.17

Notes. Est., unstandardized regression slope parameter of Egger-type test; *LB*, lower bound of 95% confidence interval; *UB*, upper bound of 95% confidence interval; *RD*, reading learning difficulties; *MD*, math learning difficulties; *RDMD*, combined learning difficulties in math and reading; *C*, control

in mathematical outcomes. Moreover, the MD group displayed larger deficits than the RD group in mathematical outcomes. The same pattern emerged at the level of mathematical outcome categories.

Post hoc testing revealed differences of factor levels only for a few moderators in group comparisons: Results for “type of math outcomes” in C-RDMD as well as MD-RDMD indicated higher differences between groups in math tasks addressing symbolic verbal-auditory and symbolic visual processing compared to math tasks addressing non-symbolic approximate processing. Moreover, for group comparisons of MD-RDMD, the “exclusion of children with ADHD” decreased effect sizes in math outcomes. Furthermore, the consideration of the “IQ discrepancy criterion” to classify children with MD increased group differences of C-MD.

Overall and Moderator Effects for Reading Outcomes

Similar to math outcomes, the overall effect sizes of group comparisons in reading outcomes (cf. Table 5) for C-RD (0.51), C-MD (0.15), and C-RDMD (0.69) pointed to an additive effect for the cognitive profile of children with RDMD. Again, these three effects differed significantly from each other (all $p<0.01$), suggesting that the comorbid group was more strongly impaired than the RD and MD group in reading

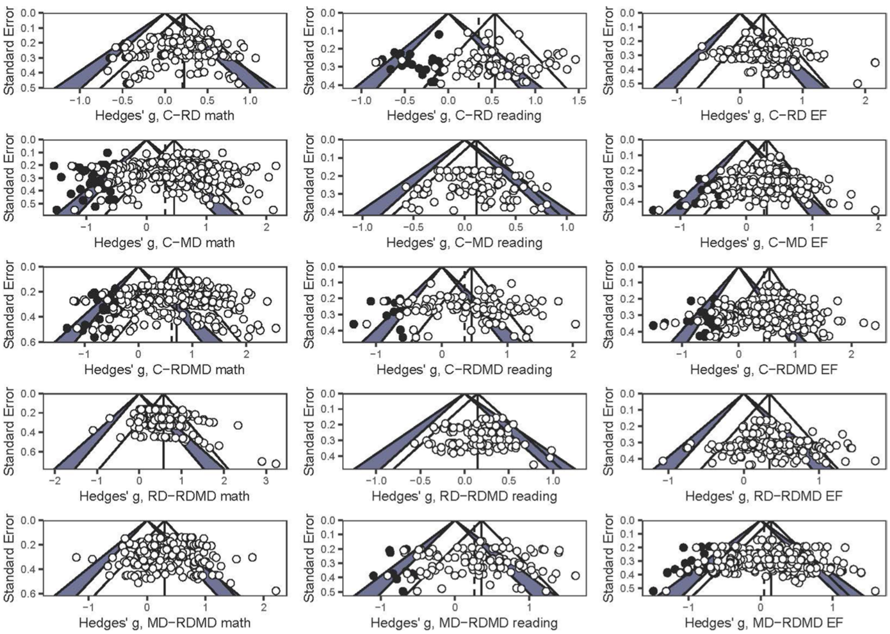

Fig. 2 Funnel plots under use of the trim and fill method for group comparisons in math, reading, and executive function outcomes. White dots indicate observed effect sizes; black dots indicate imputed missing effect sizes. RD, reading learning difficulties; MD, math learning difficulties; RDMD, combined learning difficulties in math and reading; C, control

outcomes. Moreover, the RD group showed larger deficits in reading outcomes than the MD group. However, we found that RD and RDMD groups did not differ significantly in RAN ($p = 0.69$) and reading skills ($p = 0.83$). The latter result can be explained in terms of the small number of studies on which it is based.

In comparing children with RD to those without (C-RD, C-RDMD, MD-RDMD), effect sizes increased hierarchically for the order of the following factor levels: RAN < language skills < phonological processing < reading. Deficits of children with RD or RDMD were mostly pronounced in general reading tasks. For group comparisons of C-MD, the sequence of phonological processing and reading was the other way around (RAN < language skills < reading < phonological processing). This finding suggests that children with MD struggle more in phonological processing than in general reading tasks. Besides these findings, post hoc testing also revealed a decrease of group differences in C-RD when children with ADHD were excluded.

Overall and Moderator Effects for Executive Function Outcomes

Finally, overall effect sizes of group comparisons for executive function skills (Table 6) again suggested additivity (C-RD = 0.35; C-MD = 0.40; C-RDMD = 0.71). Two of these three effects differed significantly from each other: the comorbid group was significantly more impaired than both the MD and RD group (both $p < 0.01$). However,

