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RESEARCH ARTICLE

Neurocognitive mechanisms of co-occurring math difficulties in dyslexia: Differences in executive function and visuospatial processing

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Abstract

Children with dyslexia frequently also struggle with math. However, studies of reading disability (RD) rarely assess math skill, and the neurocognitive mechanisms underlying co-occurring reading and math disability (RD+MD) are not clear. The current study aimed to identify behavioral and neurocognitive factors associated with co-occurring MD among 86 children with RD. Within this sample, 43% had co-occurring RD+MD and 22% demonstrated a possible vulnerability in math, while 35% had no math difficulties (RD-Only). We investigated whether RD-Only and RD+MD students differed behaviorally in their phonological awareness, reading skills, or executive functions, as well as in the brain mechanisms underlying word reading and visuospatial working memory using functional magnetic resonance imaging (fMRI). The RD+MD group did not differ from RD-Only on behavioral or brain measures of phonological awareness related to speech or print. However, the RD+MD

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[Correction made on 20 September 2023, after first online publication: 'RD > RD+MD' has been removed from the labels in Figure 1 in this version.]

group demonstrated significantly worse working memory and processing speed performance than the RD-Only group. The RD+MD group also exhibited reduced brain activations for visuospatial working memory relative to RD-Only. Exploratory brain-behavior correlations along a broad spectrum of math ability revealed that stronger math skills were associated with greater activation in bilateral visual cortex. These converging neuro-behavioral findings suggest that poor executive functions in general, including differences in visuospatial working memory, are specifically associated with co-occurring MD in the context of RD.

KEYWORDS
executive function, learning disabilities, math, reading, visuospatial processing, working memory

Research Highlights

- Children with reading disabilities (RD) frequently have a co-occurring math disability (MD), but the mechanisms behind this high comorbidity are not well understood.
- We examined differences in phonological awareness, reading skills, and executive function between children with RD only versus co-occurring RD+MD using behavioral and fMRI measures.
- Children with RD only versus RD+MD did not differ in their phonological processing, either behaviorally or in the brain.
- RD+MD was associated with additional behavioral difficulties in working memory, and reduced visual cortex activation during a visuospatial working memory task.

1 | INTRODUCTION

Math and reading difficulties frequently co-occur (Landerl & Moll, 2010; Moll et al., 2019; Willcutt et al., 2013; Wilson et al., 2015), but the mechanisms underlying the convergence of these difficulties remain unclear. This study aimed to identify neurocognitive factors associated with co-occurring reading disability (RD) and math disability (MD). We investigated the extent to which students with RD but without MD (RD-Only) versus students with both RD and MD (RD+MD) differ behaviorally in phonological awareness, reading skills, and executive functions (EFs), as well as in the brain mechanisms underlying word reading and working memory, in order to adjudicate between competing theoretical explanations for RD+MD co-occurrence. This converging brain-behavior approach illuminates the correlates and potential underlying mechanisms of math learning challenges in RD.

1.1 | RD or dyslexia

Reading disabilities are the most frequently diagnosed specific learning disorder, affecting 5%–17% of children (Shaywitz, 1998). *Developmental dyslexia*, the most common RD, is a heritable, life-long difficulty with word reading despite adequate intelligence and education. RD is typically associated with neurocognitive differences in phonological (speech sound) awareness (Hoeft et al., 2006; Kovelman et al., 2012; Shaywitz et al., 1998; Temple et al., 2001). Phonological difficulties may impede children's ability to connect speech sounds to print, decode words, and read fluently. Individuals with RD demonstrate differences throughout the reading system, including left inferior frontal, occipitotemporal, and temporoparietal brain regions (Kronbichler & Kronbichler, 2018; Martinez-Lincoln et al., 2023; Pugh, 2001; Richlan, 2012; van der Mark et al., 2011). RD is also frequently linked to difficulties with rapid automatized naming (RAN) (Norton & Wolf, 2012) and executive functioning (Al Dahhan et al., 2022; Daucourt et al., 2020; Lonergan et al., 2019), as well as perceptual differences (e.g., in visual processing and visuospatial attention; see Kristjánsson & Sigurdardóttir, 2023 for a review).

1.2 | High co- occurrence of RD and MD

RD frequently co-occurs with *developmental dyscalculia* (also known as MD), a specific learning disability in math. Children with MD tend to struggle with arithmetic fact retrieval, which may impede learning more advanced mathematical procedures and efficient problem-solving strategies (Price & Ansari, 2013). MD is also often associated with a deficit in numerical processing or number sense (Landerl et al., 2013; however, also see Mammarella et al., 2021). Studies of the neurobiology of MD have frequently pointed to the intraparietal sulcus as a hub of numerical processing, with reduced activation during math tasks in individuals with MD compared to peers without MD (Ashkenazi et al., 2012, 2013; Martinez-Lincoln et al., 2023; Price et al., 2007).

Although RD and MD are often identified and studied independently, RD+MD co-occurrence is substantially higher than would be expected by chance in the general population (Landerl & Moll, 2010). Children with RD tend to score lower on arithmetic tasks than their typically-developing peers (De Smedt & Boets, 2010; Koerte et al., 2016); a child with MD is more than twice as likely to also have RD than a child with typical math skills (Joyner & Wagner, 2020). This high comorbidity suggests that the etiology of both RD and MD may be at least partially linked to skills or cognitive mechanisms that underlie both disorders.

1.3 | Phonological processing in RD and MD

One theory for high RD+MD co-occurrence points to phonological difficulties in RD as a challenge that also impacts math learning. Although RD is multifaceted and etiologies are not homogeneous (O'Brien & Yeatman, 2021), conceptualizations of RD frequently place poor phonological processing at the center of individuals' challenges in learning to read. Differences in phonological processing may impact learning in other academic domains as well. Math teaching and learning frequently relies on verbal strategies such as rote memorization of small number addition and multiplication. As mental representations of numbers and math facts may be linguistic in nature (De Smedt, 2018; Dehaene, 1992), their rapid retrieval may partially depend on phonological processing (Polspoel et al., 2017). Indeed phonemic awareness is correlated with math fact retrieval skills in children with learning disabilities (Matejko et al., 2022). Phonological challenges in RD may also impede mathematics because of children's reliance on phonological working memory (Simmons & Singleton, 2008; Swanson, 2020).

Phonological processing performance is correlated with early mathematical skills before formal schooling (Vanbinst et al., 2020; Viesel-Nordmeyer et al., 2022) and has been identified as a shared risk factor for both RD and MD in 7—11-year old children (Slot et al., 2016). The relation between phonology and arithmetic is also apparent in older children and adults, behaviorally and in the brain, for typically-developing individuals (De Smedt & Boets, 2010; Evans et al., 2016; Hecht et al., 2001; Pollack & Ashby, 2018; Prado, 2018; Suárez-Pellicioni et al., 2019) and those with RD (Evans et al., 2014; Matejko et al., 2022; Träff et al., 2017). Yet while many children with RD have poor phonological awareness, not all of these children struggle with math. A precise comparison of children with RD-Only versus those with RD+MD may illuminate whether phonological abilities in RD differ across children with and without added math difficulties, and clarify the role of phonological processing in RD+MD co-occurrence.

