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Neurocognitive risk factors for co-occurring math difficulties in dyslexia: Differences in executive function and visuospatial processing

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Abstract

What makes math difficulties so common in children with dyslexia? The current study aimed to identify behavioral and neurocognitive factors associated with co-occurring reading disability (RD) and math disability (MD). We tested reading, math, and cognitive skills in a sample of 86 children in 3^{rd}–7^{th} grade (ages 9-13) with RD. Within this sample, 35% of children had RD only with no weakness in math, 43% had co-occurring RD+MD, and over 20% demonstrated a possible vulnerability in math. We investigated whether RD-Only and RD+MD students differed behaviorally in their phonological awareness, reading skills, or executive function, as well as in the brain mechanisms underlying word reading and visuospatial working memory using fMRI. We found that the additional difficulty with math in children with RD was unrelated to differences in behavioral or brain measures of phonological awareness related to speech or print. However, the RD+MD group performed significantly worse than the RD-Only group on multiple measures of executive function, including working memory and processing speed. The RD+MD group also exhibited reduced brain activations for visuospatial working memory relative to the RD-Only group. Continuous analyses along a spectrum of math ability revealed that greater math difficulties were associated with reduced activation in the visual cortex. These converging neuro-behavioral findings suggest that poor executive function in general, and differences in visuospatial working memory in particular, are associated with co-occurring MD among children with RD.

Keywords
Reading, math, learning disabilities, working memory, visuospatial processing, executive function

Highlights (85 characters each)

- Children with reading disabilities (RD) frequently also have math disabilities (RD+MD)
- We investigated differences between RD vs. RD+MD with behavioral and fMRI measures
- RD+MD was not related to brain or behavioral differences in phonological processing
- RD+MD was associated with additional difficulties in working memory (WM)
- RD+MD was associated with reduced visual cortex activation during visuospatial WM

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Neurocognitive risk factors for co-occurring math difficulties in dyslexia: Differences in executive function and visuospatial processing

Math and reading difficulties frequently co-occur (Landerl & Moll, 2010; Moll et al., 2019; Willcutt et al., 2013) with some estimates suggesting that up to 40% of all impaired readers also struggle with math (Wilson et al., 2015). The potential mechanisms behind this high comorbidity, however, remain unclear. The current study aimed to identify underlying neurocognitive factors associated with co-occurring reading disability (RD) and math disability (MD). We investigated the extent to which RD-Only and RD+MD students differ behaviorally in their phonological awareness, reading skills, and executive function (EF), as well as in the brain mechanisms underlying word reading and EF (i.e., visuospatial working memory), in order to adjudicate between competing theoretical explanations for high RD+MD comorbidity. This converging brain-behavior approach aimed to illuminate the correlates and potential underlying mechanisms of math difficulties in RD.

Reading disability (RD) or dyslexia

Reading disabilities are the most commonly diagnosed specific learning disorder, affecting 5-17% of children (Shaywitz, 1998). *Developmental dyslexia*, the most frequently occurring type of RD, is a heritable, life-long difficulty with word reading despite adequate intelligence and education.

RD is multifaceted and has numerous presentations and underlying risk factors (Catts & Petscher, 2022). Most frequently, RD is associated with core neurocognitive differences in phonological awareness. Phonological (sound) awareness deficits may impede children's ability to connect sounds to letters, decode unfamiliar words, and recognize words fluently. Studies of the neurobiology of RD, which have frequently used phonological awareness tasks such as rhyme judgments, reveal differences in the functionality of language regions of the brain (Kovelman et al., 2012). Left temporoparietal regions associated with integrating representations of sound and print are frequently under-activated by readers with RD during phonology tasks (Hoeft et al., 2006; Shaywitz et al., 1998; Temple et al., 2001). More broadly, individuals with RD demonstrate differences across the reading system, including left inferior frontal and occipitotemporal regions (Kronbichler & Kronbichler, 2018; Richlan, 2012; van der Mark et al., 2011). RD is also frequently linked to poor rapid automatized naming (RAN) skill (Norton & Wolf, 2012), as well as perceptual differences, e.g., in visual processing (Schulte-Körne & Bruder, 2010; Sigurdardottir et al., 2015) or visuo-spatial attention (Franceschini et al., 2022; Taran et al., 2022). Children with RD often demonstrate additional EF difficulties, a set of cognitive skills associated with goal-directed behavior, including working memory, processing speed, directed attention, and inhibitory control (Al Dahhan et al., 2022; Daucourt et al., 2020; Lonergan et al., 2019).