Table 4 Overall and moderator effects for math outcomes

Effect	C-RD ES	C-RD p	C-RD LB	C-RD UB	C-RD m	C-RD k	C-RD N	C-MD ES	C-MD p	C-MD LB	C-MD UB	C-MD m	C-MD k	C-MD N
Overall effect	.27	<.001	.20	.35	22	175	2674	.64	<.001	.52	.76	31	229	3180
Sample-specific moderators														
Year of publication	.05	.16	−.02	.12	22	175	2674	.01	.87	−.12	.14	31	229	3180
Age	.00	.75	−.01	.01	13	129	1750	.01	.10	−.00	.02	20	180	2104
IQ discrepancy criterion														
No	.27a	<.001	.18	.35	19	149	2411	.60a	<.001	.48	.71	28	203	2911
Yes	.32a	<.001	.11	.53	3	26	263	1.01b	<.001	.66	1.37	3	26	269
IQ difference	.01	.58	−.02	.03	10	87	705	.01	.51	−.02	.03	15	134	1226
Classification percentile rank														
1–10	.62a	<.01	.24	1.00	2	3	129	.41a	.04	.03	.80	3	16	189
11–25	.31a	<.001	.21	.41	11	97	1756	.65a	<.001	.49	.80	15	97	1954
>25	.14a	.04	.00	.29	6	50	568	.41a	<.001	.17	.65	6	50	588
ADHD excluded														
No	.29a	<.001	.18	.39	13	84	1640	.58a	<.001	.42	.74	19	120	2110
Yes	.26a	<.001	.14	.37	9	91	1097	.73a	<.001	.53	.92	12	109	1070
SES difference	.02	.08	−.00	.04	8	54	989	−.00	.85	−.01	.01	9	62	1236
Task-specific moderators														
Math screening content														
Arithmetic	.32a	<.001	.21	.43	11	86	1155	.68a	<.001	.52	.83	18	132	1707
Mixed (e.g., word problems, geometry)	.23a	<.001	.12	.34	11	89	1519	.54a	<.001	.35	.72	12	95	1427
Math screening type														
Power test	.24a	.01	.05	.42	5	34	282	.58a	<.001	.34	.81	8	56	447
Speeded test	.17a	.06	−.01	.35	5	33	334	.44a	<.001	.16	.72	6	36	392
Time-limit test	.37a	<.001	.23	.44	11	97	1704	.70a	<.001	.54	.86	15	131	2170
Math outcome category														
Non-symbolic approximate magnitude processing	.18a	<.001	.08	.29	15	35	1585	.53a	<.001	.38	.67	20	50	1980
Symbolic verbal-auditory processing	.29a	<.001	.21	.38	15	82	1978	.62a	<.001	.49	.75	19	101	2358
Symbolic visual processing	.29a	<.001	.20	.39	13	56	1327	.66a	<.001	.52	.80	18	74	1357

Table 4 (continued)

	C-RDMD							RD-RDMD						
Effect	ES	*p*	LB	UB	*m*	*k*	*N*	ES	*p*	LB	UB	*m*	*k*	*N*
Overall effect	.84	< .001	.69	1.00	32	243	3632	.53	< .001	.36	.71	22	175	1661
Sample-specific moderators														
Year of publication	− .13	.10	− .28	.03	32	243	3632	− .17	< .05	− .31	− .04	22	175	1661
Age	.01	.15	− .00	.02	20	183	2233	.01	.21	− .00	.02	13	129	1079
IQ discrepancy criterion														
No	.82a	< .001	.69	1.00	29	217	3315	.52a	< .001	.33	.71	19	149	1431
Yes	.91a	< .001	.40	1.43	3	26	317	.59a	< .05	.11	1.06	3	26	230
IQ difference	.01	.44	− .02	.04	16	140	1376	.03	.19	− .01	.07	10	87	323
Classification percentile rank														
1–10	.51a	.22	− .31	1.33	2	3	98	− .02a	.93	− .77	.71	2	3	86
11–25	.94a	< .001	.70	1.17	15	113	2159	.52a	< .001	.27	.77	11	97	811
> 25	.69a	< .001	.35	1.03	7	55	756	.64a	< .001	.29	.99	6	50	507
ADHD excluded														
No	.88a	< .001	.69	1.08	21	137	2494	.59a	< .001	.36	.83	13	84	991
Yes	.77a	< .001	.51	1.04	11	106	1206	.45a	< .001	.19	.72	9	91	670
SES difference	.03	< .001	.01	.04	10	67	1419	− .02	.50	− .08	.04	8	54	1042
Task-specific moderators														
Math screening content														
Arithmetic	.76a	< .001	.55	.96	18	135	1841	.42a	< .001	.18	.67	11	86	783
Mixed (e.g., word problems, geometry)	.92a	< .001	.68	1.15	13	106	1745	.64a	< .001	.40	.89	11	89	878
Math screening type														
Power test	.89a	< .001	.62	1.17	8	56	413	.64a	< .001	.39	.88	5	34	219
Speeded test	.43a	< .05	.08	.79	5	33	345	.25a	< .05	.02	.49	5	33	259
Time-limit test	.82a	< .001	.64	1.01	16	137	2362	.54a	< .001	.40	.69	11	97	1122
Math outcome category														
Non-symbolic approximate magnitude processing	.58a	< .001	.40	.77	19	49	1920	.42a	< .001	.24	.61	15	35	1144
Symbolic verbal-auditory processing	.90b	< .001	.74	1.06	20	110	2703	.58a	< .001	.41	.75	15	82	1285
Symbolic visual processing	.86b	< .001	.69	1.04	19	80	1842	.56a	< .001	.38	.74	13	56	940

Table 4 (continued)