1.4 | Working memory and executive function in RD and MD

A second conceptualization for high RD+MD co-occurrence is an underlying difficulty with EF that affects both reading and math. EFs are a set of cognitive skills associated with goal-directed behavior, including working memory, processing speed, directed attention, and inhibitory control. In particular, RD+MD comorbidity is associated with poor working memory and processing speed (Willcutt et al., 2013). One possibility is that more severe EF difficulties may result in learning challenges across reading and math domains.

There is some evidence that reading may be more closely related to *phonological* working memory while math may be more closely related to *visuospatial* working memory (Giofrè et al., 2018; Peters et al., 2020; Schuchardt et al., 2008). Poor verbal or phonological short term memory are common in RD (Griffiths & Snowling, 2002), and play a role in early math skill (Viesel-Nordmeyer et al., 2022). Studies with older children often suggest a critical association between visuospatial working memory and arithmetic (Li & Geary, 2013, 2017; Metcalfe et al., 2013), as well as reduced visuospatial working memory in MD (Szucs et al., 2013). Notably, brain regions involved in magnitude representation and visuospatial working memory overlap; functional differences in these areas may contribute to difficulties with working memory as well as math skill (Dumontheil & Klingberg, 2012; Matejko & Ansari, 2021; Menon, 2016; Rotzer et al., 2009). In sum, poor working memory has been linked to both reading and math challenges. Reduced working memory capacity is thus a strong candidate for a domain-general weakness that may underlie RD, MD, and their co-occurrence.

1.5 | Neurocognitive bases of RD+MD

There is limited work to date examining the brain bases of co-occurring RD+MD, particularly in relation to domain-general cognitive processes. A few studies have investigated brain connectivity at rest in association with math ability (Nemmi et al., 2018; Price et al., 2018), reading ability (Cross et al., 2021), or both (Chaddock-Heyman et al., 2018; Chang et al., 2018; Skeide et al., 2018; Westfall et al., 2020). However, little is known about co-occurring math and reading difficulties as they relate to functional or task-related brain activation. A meta-analysis of RD and MD revealed mostly distinct neurocognitive correlates of the two disorders (Martinez-Lincoln et al., 2023); however, nearly all the studies included in this meta-analysis involved one domain-specific task (i.e., reading-related activation for RD samples or math-related activation for MD samples).

One prior study examined the neural correlates of RD+MD by employing a subtraction task with typically developing children and their peers with RD ($N = 19$), MD ($N = 11$) or both ($N = 8$) (Peters et al., 2018). Despite observing expected behavioral differences between groups, there were no neurocognitive differences between RD-Only, MD-Only, and RD+MD participants. How other cognitive mechanisms that may underlie RD+MD co-occurrence, such as phonological processing or working memory, manifest in the brains of children with co-occurring learning difficulties remains largely unknown. Here we examine behavioral and neurocognitive factors in relation to reading and math skills in children with RD-Only as well as RD+MD. The present study aims to better understand potential mechanisms leading to co-occurring math difficulties in RD.

1.6 | Disambiguating theoretical explanations of RD+MD co-occurrence

We investigated two hypotheses and predictions in a sample of 86 children with RD in 3rd–7th grade across a range of math ability. The first hypothesis (H1) posits that RD+MD may be related to underlying phonological difficulties. In support of H1, we predict greater phonological processing difficulties reflected in brain and behavior data among students with more severe math challenges. The second hypothesis (H2) posits that difficulties with EF increase the risk of co-occurring RD and MD. In support of H2, we predict greater behavioral EF difficulties among students with more severe math challenges. We also predict differences between children with RD-Only as compared to those with RD+MD in the neurocognitive processes underlying EF as measured through visuospatial working memory. Because visuospatial working memory does not inherently rely on language or print-related processes, it is a promising lens through which to dissociate language-based versus EF mechanisms underlying RD+MD co-occurrence.

We tested these hypotheses with two complementary approaches: first, a direct categorical comparison between students with RD-Only versus RD+MD, and second, a continuous analysis across a spectrum of math ability. This second approach included children with RD whose math performance fell between categorical criteria ("Other," see *Participant Group Assignment* below). We conducted whole-brain analyses to investigate the possibility of differences throughout the brain, as well as post hoc region of interest (ROI) analyses within brain regions associated with reading and working memory processes.

2 | MATERIALS AND METHODS

Eighty-six children in 3rd–7th grade (*M* age = 11.31, SD = 0.82, 43 boys/43 girls) participated in this study. Participation was restricted to English speaking children with nonverbal cognitive ability in or above the typical developmental range (standard score $\geq$ 80) and without neurological disorders. All participants were classified as having RD according to at least one of the two following criteria: the child scored below the typical range (standard score <85) on at least two of four standardized word reading measures, or their guardian indicated that the child had a current diagnosis of RD. Forty-four (51%) participants met both criteria; 16 (19%) met the testing criteria only; and 26 (30%) had an RD diagnosis, but performed in the typical range on three or more word reading tasks on the day of testing. Participants were classified as having MD if they performed below the typical range (standard score <85) on at least two of four standardized math measures (see below for more detail). Prior ADHD diagnosis was not grounds for exclusion, given the high prevalence of comorbid dyslexia and ADHD (Carroll et al., 2005; Willcutt et al., 2010).

Participation involved two sessions for behavioral testing and fMRI neuroimaging. Legal guardians provided written consent and participants completed assent forms. Guardians also completed a comprehensive survey detailing their child's development and history of learning difficulties, as well as the Barratt Simplified Measure of Social Status (Barratt, 2006), which quantifies socioeconomic status ranging from 8 to 66 using the average of maternal occupation and education. This research was approved by the Committee on the Use of Humans as Experimental Subjects at the Massachusetts Institute of Technology.

2.1 | Behavioral assessments

2.1.1 | Nonverbal cognition

Cognitive ability was assessed using the Kaufman Brief Intelligence Test (KBIT-2; Kaufman & Kaufman, 2004) Matrices subtest. Inclusion was limited to participants with a standard score greater than 80.

2.1.2 | Single word reading

Untimed single word reading and pseudoword decoding skills were assessed with the Word Identification and Word Attack subtests of the Woodcock Reading Mastery Tests (WRMT-III; Woodcock, 2011), comprising the Basic Reading Skills cluster. Timed single word reading and pseudoword decoding skills were assessed with the Sight Word Efficiency (SWE) and Phonemic Decoding Efficiency (PDE) subtests from the Test of Word Reading Efficiency (TOWRE-2; Torgesen et al., 2012), comprising the Total Word Reading Efficiency composite.

2.1.3 | Other reading and reading-related skills

Reading comprehension was assessed using the WRMT-III Passage Comprehension subtest (Woodcock, 2011). Participants also completed standardized assessments of RAN (Letters subtest of RAN/RAS; Wolf & Denckla, 2005) and phonological awareness (Elision subtest of the Comprehensive Test of Phonological Processing; Wagner et al., 2013).

2.1.4 | Mathematics

Participants completed individual, 1-minute tests of addition, subtraction and multiplication, comprising the Math Fluency composite of the Wechsler Individual Achievement Test (WIAT-III; Wechsler, 2009). Timed arithmetic fluency was also measured using the Math Fluency subtest of the Woodcock Johnson (WJ-IV; Schrank et al., 2014). Math calculation skills were assessed using the WJ-IV Calculation subtest, which is an untimed test of calculation problems ranging from single-digit arithmetic through calculus, and the WJ-IV Applied Problems subtest, in which children solve mathematics word problems. The WJ-IV Math Fluency and Calculation subtests comprise the Math Calculation Skills cluster.