High co-occurrence of RD and math disability (MD)

RD frequently co-occurs with *developmental dyscalculia* (also known as MD), a specific

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learning disability in math that affects children's ability to acquire arithmetic skills (Price & Ansari, 2013). Children with MD tend to struggle with arithmetic fact retrieval. As successful arithmetic learning often relies on fluent memory of arithmetic facts to allow for efficient problem solving, children with MD may struggle to learn more advanced mathematical procedures and efficient strategies (Price & Ansari, 2013). MD is also often associated with a core deficit in numerical processing or number sense, such as comparing magnitudes (Landerl et al., 2013; however also see Mammarella et al., 2021). Studies of the neurobiology of MD have frequently pointed to bilateral parietal regions, namely the intraparietal sulci (IPS), as key hubs of numerical processing, with reduced activation during math tasks in individuals with MD compared to peers without MD (Ashkenazi et al., 2012, 2013; Price et al., 2007).

Although RD and MD are often identified or studied independently, RD+MD comorbidity is substantially higher than would be expected by chance in the general population (Landerl & Moll, 2010). In general, children with RD tend to score lower on measures of arithmetic than their typically-developing peers (De Smedt & Boets, 2010; Koerte et al., 2016). A meta-analysis suggests that a child with MD is more than twice as likely as a child with typical math skill to also have a reading impairment (Joyner & Wagner, 2020). This high comorbidity suggests that the etiology of both RD and MD may be at least partially linked to skills that underlie both disorders. The present study investigated two possible skills associated with both reading and math ability that may help to explain mechanisms underlying high RD+MD comorbidity: differences in phonological processing and working memory.

Phonological processing in RD and MD

One theory for the high co-occurrence of RD+MD points to the core difficulties with phonological processing in RD as a challenge that also impacts math learning. Math teaching and learning, especially arithmetic, frequently relies on verbal strategies such as rote memorization of small number addition and multiplication. Mental representations of numbers and math facts may be linguistic in nature (De Smedt, 2018; Dehaene, 1992), and so their rapid retrieval may depend, at least partially, on phonological processing (Polspoel et al., 2017). Phonological deficits common to RD may also impede math learning and arithmetic fact retrieval because of children's reliance on phonological working memory (Simmons & Singleton, 2008), which may 'create a bottleneck' that impairs general information processing (Swanson, 2020).

Phonological processing performance is correlated with early mathematical skills, symbol processing skills, and early arithmetic performance before formal schooling (Vanbinst et al., 2020; Viesel-Nordmeyer et al., 2022). Phonological awareness has been identified as a shared risk factor for both RD and MD in 7-11 year old children (Slot et al., 2016). A proposed neural mechanism underlying this association is the overlap of brain regions involved in phonological processing and arithmetic (Pollack & Ashby, 2018). Among 8-10 year old children, brain activation during a rhyme judgment in frontal and temporal regions associated with phonological processing and retrieval predicted gains in math fact retrieval two years later (Suárez-Pellicioni et al., 2019). The relation between phonological processing and arithmetic is also apparent in older children and

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adults, both behaviorally and in the brain networks, for typically-developing individuals (De Smedt & Boets, 2010; Evans et al., 2016; Hecht et al., 2001; Prado, 2018) and those with dyslexia (Evans et al., 2014; Matejko et al., 2022; Träff et al., 2017). Importantly, however, others find a limited association between phonology and arithmetic (Amland et al., 2021). A precise examination of children with RD-Only versus those with RD+MD may help to clarify the role of phonological processing in MD by illuminating whether phonological abilities in RD differ across children with and without added math difficulties.

Working memory and executive function in RD and MD

Students with RD who also struggle with math may have an underlying difficulty with EF that affects both math and reading. Both reading and math ability rely on procedural automaticity (Prado, 2018), as well as the management of numerous high-level cognitive processes, requiring sustained attention, working memory, and inhibition. EF difficulties may contribute to both RD and MD, with evidence that RD+MD comorbidity is associated with poor working memory and processing speed (Willcutt et al., 2013).

There is some evidence to suggest that reading skill may be more closely related to *phonological* working memory while math skill may be more closely related to *visuospatial* working memory (Giofrè et al., 2018; Peters et al., 2020; Schuchardt et al., 2008). Verbal or phonological short term memory deficits are frequently documented in RD (Griffiths & Snowling, 2002), and play an important 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 abilities (Li & Geary, 2013, 2017; Metcalfe et al., 2013), as well as a visuospatial working memory deficit in MD (Szucs et al., 2013). Notably, there is overlap in the brain regions involved in representations of magnitude and visuospatial working memory; functional differences in these areas may contribute to difficulties with working memory as well as math skill (Matejko & Ansari, 2021; Menon, 2016). For instance, 8-10 year olds with MD showed reduced activation during a visual working memory task in the right inferior frontal region and IPS compared to age-matched controls with typical math skills (Rotzer et al., 2009). IPS activation during a similar working memory task predicted arithmetic performance two years later in 6-16 year olds (Dumontheil & Klingberg, 2012).

Importantly, visuospatial working memory does not inherently rely on language or print-related processes. Visuospatial working memory is thus a promising lens through which to examine RD+MD co-occurrence, and to dissociate language-based vs. EF mechanisms underlying these two related disorders.