Effect	ES	p	MD-RDMD LB	UB	m	k	N
Overall effect	.24	< .001	.16	.32	37	271	2892
Sample-specific moderators							
Year of publication	− .04	.30	− .12	.04	37	271	2892
Age	.00	.26	− .00	.01	24	198	1857
IQ discrepancy criterion							
No	.26a	< .001	.18	.34	34	245	2662
Yes	.02a	.90	− .25	.28	3	26	230
IQ difference	− .00	.91	− .02	.02	21	162	800
Classification percentile rank							
1–10	.10a	.55	− .24	.44	3	10	225
11–25	.26a	< .001	.14	.38	17	122	1359
> 25	.32a	< .001	.16	.49	8	61	790
ADHD excluded							
No	.31a	< .001	.23	.40	25	158	2007
Yes	.10b	.09	− .02	.22	12	113	885
SES difference	− .01	.45	− .02	.01	15	88	1628
Task-specific moderators							
Math screening content							
Arithmetic	.23a	< .001	.12	.34	22	156	1728
Mixed (e.g., word problems, geometry)	.28a	< .001	.14	.42	13	106	1007
Math screening type							
Power test	.38a	< .001	.21	.55	9	64	437
Speeded test	.18a	.08	− .03	.40	6	39	299

Table 4 (continued)

Time-limit test	.18a	< .01	.07	.29	18	144	1861
Math outcome category							
Non-symbolic approximate magnitude processing	.15a	< .05	.03	.26	20	55	1374
Symbolic verbal-auditory processing	.31b	< .001	.21	.40	23	116	2111
Symbolic visual processing	.24a,b	< .001	.14	.34	22	90	1666

Notes. *ES*, effect size estimator of Hedges' *g*; *p*, *p*-value of significance; *LB*, lower bound of confidence interval; *UB*, upper bound of confidence interval; *m*, number of studies included; *k*, numbers of included effect sizes of individual studies; *N*, overall sample size; *MD*, math learning difficulties; *RD*, reading learning difficulties; *MD/RD*, combined learning difficulties in math and reading; *C*, control. All post hoc comparisons between factor levels (indicated by subscripts) were based on Tukey's HSD with adjusted *p*-values based on the Holm procedure. Different subscripts point to significant differences between respective factor levels

Table 5 Overall and moderator effects for reading outcomes

	C-RD							*C-MD*						
Effect	ES	*p*	LB	UB	*m*	*k*	*N*	ES	*p*	LB	UB	*m*	*k*	*N*
Overall effect	.51	< .001	.38	.65	20	88	1930	.15	< .01	.06	.25	21	90	2127
Sample-specific moderators														
Year of publication	− .00	.94	− .15	.14	20	88	1930	− .06	.22	− .17	.04	21	90	2127
Age	.00	.95	− .01	.01	17	80	1751	− .00	.30	− .01	.00	17	80	1726
IQ discrepancy criterion														
No	.52a	< .001	.38	.66	19	85	1888	.15a	< .01	.05	.25	20	87	2093
Yes	.47a	.16	− .19	1.12	1	3	42	.19a	.49	− .36	.74	1	3	34
IQ difference	.04	.15	− .02	.09	13	48	778	.01	.16	− .00	.03	13	48	838
Classification percentile rank														
1–10	.45a	.02	.06	.84	3	9	202	.16a	.23	− .11	.43	3	9	199
11–25	.55a	< .001	.36	.74	11	51	1408	.10a	.09	− .02	.22	12	53	1573
> 25	.46a	< .01	.12	.81	3	22	189	.24a	.04	.01	.47	3	22	216
ADHD excluded														
No	.69a	< .001	.54	.85	10	44	1000	.19a	< .01	.05	.32	11	46	1285
Yes	.35b	< .001	.19	.50	10	44	930	.12a	.10	− .02	.26	10	44	842
SES difference	.02	.15	− .01	.04	4	7	585	.06	.11	− .02	.15	4	7	617
Task-specific moderators														
Reading screening content														
Word reading accuracy	.62a	< .001	.40	.84	7	33	812	.13a	.17	− .06	.32	7	33	869
Word reading fluency	.54a	< .001	.33	.75	7	36	741	.18a	< .05	.00	.35	7	36	702
Word reading accuracy and fluency	.37a	.01	.08	.66	4	15	227	.18a	.11	− .04	.40	5	17	408
Reading comprehension	.29a	.22	− .18	.76	2	4	150	.05a	.79	− .33	.43	2	4	148
Reading outcome category														
RAN	.39a	< .001	.22	.57	13	45	1247	.09a	.13	− .03	.21	14	47	1542
Phonological processing	.70b	< .001	.51	.90	11	23	1459	.27b	< .01	.14	.40	11	23	1445
Language skills	.43a,b	< .01	.14	.72	6	13	645	.14a,b	.23	− .09	.36	6	13	529
Reading	.99c	< .001	.57	1.32	2	7	136	.24a,b	.02	.05	.44	2	7	165

Table 5 (continued)