2.1.5 | Executive functions (EFs)

The present study measured three components of EF. Processing speed was assessed using the Coding and Symbol Search subtests of the Wechsler Intelligence Scale for Children (WISC-IV; Wechsler, 2003); these two subtests make up the Processing Speed composite. Phonological working memory was assessed using the Digit Span and Letter-Number Sequencing subtests of the WISC-IV; these subtests make up the Auditory Working Memory Index (AWMI). Finally, participants completed the Spatial Span task from the Cambridge Neuropsychological Test Automated Battery (CANTAB; Cambridge Cognition). This touch-screen based measure presents participants with a group of boxes, and asks them to tap boxes to determine whether or not each is hiding a "token," using a process of elimination. Participants must remember which boxes have already held a hidden token in order to search efficiently across trials of four, six, or eight boxes. We present data on participants' spatial working memory span (higher numbers represent greater capacity), and search errors (higher numbers indicate *less* strategic task performance, in which participants revisit boxes searched previously).

2.2 | Participant group assignment

Participants were classified into one of three groups: reading difficulties only (RD-Only; $N = 30$), co-occurring math and reading difficulties (RD+MD; $N = 37$), and "Other" ($N = 19$, details below). All participants met the criteria for RD: either two or more standardized word reading measures below the typical developmental range (standard scores <85 on TOWRE-2 PDE and SWE, WRMT-III Word Identification and/or Word Attack), and/or a current diagnosis of RD as indicated by a parent or guardian.

Participants in the RD-Only Group scored in the typical range (standard score ≥ 85) on all four math assessments. Within this group, no parents or guardians reported that their child had ever been diagnosed with MD or a learning disability in math. Participants in the RD+MD Group scored at least one standard deviation below the mean (standard score <85) on at least two of the four standardized math assessments (WIAT-III Math Fluency Composite, and WJ-IV Math Fluency, Calculation, and Applied Problems). Of these participants with RD+MD, 17 had been previously diagnosed with dyscalculia or a specific math learning disability.

Finally, 19 children were classified in the Other Group, either because they scored <85 on only one math assessment, indicating a possible vulnerability in math ($N = 13$), or due to incomplete math data ($N = 6$). Specifically, three participants had standard scores between 70–80 on a single math measure, but were missing data from other math task(s) and therefore could not be evaluated for the MD criteria (2+ standard scores <85). Three additional children in the Other category clearly met the criteria for RD, and scored in the typical range on one math assessment, but were missing data from the other three math measures.

2.3 | FMRI tasks

2.3.1 | Phonological word reading task

Participants completed a visual phonological awareness task in which they read two words and made a rhyme judgment (e.g., "bear—chair" = yes, "crate—train" = no). Rhyming words had rime patterns with different spellings (e.g., "metal," "kettle"). Word rhyming was compared to a control condition of face-matching judgements (see Supplement and Al Dahhan et al., 2022 for additional details). All analyses were conducted with the Word Reading > Face Matching contrast.

2.3.2 | Visuospatial working memory task

To isolate networks involved in visuospatial working memory (VSWM), children completed an adapted dot matrix task (Klingberg et al., 2002) in which a sequence of circles appeared on a 4 × 4 grid. This task consisted of two VSWM conditions, in which participants were instructed to remember the locations of the circles, and two control conditions (see Supplementary Material). All analyses were conducted with the VSWM > Control contrast.

2.4 | MRI image acquisition and preprocessing

All images were acquired using a 3T Siemens Prisma Fit scanner. Participants wore a standard 32-channel head coil. A T1-weighted (T1w) image was acquired with the following parameters: TR = 2.53s, TE = 1.69 ms, flip angle = 7°, voxel size = 1 mm isotropic. All BOLD images were acquired with the following parameters: TR = 2s, TE = 30 ms, flip angle = 90°, voxel size = 3 × 3 × 3.6 mm. Preprocessing and resampling to MNI152NLin6Asym space with 2 mm isotropic voxels were performed by fMRIPrep 21.0.2 (Esteban et al., 2019 ; RRID:SCR_016216), which is based on Nipype 1.6.1 (K. Gorgolewski et al., 2011; K. J. Gorgolewski et al., 2018; RRID:SCR_002502). fMRIPrep generates detailed descriptions of data processing distributed under a Creative Commons license, which are available in the Supplementary Material.

2.4.1 | Inclusion criteria

Sixty children (out of 86) completed one or more functional tasks. Individual task runs were excluded due to motion (<30% of frames annotated as motion outliers), leaving 52 potentially usable runs/participants for each task. Data were then visually inspected to ensure that the full cortex was captured within the bounding box. Some participants who were fully within the bounding box during the VSWM task slid down in the scanner over the course of the scanning session, resulting in a phonological word reading scan that failed to capture some ventral regions. This visual quality check thus identified usable word rhyming task data from 44 participants ($N = 18$ RD-Only, $N = 18$, RD+MD, $N = 8$ Other); and visuospatial working memory data from 52 participants ($N = 20$ RD-Only, $N = 21$ RD+MD, $N = 11$ Other).

2.4.2 | Modeling and statistics

First-level models were run with FitLins 0.10.1 (https://github.com/poldracklab/fitlins). We convolved task timing blocks with the canonical hemodynamic response function provided by SPM. For each subject and task, we ran general linear models to predict magnitudes of BOLD activation from the convolved task blocks. Our covariates included translation and rotation head motion parameters, their temporal derivatives, squared expansion terms, and enough ACompCor components to explain 50% of variance within a combined white matter/cerebrospinal fluid mask (Behzadi et al., 2007). Discrete-cosine transformation regressors acted as high-pass filters (128 s). We computed subject-level effect size maps for the task contrast of interest, which were the basis of our second-level group-wise and correlation analyses conducted in Nilearn version 0.9.1. Two-sample *t*-tests comparing RD-Only and RD+MD Groups did not include any subject-level covariates, as groups did not differ by age, sex, socioeconomic status, task accuracy, task reaction time, or framewise displacement. All reported group comparisons are thresholded at an FDR corrected $p < 0.05$, and exploratory whole-brain correlation analyses are thresholded at an uncorrected $p < 0.001$.

Post-hoc Bayesian analyses were conducted in independent regions of interest identified by a meta-analysis of reading-related activation in children (Martin et al., 2015) and working memory-related activation in children (Yaple & Arsalidou, 2018). We extracted mean statistical values from 6 mm spheres drawn around each set of MNI coordinates using 3dROIstat in AFNI (Cox, 1996). These values were then used in both frequentist and Bayesian independent sample *t*-tests and correlations to establish evidence for the alternative hypothesis versus the null hypothesis. These analyses were conducted using the “jsq” module in *jamovi* software version 2.3.26.0 (The Jamovi Project, 2023) with the default Cauchy prior of 0.707.

3 | RESULTS

Descriptive statistics across all variables used for study inclusion and group classification are presented in Table 1. Participant demographics are presented in Table 2.

TABLE 1 Performance on standardized assessments across all participants.

	N	*M*	SD	Range
Nonverbal cognition[1]	86	105.07	12.78	82–136
Sight word efficiency[2]	86	86.33	10.87	55–113
Pseudoword decoding efficiency[2]	85	80.64	11.37	60–113
Word identification[3]	85	86.20	12.25	55–117
Word attack[3]	85	80.92	11.12	55–115
Math fact fluency composite[4]	86	87.59	13.99	54–142
Math fluency[5]	80	83.75	14.73	40–129
Calculation[5]	78	88.55	13.34	45–135
Applied problems[5]	80	100.71	16.03	52–133

Note: *M* = mean, *SD* = standard deviation. [1]Kaufman Brief Intelligence Test (KBIT-2); [2]Test of Word Reading Efficiency (TOWRE-2); [3]Woodcock Reading Mastery Tests (WRMT-III); [4]Wechsler Individual Achievement Test (WIAT-III); [5]Woodcock Johnson Tests of Achievement (WJ-IV).

TABLE 2 Demographic characteristics of three participant groups.

	RD-Only		RD+MD		Other	
	N	%	*N*	%	*N*	%
Total	30		37		19	
Gender						
Boys	18	60.0	17	45.9	8	42.1
Girls	12	40.0	20	54.1	11	57.9
Grade						
3rd	–	–	1	2.7	2	10.5
4th	1	3.3	1	2.7	1	5.3
5th	14	46.7	18	48.6	9	47.4
6th	14	46.7	15	40.5	6	31.6
7th	1	3.3	2	5.4	1	5.3
Race						
African American/Black	–	–	3	8.1	1	5.3
Asian	–	–	–	–	–	–
White	25	83.3	28	75.7	16	84.2
Multiracial or multi-ethnic	4	13.3	4	10.9	2	10.6
Missing	1	3.3	–	–	–	–
Ethnicity						
Latina/o/x	–	–	5	13.5	1	5.3
Prior SLD diagnosis						
RD or dyslexia	25	83.3	32	86.5	13	68.4
MD or dyscalculia	–	–	17	45.9	–	–
ADHD	12	40.0	15	40.5	6	31.6

Abbreviations: RD, reading disability; MD, math disability. $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$.

TABLE 3 Comparison between RD-Only and RD+MD behavioral performance on cognitive, academic, and fMRI tasks.

	RD-Only (*N* = 30)		RD+MD (*N* = 37)		Group differences		Effect size
	M	SD	*M*	SD	*t*	*p*	*d*
Age	11.43	0.70	11.36	0.81	0.37	0.713	0.09
Grade	5.50	0.63	5.43	0.77	0.39	0.699	0.10
Sex (1 = M, 2 = F)	1.40	0.50	1.54	0.51	−1.14	0.259	-0.28
Socioeconomic status[1]	56.94	8.04	51.54	11.89	2.04	0.045*	0.52
Nonverbal cognition[2]	107.67	10.87	102.70	11.01	1.85	0.069	0.45
Reading and related skills							
Phonological awareness[3]	8.28	2.43	7.73	2.85	0.82	0.414	0.20
Word reading efficiency[4]	83.97	8.27	78.56	10.07	2.35	0.022*	0.58
Basic reading skills cluster[5]	82.70	9.90	79.75	9.86	1.21	0.232	0.30
Mathematics							
Math facts fluency composite[6]	97.77	11.70	76.51	8.70	8.52	<0.001***	2.09
Math calculation skills cluster[7]	97.45	8.83	76.12	8.82	9.88	<0.001***	2.44
Executive function							
Processing speed[8]	97.17	12.21	87.11	13.11	3.17	0.002**	0.74
Auditory working memory index[8]	93.62	14.23	84.57	10.34	2.99	0.004**	2.58
Visuospatial working memory span[9]	6.29	1.23	5.44	1.34	2.23	0.030*	0.65
Visuospatial working memory errors[9]	11.33	6.41	17.07	7.61	−2.78	0.008**	-0.81
fMRI tasks							
Word reading task accuracy	83.22	16.75	77.50	19.63	0.99	0.330	0.31
Word reading response time (s)	1.86	0.28	1.80	0.32	0.63	0.536	0.20
VSWM task accuracy	82.14	14.20	71.88	23.39	1.75	0.088	0.52
VSWM response time (s)	0.91	0.15	0.94	0.17	−0.72	0.477	-0.22

Note: * $p < .05$, ** $p < .01$, *** $p < .001$. [1]Barratt Simplified Measure of Social Status (BSMSS); [2]Kaufman Brief Intelligence Test (KBIT-2); [3]Comprehensive Test of Phonological Processing (CTOPP-2) Elision subtest; [4]Test of Word Reading Efficiency (TOWRE-2); [5]Woodcock Reading Mastery Tests (WRMT-III); [6]Wechsler Individual Achievement Test (WIAT-III); [7]Woodcock Johnson Test of Achievement (WJ-IV); [8]Wechsler Intelligence Scale for Children (WISC-IV); [9]Cambridge Neuropsychological Test Automated Battery (CANTAB). VSWM = Visuospatial Working Memory fMRI task.

3.1 | Behavioral differences between RD-only and RD+MD groups

T-test comparisons (Table 3) revealed no significant differences between the RD-Only and RD+MD groups in age, grade, sex, nonverbal cognition, phonological awareness, or untimed reading skill as measured using the WJ Basic Reading cluster (a composite of real word reading and pseudoword decoding). Groups did differ in socioeconomic status (RD-Only > RD+MD, $d = 0.52$). The RD-Only group performed significantly better than RD+MD in timed word reading fluency, all measures of math skill, and all measures of EF (processing speed, auditory working memory, and visuospatial working memory).

3.2 | Neurocognitive differences between RD-only and RD+MD groups

Figure 1 visualizes all participants' brain activation associated with the Word Reading > Face Matching contrast ($N = 44$) and the VSWM > Control contrast ($N = 52$), respectively, at the whole brain level, FDR corrected $p < .05$. As expected, the phonological word reading task engaged a left-lateralized network of frontal, temporo-parietal and occipital regions in the perisylvian language network. The VSWM task engaged the bilateral superior parietal and temporal lobes, and primarily right-lateralized frontal regions, as well as bilateral subcortical regions.

We then examined how co-occurring math difficulties might be associated with neurocognitive differences during phonological processing and VSWM using two complementary approaches: categorical comparison of RD-Only and RD+MD groups using both frequentist and Bayesian statistical approaches, and a continuous analysis of all participants.

First, we examined RD-Only versus RD+MD categorical group differences in the phonological word reading task. We conducted two sample *t*-tests between the RD-Only versus RD+MD groups (Table 4, Figure 2). A whole-brain independent samples *t*-test revealed no significant differences in the Word Reading > Face Matching contrast between RD-Only ($N = 18$) and RD+MD groups ($N = 18$). No significant clusters of voxels emerged, even at a reduced threshold of $p <$

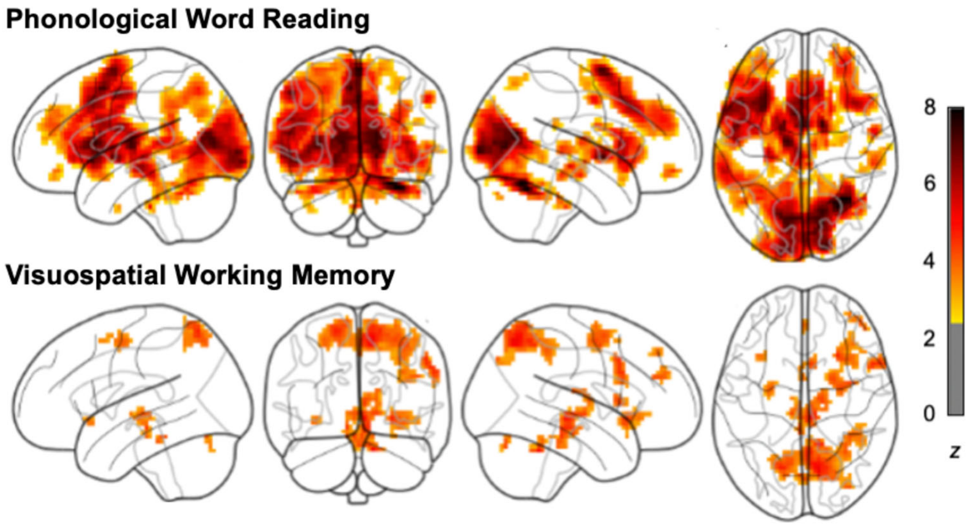

FIGURE 1 Experimental task > control condition contrasts for all participants.