	C-RDMD							RD-RDMD						
Effect	ES	*p*	LB	UB	*m*	*k*	*N*	ES	*p*	LB	UB	*m*	*k*	*N*
Overall effect	.69	< .001	.55	.83	21	90	2137	.17	< .001	.10	.25	22	99	1344
Sample-specific moderators														
Year of publication	– .02	.81	– .17	.13	21	90	2137	.01	.78	– .06	.08	22	99	1344
Age	.01	.35	– .01	.02	17	80	1759	.00	.39	– .00	.01	18	85	541
IQ discrepancy criterion														
No	.68a	< .001	.53	.82	20	87	2105	.18a	< .001	.09	.26	20	91	1251
Yes	.93a	.02	.16	1.69	1	3	32	.19a	.17	– .08	.45	2	8	93
IQ difference	.01	.34	– .02	.05	13	48	851	.01	.64	– .02	.04	13	48	338
Classification percentile rank														
1–10	.60a	< .01	.20	.99	3	9	202	.10a	.43	– .15	.35	3	9	120
11–25	.72a	< .001	.54	.90	12	53	1594	.19a	< .001	.10	.28	14	61	1109
> 25	.49a	< .01	.18	.81	3	22	210	.04a	.74	– .18	.26	2	19	67
ADHD excluded														
No	.80a	< .001	.61	.98	11	46	1252	.16a	< .01	.06	.26	12	55	767
Yes	.56a	< .001	.37	.75	10	44	885	.20a	< .01	.08	.31	10	44	577
SES difference	.02	.50	– .04	.07	4	7	616	– .00	.85	– .06	.05	4	7	616
Task-specific moderators														
Reading screening content														
Word reading accuracy	.71a	< .001	.47	.96	7	33	857	.12a	.06	– .01	.25	8	38	474
Word reading fluency	.77a	< .001	.54	1.00	7	36	682	.23a	< .01	.09	.37	7	36	437
Word reading accuracy and fluency	.51a	< .001	.22	.81	5	17	438	.15a	.06	– .00	.30	5	21	327
Reading comprehension	.65a	.02	.12	1.18	2	4	160	.32a	.06	– .01	.65	2	4	106
Reading outcome category														

Table 5 (continued)

RAN	.47a	<.001	.28	.66	14	47	1501	.08a	.10	−.02	.18	14	49	844
Phonological processing	1.08b	<.001	.87	1.30	11	23	1451	.31b	<.001	.18	.43	11	23	806
Language skills	.71a,b	<.001	.39	1.03	6	13	577	.24a,b	.02	.05	.43	6	13	394
Reading	1.15b	<.001	.81	1.49	2	7	151	.23a,b	<.01	.07	.39	4	14	286
			MD-RDMD											
Effect	ES	*p*	LB	UB	*m*	*k*	*N*							
Overall effect	.54	<.001	.39	.68	21	90	1216							
Sample-specific moderators														
Year of publication	.02	.81	−.13	.18	21	90	1216							
Age	.01	.22	−.00	.02	17	80	1005							
IQ discrepancy criterion														
No	.53a	<.001	.38	.68	20	87	1196							
Yes	.73a	.07	−.06	1.51	1	3	20							
IQ difference	.02	.46	−.04	.08	13	48	338							
Classification percentile rank														
1–10	.44a	.03	.04	.84	3	9	117							
11–25	.61a	<.001	.43	.78	14	57	924							
>25	.19a	.32	−.19	.58	2	19	94							
ADHD excluded														
No	.62a	<.001	.43	.82	11	46	727							
Yes	.44a	<.001	.23	.64	10	44	489							
SES difference	−.03	.25	−.09	.03	4	7	616							
Task-specific moderators														
Reading screening content														
Word reading accuracy	.60a	<.001	.34	.86	7	33	466							
Word reading fluency	.59a	<.001	.35	.84	7	36	398							

Table 5 (continued)

Word reading accuracy and fluency	.35a	.03	.04	.65	5	17	248
Reading comprehension	.57a	.04	.03	1.11	2	4	104
Reading outcome category							
RAN	.39a	< .001	.22	.56	14	47	879
Phonological processing	.78b	< .001	.58	.97	11	23	792
Language skills	.55a,b	< .001	.24	.86	6	13	278
Reading	.94b	< .001	.64	1.24	2	7	136

Notes. *ES*, effect size estimator of Hedges' *g*; *p*, *p*-value of significance; *LB*, lower bound of confidence interval; *UB*, upper bound of confidence interval; *m*, number of studies included; *k*, numbers of included effect sizes of individual studies; *N*, overall sample size; *RD*, reading learning difficulties; *MD*, math learning difficulties; *RDMD*, combined learning difficulties in math and reading; *C*, control. All post hoc comparisons between factor levels (indicated by subscripts) were based on Tukey's HSD with adjusted *p*-values based on the Holm procedure. Different subscripts point to significant differences between respective factor levels

MD and RD groups did not significantly differ from each other ($p=0.66$), suggesting similar overall EF deficits in the isolated LD groups. At the level of EF outcome categories, the comorbid group differed from the MD group and the RD group in all EF categories except attention (attention: $p=0.31$ and $p=0.43$, respectively).

Post hoc testing of moderator analyses provided evidence for the specific role of "type of executive function outcome" for C-RDMD. Effect sizes of different factor levels indicated that children with RDMD seem to struggle more in working memory processes and processing speed than in attention, but displayed the strongest impairment in processing speed. Moreover, higher percentile ranks for the classification of groups seemed to increase the differences between RD-RDMD in EF outcomes.