TABLE 4 RD-Only versus RD+MD group differences in brain activation during phonological word reading and visuospatial working memory fMRI tasks.

Location of cluster	Mean T	Volume (mm)	MNI coordinates x	y	z
Phonological word reading > face matching					
No clusters for RD > RD+MD or RD+MD > RD	–	–	–	–	–
Visuospatial working memory > control					
Bilateral middle/inferior occipital gyrus	3.68	58,676	32.5	−87.5	7.9
R pre-/post-central gyrus	−3.48	1134	35.5	−24.5	47.5
Vermis lobule VI/VII, cerebellum VI, Crus I	3.16	356	5.5	−72.5	−20.9

MNI = Montreal Neurological Institute

0.001 uncorrected. To further investigate this null result, we conducted a post-hoc exploration of possible group differences in independently defined ROIs within the reading network (Martin et al., 2015), including left inferior frontal and temporoparietal regions. Bayes factors ranged from 0.33 to 0.46, providing anecdotal to moderate evidence in support of the null hypothesis (Table S1).

The VSWM > Control contrast, however, revealed significant group differences. The RD-Only Group (N = 20) demonstrated significantly greater activation of bilateral occipital cortex than the RD+MD Group, whereas the RD+MD Group (N = 21) showed greater activation than the RD-Only Group in a small cluster in right primary motor cortex. Decoding via the large compilation of neuroimaging results on Neurosynth (Yarkoni et al., 2011) revealed that this region is most frequently associated with left-hand finger tapping or tracing, potentially reflecting a task strategy more frequently used by the RD+MD participants. Notably, no significant differences emerged in regions typically associated with working memory processes. We explored possible group differences in independently defined regions from a meta-analysis of working memory in children (Yaple & Arsalidou, 2018), namely left middle/superior frontal gyri, bilateral superior parietal lobules and right inferior parietal lobule. Bayes factors ranged from 0.31 to 0.60, providing anecdotal to moderate evidence in support of the null hypothesis in each working memory ROI (Table S2). In contrast, a Bayesian independent sample t-test comparing mean activations in the visual cortex, identified using an association test with the term "visual cortex" in Neurosynth (Yarkoni et al., 2011), provided decisive evidence for differences between the RD-Only and RD+MD groups (BF_{10} = 1,045.50).

Notably, there were no significant differences between RD-Only and RD+MD groups (with imaging data) on mean framewise displacement in the scanner, grade, socioeconomic status, or accuracy on either task. (This stands in contrast to the full behavior sample, in which the RD+MD Group was of lower average socioeconomic status.) Nevertheless sensitivity analyses revealed that the whole-brain differences between groups were robust when these nuisance regressors were included. For the VSWM task, there were significant differences for RD-Only > RD+MD in bilateral occipital cortex when controlling for all of the above variables; RD+MD > RD-Only activation in right primary motor cortex did not survive when controlling for socioeconomic status or task accuracy. For the fMRI word reading task, there were no significant group differences when each nuisance regressor was included, even at a reduced threshold.

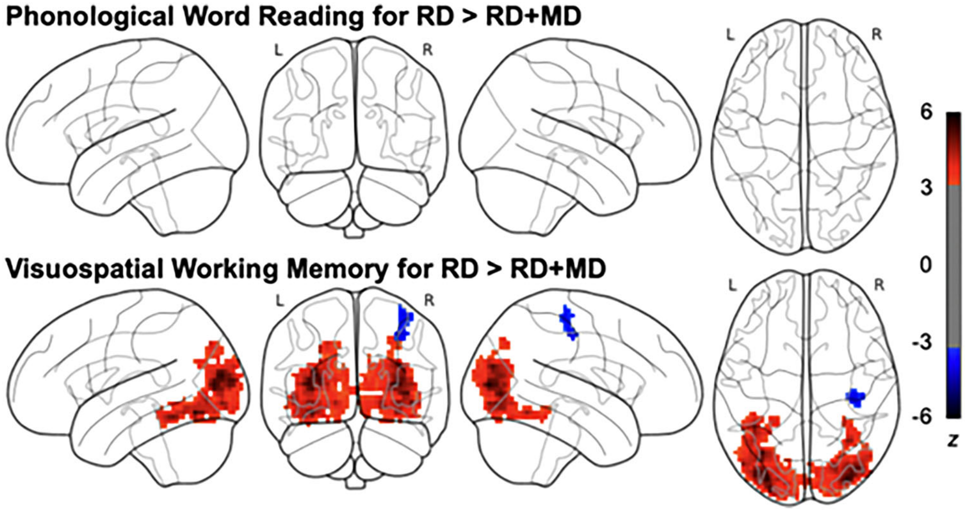

FIGURE 2 Experimental task > control condition comparison for reading disability (RD-Only) > reading + math disability (RD+MD).

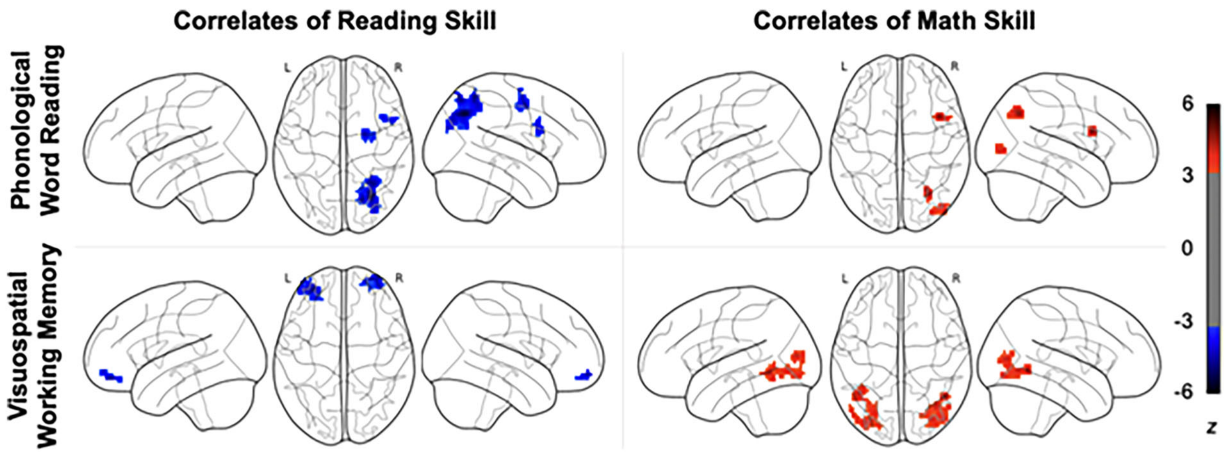

FIGURE 3 Brain-behavior associations between reading and math skills during fMRI tasks.