Testing the Linear Hypothesis

Overall results (Table 7) provided evidence for an additive effect for the cognitive profile of RDMD in math, reading, and executive function skills, respectively. However, this result seemed to be less clear-cut for EF ($p=0.06$) than for math or reading. This becomes clear when focusing on outcome-specific results for EF: in inhibition, shifting, and updating, profiles of children with comorbid RD and MD were clearly under-additive ($g_{Add}=0.22$, $p<0.01$), implying that children with RDMD were less impaired in inhibition, shifting, and updating than expected in the case of additivity (Table 7). Testing effects of potential moderators of additivity did not provide any notable results. Specifically, when taking age into account, a negligible effect of under-additivity in math emerged ($g_{Add}=0.16$, $p=0.04$), whereas a small effect of over-additivity in math was detected when taking SES into account ($g_{Add}=-0.28$, $p=0.05$). Furthermore, concerning EF, a negligible effect of under-additivity was found when taking publication year into account ($g_{Add}=0.11$, $p=0.04$). All other results at the outcome level support the notion of additivity, albeit at times with substantial uncertainty due to small sample sizes.

Furthermore, we investigated whether additivity was given from a practical point of view by checking whether g_{Add} deviated from zero, using equivalence testing (Lakens, 2017). We determined a small effect ($g_{Add}=0.20, -g_{Add}=-0.20$) as the smallest effect size of interest (SESOI), indicating that practical additivity was present in the case of absolute values were smaller than 0.20 ($|g_{Add}|<0.20$). Statistically, we investigated whether the 90% confidence intervals included or exceeded the SESOI (0.20, −0.20; Lakens, 2017). We found 90% confidence intervals of g_{Add} for math [−0.08, 0.16], reading [−0.10, 0.13], and EF [0.01, 0.19] all within the acceptable SESOI range for equivalence, supporting the notion that at the overall level, additivity was present in math, reading, and EF.

Discussion

The key goal of the present meta-analysis was to answer the question whether the cognitive profiles of children with comorbid RDMD show additive or rather interactive effects (over- or under-additivity; cf. Landerl et al., 2009) of isolated RD and

Table 6 Overall and moderator effects for executive function outcomes

	C-RD							*C-MD*						
Effect	ES	*p*	LB	UB	*m*	*k*	*N*	ES	*p*	LB	UB	*m*	*k*	*N*
Overall effect	.35	< .001	.25	.45	30	189	2262	.40	< .001	.33	.47	35	214	3590
Sample-specific moderators														
Year of publication	−.05	.31	−.14	.04	30	189	2262	−.06	.12	−.13	.01	35	214	3590
Age	.00	.87	−.01	.01	26	173	2010	.00	.17	−.00	.01	30	194	3102
IQ discrepancy criterion														
No	.35a	< .001	.24	.46	26	159	1939	.40a	< .001	.32	.47	31	184	3274
Yes	.34a	.02	.06	.61	4	30	323	.44a	< .001	.24	.64	4	30	316
IQ difference	.02	.22	−.01	.04	20	107	1101	.01	.12	−.00	.03	23	127	2139
Classification percentile rank														
1–10	.34a	< .01	.11	.56	4	18	289	.38a	< .001	.19	.57	4	18	295
11–25	.34a	< .001	.21	.47	13	77	1269	.40a	< .001	.30	.50	18	99	2556
> 25	.44a	< .001	.20	.69	5	44	238	.40a	< .001	.18	.62	5	44	269
ADHD excluded														
No	.34a	< .001	.19	.48	16	84	1265	.40a	< .001	.31	.49	20	106	2594
Yes	.36a	< .001	.21	.50	14	105	902	.40a	< .001	.30	.51	15	108	996
SES difference	.01	.80	−.05	.06	6	26	661	.01	.80	−.06	.07	5	18	641
Task-specific moderators														
EF outcome category														
Inhibition, shifting, and updating	.39a	< .001	.27	.50	22	87	3118	.39a	< .001	.31	.47	27	98	3118
Working memory	.33a	< .001	.21	.44	24	81	2781	.40a	< .001	.32	.48	28	95	2781
Processing speed	.41a	< .001	.22	.61	8	13	1171	.43a	< .001	.29	.57	8	13	1171
Attention	.08a	.52	−.18	.34	5	8	337	.44a	< .001	.22	.66	5	8	337
	C-RDMD							*RD-RDMD*						
Effect	ES	*p*	LB	UB	*m*	*k*	*N*	ES	*p*	LB	UB	*m*	*k*	*N*
Overall effect	.71	< .001	.61	.82	37	238	3712	.32	< .001	.24	.41	30	189	1519

Table 6 (continued)

Sample-specific moderators														
Year of publication	−.10	.04	−.20	−.01	37	238	3712	−.03	.41	−.11	.04	30	189	1519
Age	.00	.41	−.00	.01	32	218	3254	.00	.42	−.00	.01	26	173	624
IQ discrepancy criterion														
No	.70a	< .001	.58	.81	33	208	3345	.29a	< .001	.20	.37	26	159	1245
Yes	.86a	< .001	.54	1.19	4	30	367	.49a	< .001	.29	.70	4	30	274
IQ difference	.01	.16	−.01	.03	24	132	2164	.02	.20	−.01	.05	19	102	443
Classification percentile rank														
1–10	.84a	< .001	.57	1.11	4	18	268	.07a	.48	−.14	.29	4	18	177
11–25	.63a	< .001	.46	.80	17	98	2476	.35b	< .001	.24	.47	16	88	876
> 25	.75a	< .001	.41	1.09	5	44	288	.14a,b	.22	−.09	.38	4	43	138
ADHD excluded														
No	.76a	< .001	.62	.90	22	123	2614	.36a	< .001	.24	.48	16	84	812
Yes	.65a	< .001	.49	.81	15	115	1098	.28a	< .001	.16	.40	14	105	707
SES difference	.02	.55	−.04	.08	6	26	695	.02	.45	−.03	.07	5	18	640
Task-specific moderators														
EF outcome category														
Inhibition, shifting, and updating	.70a	< .001	.59	.62	29	109	3224	.28a	< .001	.18	.39	22	87	1134
Working memory	.73a	< .001	.61	.84	31	102	2947	.34a	< .001	.24	.45	24	81	1176
Processing speed	.85a	< .001	.67	1.03	10	18	1299	.42a	< .001	.24	.59	8	13	605
Attention	.31b	.02	.05	.56	6	9	403	.23a	.07	−.03	.48	5	8	213
	MD-RDMD													
Effect	ES	*p*	LB	UB	*m*	*k*	*N*							
Overall effect	.30	< .001	.22	.38	37	241	2107							
Sample-specific moderators														
Year of publication	−.03	.36	−.10	.04	37	241	2107							
Age	−.00	.98	−.01	.01	31	215	1710							

Table 6 (continued)

IQ discrepancy criterion							
No	.29a	< .001	.21	.38	33	211	1840
Yes	.38a	< .01	.14	.62	4	30	267
IQ difference	.02	.10	− .00	.05	24	137	558
Classification percentile rank							
1–10	.19a	.07	− .01	.39	5	24	322
11–25	.33a	< .001	.22	.45	19	107	1084
> 25	.28a	.04	.01	.54	4	43	169
ADHD excluded							
No	.36a	< .001	.26	.46	22	128	1243
Yes	.22a	< .001	.10	.33	15	113	864
SES difference	.00	.86	− .03	.03	5	18	640
Task-specific moderators							
EF outcome category							
Inhibition, shifting, and updating	.32a	< .001	.23	.41	29	107	1737
Working memory	.30a	< .001	.21	.39	31	107	1719
Processing speed	.32a	< .001	.18	.46	10	18	882
Attention	.11a	.34	− .12	.34	6	9	314

Notes. *ES*, effect size estimator of Hedges' *g*; *p*, *p*-value of significance; *LB*, lower bound of confidence interval; *UB*, upper bound of confidence interval; *m*, number of studies included; *k*, numbers of included effect sizes of individual studies; *N*, overall sample size; *RD*, reading learning difficulties; *MD*, math learning difficulties; *RDMD*, combined learning difficulties in math and reading; *C*, control. All post hoc comparisons between factor levels (indicated by subscripts) were based on Tukey's HSD with adjusted *p*-values based on the Holm procedure. Different subscripts point to significant differences between respective factor levels

Table 7 Linear hypothesis testing of additivity

Effect	Est	*p*	LB	UB	*m*	*k*	*N*
Math							
g_{Add}	.04	.58	−.10	.18	33	663	8147
g_{Add} by outcome							
Non-symbolic approximate magnitude processing	.18	.12	−.04	.40	20	134	5078
Symbolic verbal-auditory processing	.01	.91	−.15	.17	20	302	6279
Symbolic visual processing	.10	.38	−.13	.33	20	217	4178
Reading							
g_{Add}	.08	.81	−.12	.16	21	253	5205
g_{Add} by outcome							
RAN	.11	.19	−.05	.26	14	129	3450
Phonological processing	.00	.98	−.30	.31	11	64	3711
Language skills	−.09	.55	−.41	.22	6	39	1587
Reading	−.16	.65	−.89	.58	2	21	495
Executive functions							
g_{Add}	.10	.06	−.01	.20	37	597	6721
g_{Add} by outcome							
Inhibition, shifting, and updating	.22	<.01	.08	.36	29	266	5305
Working memory	−.03	.68	−.54	.48	30	266	4384
Processing speed	−.01	.95	−.37	.35	9	40	3138
Attention	.26	.36	−.73	1.24	6	25	1011

Notes. $g_{Add}=[(C-RD)+(C-MD)]-(C-RDMD)$; *Est.*, estimated effect; *LB*, lower bound of 90% confidence interval; *UB*, upper bound of 90% confidence interval; *m*, number of studies included; *k*, numbers of included effect sizes of individual studies; *N*, overall sample size; groups: *RD*, reading learning difficulties; *MD*, math learning difficulties; *RDMD*, combined learning difficulties in math and reading; *C*, control

MD. Three subcomponents of risk factors were examined in order to better understand the cognitive profiles of co-occurring RDMD: reading-related skills, number processing skills (resp. math-related skills), and EF skills. Results suggest that the cognitive profiles regarding the three subcomponents were similar: Deficits in reading-related skills, number processing skills, and EF in the RDMD group represent the sum of the deficits in the isolated groups (additive profile). However, robustness of results with respect to profile additivity differed across domains, and group differences varied depending on characteristics of screening and outcome tasks. These results are discussed in more detail in the following sections.