3.3 | Neurocognitive differences across a continuous spectrum of math ability

Although learning disorder classifications are often binary, both math and reading performance occur across a continuum in a given population. As such, RD and MD diagnoses represent the tail end of a normal distribution. One of the challenges of interpreting prior research related to RD and MD is the variability in cut-offs used across studies to classify impairment (Joyner and Wagner, 2020). In the current sample, a second challenge is the 19 participants who are designated as "Other." These participants met RD criteria and had a possible weakness in math, but did not clearly meet criteria for MD. To maximize our sample of RD participants across a full spectrum of math ability, we examined brain-behavior correlations across all participants (RD-Only, RD+MD and Other).

We conducted whole-brain regression analyses using each participant's average score across all four behavioral math tasks (MathAvg) and four behavioral reading tasks (ReadAvg) as covariates (Table 5, Figure 3). This continuous analysis specifically tested the hypotheses that math skill would be correlated with brain activation related to phonological processing and visuospatial working memory, independent of reading skill. For completeness, we examined the linear associations between either ReadAvg or MathAvg during each of the two experimental task > control contrasts while holding the other constant. These exploratory analyses were thresholded at a more lenient $p < 0.001$ (uncorrected).

During the fMRI phonological word reading task, reading skill was negatively associated with right superior/inferior frontal and superior parietal activation. Math skill was positively associated with activation in right inferior frontal and occipito-parietal clusters. During the fMRI VSWM task, reading skill was negatively associated with activation of the bilateral orbitofrontal cortex, a region implicated in working memory (Owen et al., 2005). Math skill was positively associated with bilateral occipito-temporal engagement during VSWM. These associations between math skill and occipito-temporal activation are consistent with the RD-Only v. RD+MD group comparison,

TABLE 5 Brain-behavior associations between reading and math skills during fMRI tasks.

Location of cluster	Mean *T*	Volume (mm)	MNI coordinates *x*	*y*	*z*
Associations between word reading task and reading skill, controlling for math					
R superior parietal lobule[a]	−3.67	8327	29.5	−66.5	40.3
R superior frontal/precentral gyrus	−3.39	1750	23.5	−3.5	51.1
R inferior frontal/precentral gyrus	−3.45	1231	50.5	8.5	29.5
Associations between word reading task and math skill, controlling for reading					
R superior occipital cortex/angular gyrus	3.61	1328	29.5	−63.5	40.3
R middle occipital cortex	3.48	1037	44.5	−78.5	4.3
R inferior frontal gyrus	3.71	1004	41.5	11.5	22.3
Associations between VSWM task and reading skill, controlling for math					
L frontal pole	−3.63	1912	−33.5	53.5	−17.3
R frontal pole	−3.50	1814	29.5	62.5	−13.7
Associations between VSWM task and math skill, controlling for reading					
R inferior occipital cortex/fusiform gyrus	3.41	6026	44.5	−57.5	−2.9
L inferior occipital cortex/fusiform gyrus	3.36	4828	−36.5	−84.5	11.5
L inferior temporal gyrus	3.50	1717	−42.5	−54.5	−6.5

Note: Whole brain analysis, $p < 0.001$ uncorrected.
Abbreviations: L, left hemisphere; R, right hemisphere; VSWM, visuospatial working memory. MNI = Montreal Neurological Institu
[a]Cluster survives FDR correction.

supporting the interpretation that poor math ability was associated with less robust activation of visual processing regions.

The whole brain regression analysis allows for a broad, unbiased search area, revealing associations in areas beyond reading- and working memory-related regions. However, this approach may lack power; indeed, clusters that emerge at an exploratory threshold do not survive correction for multiple comparisons across all the voxels in the brain. To complement this analysis, we also explored possible associations between cognitive skills and brain activations within specific regions of interest during the phonological word reading and VSWM tasks. Bayesian correlation analyses revealed anecdotal support for the null hypothesis in the majority of ROIs, with a few notable exceptions (Figure 4). During phonological word reading, we observed decisive support ($BF_{10} > 100$) for a linear association between out-of-scanner reading skill and activation in left BA44. During VSWM, activation in bilateral visual cortex was associated with math skill ($BF_{10} = 35.39$) and processing speed ($BF_{10} = 17.56$).

4 | DISCUSSION

This study examined behavioral and neurocognitive factors associated with co-occurring math difficulties (MD) in a sample of impaired readers (RD), ages 9–13. Leading theories have pointed to phonological processing and working memory impairments as two possible challenges leading to RD+MD co-occurrence (De Smedt, 2018; Dehaene, 1992; Willcutt et al., 2013; Wilson et al., 2015). Using a combined brain-behavior approach, we found no evidence that RD+MD co-occurrence was associated with lower phonological awareness than RD-Only. In contrast, RD+MD co-occurrence was associated with worse EF performance (i.e., processing speed, auditory working memory, and visuospatial working memory) than that seen in RD-Only. Furthermore, the RD+MD Group exhibited significantly reduced activation in visual cortex during a visuospatial working memory task. These results point to difficulties with EF in general, and working memory in particular, as differentiating RD children with vs. without co-occurring MD.

4.1 | High co-occurrence of MD within RD sample

Prior research has suggested that upwards of 40% of RD students also present with MD (Willcutt, 2013; Wilson et al., 2015). In the current study, we found high RD+MD co-occurrence, with 43% of the sample clearly meeting criteria for impaired math skill, and over 20% demonstrating a possible vulnerability in math. Only 35% of participating children (30 out of 86) performed within the typical developmental range on all four math assessments. This high frequency of math difficulties among children with RD is even higher than suggested by past studies (although recruitment did specifically target children with math and reading difficulties, potentially skewing the sample). Furthermore, although 70 participants had a prior diagnosis of dyslexia or a specific learning disability in reading (83%), only 17 had a diagnosis of dyscalculia or a specific learning disability in math (20% of all participants, 46% of RD+MD Group), suggesting that MD is often under-identified in the context of RD.

Importantly, not all participants fell within the researcher-designated RD-Only or RD+MD groups. Instead, we observed heterogeneity across participants in all cognitive skills tested. All