Additivity in Math-Related Cognitive Skills

In math tasks, all three LD groups showed impairments in comparison to the control group. In line with our hypothesis, children with MD showed deficits in tasks tapping all modules of number processing (e.g., Moll et al., 2015a) including the verbal code (e.g., Viesel-Nordmeyer & Prado, 2023). In contrast, we expected that children with RD would show deficits in number processing tasks tapping the verbal code (e.g., Simmons & Singleton, 2009). However, results show deficits of children with RD in tasks tapping all modules of number processing, although deficits were less pronounced than in the MD groups.

As expected, the RDMD group showed the largest deficits in all math outcome categories. Compared to MD but also to C, the RDMD group displayed larger deficits in tasks tapping the symbolic verbal and visual code than the non-symbolic code. Consequently, our results emphasized broader problems of children with RDMD processing advanced, more demanding math skills. The latter is in line with a study examining group comparisons of isolated RD and MD, RDMD, and a control group (C) in different areas of math cognition in second graders (Hanich et al., 2001). In this study, children with RDMD performed worse than children with MD in math areas that were related to language processing (story problems, advanced arithmetic) or multiple cognitive processing (exact calculation), but not in approximate arithmetic, place value, or retrieval of number facts.

Interestingly, excluding children with ADHD leads to substantially lower math impairments of RDMD compared to MD. This finding could be explained by the higher risk of the comorbid RDMD group for additional comorbidities, such as ADHD (e.g., Czamara et al., 2013) as compared to isolated LD groups. Finally, larger differences between the C and the MD group when considering the IQ discrepancy criterion are likely to be related to the fact that the discrepancy criterion results in more strongly impaired MD children.

Eventually, linear hypothesis testing for math outcomes revealed no interaction between RD and MD. Therefore, additivity of the cognitive profiles of RD and MD for math-related cognitive skills in children with RDMD was supported.

Additivity in Reading-Related Cognitive Skills

As expected, all three LD groups showed impairments in reading-related tasks compared to the control group. In addition to differences in reading tasks, we analyzed group differences in reading-related tasks such RAN, phonological processing, and language skills. Impairments in phonological processing tasks were not only present in the RD groups (isolated RD and RDMD), but also in isolated MD. This result stands in contrast with some findings from individual studies examining phonological processing skills in group comparisons of children with isolated and combined RD and MD. For example, Peters and colleagues (2020) as well as Landerl and colleagues (2009) could not find any impairments of phonological awareness in individuals with MD. While these findings suggest that phonological awareness is a domain-specific risk factor of RD, two meta-analyses of behavioral studies, examining the relations between phonological processing skills (Yang et al., 2021) or language skills (Peng et al., 2020) and math, reported a strong relation between phonological awareness and math skills. Moreover, a meta-analysis of neuroscientific studies emphasizes substantial functional overlap of arithmetic and phonological processing areas in children's as well as adults' brains (Pollack & Ashby, 2018). Whereas the aforementioned meta-analyses did not directly target children with LD, our meta-analysis supports the view that small impairments in various reading-related skills might be evident in individuals with MD. The low degree of heterogeneity in group comparisons concerning reading in our meta-analysis, indicating small differences between individual studies, further underscores the statistical power of the current study (e.g., Lifeng, 2020). Consequently, the advantage of a meta-analysis to detect even small effect sizes in the research topic of interest can be considered promising. However, at the same time, a possible role of phonological awareness as proxy for broader language skills (e.g., Moll et al., 2015b) which are consistently shown to be a risk factor of MD should be taken into account.

As already reported for mathematics, we did not find strong support for an interaction of RD and MD testing our linear hypothesis. Thus, our results for the group comparisons in reading-related skills point to an additive RDMD profile. This is in line with the majority of findings from individual studies. In these studies, no interaction of RD and MD was reported for reading speed (Peters et al., 2020) as well as RAN (Kißler et al., 2020). To the best of our knowledge, there is just one individual study reporting an interaction of RD and MD for reading comprehension skills (Dirks et al., 2008). The effect size in this study, however, was small.

Finally, when comparing the screening results in the RD group with the unimpaired control group, we found out that effect sizes depend on the presence or absence of co-occurring ADHD in the RD group. Effect sizes between RD and controls were larger when RD co-occurred with ADHD, which is in line with the high comorbidity rates observed between RD and ADHD as well as between RD, MD, and ADHD (e.g., Czamara et al., 2013).

Additivity in Executive Function Skills

As expected, all three LD groups showed impairments in at least some components of EF skills, indicating that EF underlie adequate processing in reading and math skills (e.g., Watson, 2016). Thereby, MD groups seem to be more impaired in EF skills than RD groups. Based on recent individual studies regarding the cognitive profile of children with MD, MD can be seen as a strongly heterogeneous group (e.g., Salvador et al., 2019) with different manifestations. The different manifestations or symptoms of math problems are likely to be related to different cognitive risk factors (e.g., Dehaene, 1992), including various components of EF skills (e.g., Gilmore & Cragg, 2018).