Behavioral measures	1	2	3	4	5	6	7	8
1. Age	—							
2. Nonverbal IQ	0.17	—						
3. Reading skill	0.84	0.18	—					
4. Phonological awareness	0.17	1.07	43.23	—				
5. Math skill	0.64	8.28	25.47	0.29	—			
6. Processing speed	0.33	0.26	2.23	0.20	>10,000	—		
7. Auditory working memory	0.84	1.30	>1000	49.24	477.72	4.35	—	
8. Spatial working memory	0.19	1.26	0.19	0.79	6.36	1.42	2.01	—
ROI activation during Phonological Word Reading								
L middle frontal gyrus	0.29	0.28	0.29	0.19	0.20	0.19	0.20	0.24
L inferior frontal gyrus/BA44	0.19	0.19	43.14	0.20	2.65	0.50	1.41	0.29
L inferior frontal gyrus/BA45	0.22	0.21	0.67	0.19	0.29	0.19	0.22	0.22
L precentral gyrus	0.24	0.22	0.34	0.22	0.93	0.23	0.19	0.25
L supplementary motor area	0.19	0.22	0.24	0.41	1.09	0.19	0.20	3.71
R supplementary motor area	0.19	0.21	0.25	0.19	0.75	0.54	0.33	0.38
L superior parietal lobule	0.25	0.20	0.19	0.27	0.32	0.42	0.20	0.38
L superior temporal gyrus	0.36	0.39	0.47	1.17	0.92	0.50	0.31	1.19
L middle temporal gyrus	0.19	0.21	0.20	0.20	0.20	0.19	0.19	0.22
L inferior temporal gyrus	0.20	0.25	0.19	0.20	0.20	0.19	0.19	0.24
ROI activation during Visuospatial Working Memory								
L middle frontal gyrus	0.64	0.19	0.27	0.18	0.19	0.19	0.18	0.40
L superior frontal gyrus	0.38	0.18	0.19	0.21	0.26	0.23	0.21	0.22
R insula	0.26	0.41	0.18	0.19	0.19	0.49	0.18	0.58
L precentral gyrus	0.18	0.18	0.19	1.71	0.18	0.20	0.23	0.25
L superior parietal lobule	0.32	0.37	0.23	0.29	0.18	0.18	0.22	0.20
R superior parietal lobule	0.27	0.27	0.28	0.32	0.23	0.29	0.19	0.20
R inferior parietal lobule 1	0.21	0.44	0.54	0.17	0.20	0.23	0.18	0.26
R inferior parietal lobule 2	0.27	0.41	1.26	0.18	0.18	0.17	0.18	0.22
R inferior parietal lobule 3	0.30	0.51	0.94	0.17	0.19	0.17	0.17	0.27
R inferior parietal lobule 4	0.57	0.34	0.78	0.14	0.19	0.18	0.18	0.41
Bilateral visual cortex	0.17	0.20	0.18	0.43	35.39	17.56	1.75	0.77

FIGURE 4 Bayes factors supporting correlations between region of interest (ROI) activation and behavioral measures.

participants were classified as having reading difficulties, yet across all four single word reading measures, standard scores ranged from three standard deviations below the age-normed mean, to one standard deviation *above* the mean. Many of these above-average scores were obtained by children with a prior diagnosis of dyslexia who performed in the typical range on the day of testing. This heterogeneity across participants only begins to reveal the true diversity of struggling learners, and reflects the inherent challenge in defining learning difficulties categorically (Sonuga-Barker & Thapar, 2021).

4.2 | Behavioral differences between RD-only and RD+MD groups

In general, we observed slightly better performance on neuropsychological measures of cognitive and academic skills in the RD-Only Group. Higher cognitive and academic performance from children with reading difficulty only as compared to those with co-occurring learning difficulties is consistent with prior research. For instance, a large-scale study of RD and MD in children ages 8–15 revealed lower performance on measures of cognition, reading, and math among RD+MD participants as compared to children with RD or MD alone (Willcutt, 2013). In the current sample, there were no significant differences between groups on measures of nonverbal cognitive ability, phonological awareness or untimed reading skills. However, the RD-Only Group out-performed the RD+MD Group in timed reading, and all behavioral measures of EF (processing speed, auditory working memory, and visuospatial working memory). The specific association between EF difficulty and reading fluency in RD as opposed to untimed reading accuracy is consistent with other behavioral and neuroimaging evidence (Al Dahhan et al., 2022). Furthermore, children who struggle with both reading and math demonstrate consistent fluency difficulties across both domains (Koponen et al., 2018).

4.3 | No evidence for phonological processing difficulties underlying RD+MD compared to RD-only

Our first hypothesis (H1) was that co-occurring RD+MD was related to underlying phonological difficulties, but this was not supported by the findings. Both groups demonstrated low phonological awareness, and there was no significant difference between the RD+MD and RD-Only groups. Aligned with the present findings, prior work showed phonological awareness in a group of 2nd graders predicted variance in reading only and not math skill (Child et al., 2019).

The fMRI word reading task also revealed no statistically significant group differences in brain activation, even at a lenient, exploratory threshold. The absence of a brain activation difference between groups is consistent with behavioral evidence indicating that the groups did not differ in their phonological awareness. Whole-brain regression analyses with the full sample (RD-Only, RD+MD and Other) did reveal specificity in the brain-behavior associations between phonological processing and reading or math skill, respectively. Reading skill (controlling for math) was negatively associated with activation in right inferior/superior frontal cortex and the right superior parietal lobule. This negative association with reading skill indicates that less proficient readers may have been relying more heavily on right hemisphere compensatory resources during the word reading task. In contrast, math skill (controlling for reading) was positively associated with right inferior frontal and inferior parietal/occipital clusters of activation. In particular, bilateral inferior/superior parietal engagement was positively associated with math skill. Bilateral parietal regions are thought to be key hubs of numerical processing, and the association between greater parietal activation and math skill has often been found during math tasks (Ashkenazi et al., 2012; Price et al., 2007). A meta-analysis also points to the left inferior parietal lobe as a region supporting both arithmetic and phonological processing (Pollack & Ashby, 2018).

Finally, post hoc ROI analyses within the reading network provided strong evidence for a correlation between reading skill and activation in the left IFG, specifically Broadman's Area 44. This inferior frontal region is critically involved in phonological decoding of words and grapheme-to-phoneme mapping (Fiebach et al., 2002; Heim et al., 2005). While IFG activation is generally thought to decrease as readers become more proficient (Turkeltaub et al., 2003), the readers in the current study are both still learning how to read, and are struggling readers; this greater activation of left inferior regions among more skilled readers suggests more effective recruitment of decoding resources.

4.4 | Behavioral differences in EF and working memory

Our second hypothesis (H2) was that co-occurring RD+MD was related to greater EF difficulties. As predicted, we observed significantly higher EF performance among students with RD-Only as compared to the RD+MD Group. The RD-Only Group demonstrated faster processing speed and greater working memory span with medium-to-large effect sizes, as well as more efficient and strategic performance on the out-of-scanner spatial working memory task. The most substantial group difference was in auditory working memory span, extending prior research suggesting that impairments in auditory working memory or the phonological loop may be particularly relevant for co-occurring learning difficulties (Swanson, 2020).

This evidence supports the hypothesis that greater challenges with EF, including working memory, may increase RD+MD risk. Independently, RD (Al Dahhan et al., 2022; Alt et al., 2022; Reiter et al., 2005) and MD (David, 2012; Geary, 2004; Mammarella et al., 2018) have both been associated with poor EF. There are also numerous studies suggesting a shared role of EF and working memory in both reading and math. Among second graders, verbal and visuospatial working memory span explain reading and math skills independently, as well as their overlap (Child et al., 2019). Adults with RD+MD demonstrate more severe challenges in verbal and semantic working memory than those with RD or MD only (Grant et al., 2020). In contrast, others have found reduced working memory capacity among children with RD compared to their typically developing peers, but similar EF skills between children with RD-Only and RD+MD (De Weerdt et al., 2013). The role of EF, and working memory more specifically, in RD+MD co-occurrence therefore requires attention in future research.

4.5 | Neurocognitive differences in visuospatial processing during working memory task

In addition to behavioral differences in EF, we hypothesized that co-occurring math difficulties were associated with activation differences underlying a visuospatial working memory task. A direct comparison of the RD-Only and RD+MD Groups revealed no significant differences during the VSWM task in regions typically associated with memory span (Klingberg et al., 2002; Matejko & Ansari, 2021). However, there were striking differences between groups in regions associated with visual processing and motor control. The RD+MD Group had greater engagement in the right primary motor cortex. As participants were all holding a button box and responding to the task using their right hand, we posit that children in the RD+MD Group—who showed greater difficulty with EF tasks behaviorally—were more likely to use the fingers on their left hand as a memory aid to trace the pattern of presented dots (a strategy anecdotally observed during behavioral testing). The RD+MD Group also showed substantially less engagement of bilateral visual cortex. This finding was replicated in a complementary whole-brain regression analysis: greater math skill was associated with greater engagement of visual cortex, including bilateral clusters in the inferior/superior occipital gyrus and fusiform gyrus.