Against our expectations, the MD group was impaired in all considered EF skills. This finding underscored the aforementioned role of various cognitive skills in mathematical processing (e.g., Gilmore & Cragg, 2018). For the RD group, almost the same results were found, with the exception of attention, for which no differences between RD and C could be detected. On the one hand, this finding contrasts with our hypothesis as well as with the results of a previous meta-analysis addressing EF deficit profiles in RD and RDMD (Peng et al., 2013). In this meta-analysis, children with RD only showed impairments in some of the considered EF skills, namely verbal working memory, inhibition, and processing speed. In visual working memory and updating, however, no deficits were shown in children with RD (Peng et al., 2013). On the other hand, the consideration of ADHD in the individual studies leads to decreased differences in EF between the C and RD group. It could be possible that the problems of children with ADHD in learning to read (e.g., Czamara et al., 2013) are not only based on attention problems, but also could be explained by other ADHD-related accompanying symptoms like impaired working memory processing (e.g., Kofler et al., 2019).

In line with the study by Peng and Fuchs (2014) as well as an additional meta-analysis of Peng and colleagues (2013) on working memory in children with LD, we found that children with RDMD were the most impaired group showing deficits in all EF skills with the strongest deficit in processing speed and comparably smaller deficits in attention. These results are in line with findings from a recent study (Raddatz et al., 2017) where processing speed differences in response times (but not accuracy) in a simple reaction time task between RDMD and C could be revealed. Our mentioned result of comparably lower attention problems in children with RDMD as compared to processing speed is mirrored by a similar result in the RD group. This result might be related to a substantial proportion of children with undiagnosed ADHD or attention problems without further learning problems in RD or RDMD (e.g., Mattison & Mayes, 2010) in some primary studies.

Finally, unlike for reading and math skills, testing the linear hypothesis for EF with respect to additivity revealed less robust and clear-cut results. With respect to inhibition, shifting, and updating, under-additivity was found, implying an impairment of RDMD in these specific EF skills which is smaller than expected. This finding contrasts with the result of De Weerdt and colleagues (2013a) who found additivity for the cognitive profile of RDMD, especially for inhibition. Moreover, the result by De Weerdt and colleagues (2013a) regarding the additivity of EF skills in RDMD has been reported in other studies as well (cf., additivity for spatial visualization: Peters et al., 2020; additivity for all three components of working memory: Moll et al., 2015a; Schuchardt et al., 2008). Only one previous study in which RD and MD interact with respect to the central executive was found, but only with small effect sizes (De Weerdt et al., 2013b). However, inhibition, shifting, and updating are subsumed under the umbrella of central executive tasks (e.g., Miyake et al., 2000), and thus bring our results in line with the aforementioned findings of De Weerdt and colleagues (2013b) regarding under-additivity of the central executive in the cognitive profile of RDMD.

Limitations of the Current Meta-analysis

Meta-analyses often encounter the problem of publication bias associated with missing, small, or insignificant effect sizes of smaller studies (e.g., Viechtbauer, 2010). We addressed this problem as soon as possible by conducting a three-level meta-analytic approach (Konstantopoulos, 2011) in order to take heterogeneity at different levels into account. However, heterogeneity was still present and particularly large in math skills, even after outlier adjustment (e.g., Viechtbauer, 2010). Building on theory (e.g., Triple-Code-Modell; Dehaene, 1992) and recent research (e.g., Salvador et al., 2018), we attribute this finding to the diversity of the mathematical domain and the associated diverse cognitive requirements. Even though we used a meta-analytic approach to address the problem of statistical power (e.g., Faul et al., 2007) in additivity hypothesis testing, the included numbers of studies in some sub-calculations was still small. This is especially the case for the simultaneous consideration of all moderators in linear-hypothesis testing, but even when considering them individually. However, the key results of our meta-analysis could be supported by using statistical techniques based on equivalence testing (e.g., Lakens, 2017).

Since most of the included studies are cross-sectional, a correlation of screening and outcome variables cannot be excluded. Given that EF tasks are a key outcome in this study, even with a meta-analytic approach the problem of psychometric adequacy of testing EF (e.g., Manchester et al., 2004) cannot be solved. Whereas ADHD seems to play an important role when investigating the cognitive profile of RDMD, ADHD could only be included as a covariate in this study. Consequently, despite the power of the used multivariate meta-analytic approach, some limitations remain.

Conclusions

Using a meta-analytical approach, our study helped to detect the composition of deficits in the cognitive profile of combined RDMD with respect to cognitive profiles in isolated RD and MD. With this understanding, the way to a more targeted support and prevention is paved. First of all, our study showed that it is particularly important to consider the relation of language and math skills in fostering scholastic skills in children with isolated LD. First intervention approaches considering the specific role of language in math (e.g., Arizmendi et al., 2021) already exist and should be further implemented. In addition, our study underlines that the diversity of math tasks and the different associated cognitive processes (e.g., Dehaene, 1992) should also be taken into account more explicitly. Individual learning support that considers this diversity appears to be extremely beneficial (e.g., Messer et al., 2018). Moreover, such support would meet the high heterogeneity within the MD group, which was found in our study as well as recent research (e.g., Kißler et al., 2021).

Finally, additional possible weaknesses in children such as ADHD, which can promote learning difficulties in reading and math skills as an epiphenomenon, should be considered as soon as the first problems in one of the two domains arise. Learning difficulties are usually multifactorial in their development, and central executive processing is involved in the rise of difficulties in both—reading and math skills.

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Declarations

Data availability Data are available upon request.

Ethical Approval This article does not contain any studies with human participants or animals performed by any of the authors.

Conflict of Interest The authors declare no competing interests.

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