This discovery is aligned with prior evidence suggesting visual processing differences in both RD and MD. Visual processing deficits also often arise as a possible correlate within multifactorial theories of RD, as multiple aspects of vision (i.e., motion processing, visual attention, high-level visual discrimination, as well as neurocognitive and neuroanatomical differences in the ventral visual stream) have been linked to reading difficulties (Kristjánsson & Sigurdardóttir, 2023). Visuospatial skills in children with RD, such as recalling and reproducing complex figures, may also discriminate between those with and without co-occurring math difficulties (Helland & Asbjørnsen, 2003). For MD specifically, visuospatial processing difficulties have been linked to low accuracy of the mental number line (Crollen & Noël, 2015; Tam et al., 2019) and poor calculation skill (Venneri et al., 2003). Children with RD-Only and MD-Only demonstrate similarly poor performance on a visual figure matching task; scores are even lower among those with RD+MD (Cheng et al., 2018).

The visuospatial processing differences frequently reported in RD seem to be relatively independent from the language-based or phonological difficulties that are often considered a core deficit (Helland & Asbjørnsen, 2003; Kristjánsson & Sirgudadóttir, 2023). This dissociation is also apparent at the brain level. Among children with RD, structural MRI suggests independent networks of brain regions that support phonological skill (connectivity within the left frontal cortex, and around the left middle temporal gyrus) and visual attention (occipito-parietal connectivity centered around the left superior occipital gyrus) independently (Liu et al., 2022).

Importantly, post hoc ROI analyses revealed that under-activation in the visual cortex was not only associated with math challenges, but also weakness in processing speed. Poor working memory and processing speed have been associated with both reading and math learning difficulties (Johnson et al., 2010) and are candidates for domain-general factors that may account for high comorbidity (Willcutt et al., 2013, 2019). Processing speed has also been associated with specific learning disabilities in reading and math as well as ADHD in a transdiagnostic sample of children with one or more learning or mental health disorders (Kramer et al., 2020).

To date, however, there has been limited evidence linking visual processing differences to other EFs, or to the co-occurrence of learning difficulties at the neurocognitive level. The present findings contribute to this gap in the literature by demonstrating that, even when controlling for word reading difficulties, children with math difficulties show substantially reduced engagement of visual processing resources during a VSWM task. From the current evidence, it is not clear whether this difference in visual processing is a cause, consequence, or correlate of math difficulty or differences in EFs. Nevertheless, this result demonstrates that recruitment of the visual cortex varies substantially across children with RD. Neurocognitive differences in visual processing may therefore not be at the core of all RD, but may represent an additive challenge for many RD that is associated with increased RD+MD risk.

4.6 | The role of EFS in learning challenges

In the current study, RD+MD co-occurrence was associated with weaknesses in auditory working memory, visuospatial working memory, and processing speed beyond that seen in children with RD only. This finding is consistent with transdiagnostic research, which has identified EF differences as a common thread across many learning difficulties, including RD, MD and ADHD (Willcutt et al., 2010). Importantly, broad EF screening in early childhood (3–6 years) can effectively predict kindergarten academic growth (Kalstabakken et al., 2021) and may help to identify children at risk for learning challenges at school. This is particularly promising, as academic interventions for struggling learners are generally most effective when introduced early. This reality is in tension with the fact that identification for a learning disability often requires a child to have failed to progress despite instruction, potentially delaying access to needed support. As early EF weakness can be identified at or prior to school entry (Kalstabakken et al., 2021), routine screening may help to identify and support at-risk learners.

EF is also an important factor to consider when designing supports for children whose neurodiversity is not currently well-supported by their learning environments. Aligned with universal design for learning frameworks (e.g., Jiménez et al., 2007), educators may consider how visuospatial working memory load or processing speed demands can be modified to support academic skill development for all learners, particularly those at risk. Finally, although evidence regarding the efficacy of EF training has been mixed (Melby-Lerväg & Hulme, 2013), some studies suggest promising results. For instance, a cognitive flexibility intervention designed to transfer to reading processes (flexible attention to phonological or semantic information) has been associated with significant differences in reading comprehension (Cartwright et al., 2020) and reading fluency (Cartwright et al., 2019), and might therefore be well-suited to support children with RD.

4.7 | Limitations

The present study has several limitations. In trying to disambiguate the behavioral and neurocognitive factors associated with RD and MD, an MD-Only Group would be an asset to the present design. Unfortunately, nearly all of the students with MD recruited for the present study also presented with RD, leaving only five children who could be classified as MD-Only. We therefore approach the current research questions through the lens of reading impairment and the additional difficulties that frequently co-occur in learners with RD.

Our neuroimaging group comparisons are limited by relatively small sample sizes. Although these groups are smaller than desirable, they are nevertheless larger than existing neuroimaging work that compares RD-Only and RD+MD participants (Peters et al., 2018; Skeide et al., 2018). At the same time, we recognize that categorical comparisons of researcher-defined groups do not reflect the true diversity of struggling students and heterogeneity of learning profiles (Siugzdaite et al., 2020). The goal of the current study was to examine MD co-occurrence among children with reading challenges; however, we note over a third of participants also had a prior ADHD diagnosis, and many may have other neurodevelopmental or psychiatric differences as well. Future work may consider moving away from categorical comparisons and towards more transdiagnostic approaches to understanding learning challenges across neurodiverse youth (Astle et al., 2022; Fletcher-Watson, 2022; Sonuga-Barke & Thapar, 2021).

Finally, we note that multifactorial models of learning disabilities (Catts & Petscher, 2022; O'Brien and Yeatman, 2021) indicate many possible cognitive risk factors for both RD and MD. The current study examined the brain bases of phonological word reading, and visuospatial working memory, but there are many other neurocognitive processes that may illuminate mechanisms underlying RD+MD co-occurrence. The measures in the current study are limited in scope and do not reflect the many strengths our participants with learning difficulties may have.

4.8 | Conclusion

Children with RD frequently struggle with co-occurring MD. The present study aimed to identify the specific behavioral and neurocognitive factors associated with MD in a sample of children with RD. Additional difficulty with math in RD children was unrelated to differences in behavioral or brain measures of phonological awareness related to speech or print. However, math difficulties were related to additional challenges in EF as measured behaviorally and by brain activations related to visuospatial working memory. These findings suggest that added difficulties with working memory and visual processing may increase the likelihood of MD among struggling readers.

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CONFLICT OF INTEREST STATEMENT

Conceptualization: RAM, CP, TMC, DA, JDEG, JAC. Methodology: RAM, AAM, TMC, DA, JDEG, JAC. Investigation and data curation: KW, AMD, RRR, CP, JAC. Resources: AAM, DA, JDEG, JAC. Software: SLM. Formal analysis and visualization: RAM, SLM, AAM.Writing—original draft: RAM. Writing—review and editing: All. Supervision, project administration and funding acquisition: JDEG, JAC.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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