Neurocognitive bases of RD+MD

There is limited work to date that investigates the brain bases of co-occurring RD+MD. 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.,

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2018; Chang et al., 2018; Skeide et al., 2018; Westfall et al., 2020). However, little is known about math and reading difficulties as they relate to functional or task-related brain activity.

Peters and colleagues (2018) examined the neural correlates of RD+MD by employing a subtraction task with typically developing children, ages 9-12, and their peers with RD (N = 19), MD (N = 11) or both (N = 8). Despite observing expected behavioral differences between groups, there was minimal evidence for neurocognitive differences in arithmetic between RD-Only, MD-Only, and RD+MD participants (Peters et al., 2018). How other cognitive mechanisms that may underlie RD+MD comorbidity, such as phonological processing or working memory, manifest in the brains of children with co-occurring learning difficulties remains largely unknown.

The present study: Disambiguating theoretical explanations of RD+MD comorbidity

The present study aimed to identify underlying behavioral and neurocognitive factors associated with RD+MD comorbidity. What makes MD comorbidity more likely among students with RD? We investigated two hypotheses and predictions that may contribute to RD+MD co-occurrence (phonological processing and EF via working memory) in a sample of N = 86 children with RD in 3rd–7th grade, with and without comorbid MD (RD-Only and RD+MD Groups, respectively).

The first hypothesis (H1) posits that comorbid RD+MD may be related to underlying phonological deficits. In support of H1, we would predict greater behavioral phonological awareness difficulties among students with comorbid RD+MD as opposed to those with RD-Only, as well as brain activation differences during phonological processing. We further predict that math skill would be correlated with brain activation related to phonological processing, independent of reading skill. The second hypothesis (H2) posits that difficulties with EF increase the risk of co-occurring RD and MD. In support of H2, we would predict greater behavioral EF difficulties among students with comorbid RD+MD, and differences in the neurocognitive processes underlying EF as measured through visuospatial working memory, with greater deficits in the RD+MD group as compared to RD-Only. Given the well-documented associations between visuospatial processing and math learning, we would anticipate that RD-only vs. RD+MD group differences at the neurocognitive level would also be reflected in brain-behavior associations with math skill, independent of reading skill. Notably, these two hypotheses are not competing or mutually exclusive; multifactorial theories of learning disabilities suggest that multiple risk factors in both brain and behavior may increase the likelihood of learning difficulties (Catts & Petscher, 2022; Peterson & Pennington, 2012).

We investigated these two hypotheses using two analytic approaches. First, primary analyses employed a categorical distinction between RD-Only and RD+MD Groups. A complementary analysis employed a continuous sample that also included individuals with RD whose math performance fell between the clearly intact or clearly impaired categories ('Other,' see *Participant Group Assignment* below). These two approaches allowed for strict comparison between groups, as well as continuous brain-behavior associations to test H1 and H2.

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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 the typical developmental range (standard score ≥ 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. Of the final sample of 86 children, 44 (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 visits to the lab: one for behavioral testing, and one for fMRI neuroimaging. Legal guardians provided written consent and participants completed assent forms prior to testing. 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 of the Massachusetts Institute of Technology.

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Behavioral assessments

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.

Single word reading**.** Participants' 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). These subtests comprise the Total Word Reading Efficiency composite. 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), together comprising the Basic Reading Skills Cluster.

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 rapid automatized naming (Letters subtest of RAN/RAS; Wolf & Denckla, 2005) and phonological awareness (Elision subtest of the Comprehensive Test of Phonological Processing [CTOPP-2]; Wagner et al., 2013).

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, Psychological Corporation, 2009). Timed arithmetic fluency was also measured using the Math Fluency subtest of the Woodcock Johnson (WJ-IV; Schrank et al., 2014), which is a 3-minute test of addition, subtraction, and multiplication facts. 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.

***Executive function (EF)*.** 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. Finally, participants completed the Spatial Span task from the Cambridge Neuropsychological Test Automated Battery (CANTAB; Cambridge Cognition, 2019). 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. Here, we present data on participants' spatial working memory span (higher numbers represent greater working memory capacity), and search errors (higher numbers indicate *less* strategic task performance, in which participants revisit boxes searched previously).

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), 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), akin to our criteria for classifying a participant as reading impaired. 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

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on a single math measure, but were missing data from other math task(s) and therefore did not meet the criteria for MD (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.

fMRI tasks

Phonological word reading task. To elicit reading-specific activations, participants completed a visual phonological awareness task. In the target condition, participants made word-rhyming judgments via button press. Word stimuli were selected for the word-rhyme condition based on the criteria that pairs had ending sounds matching exactly, and that rime patterns were non-identical in spelling (e.g., 'metal,' 'kettle'). Word stimuli pairs were further matched for written frequency, verbal frequency, number of letters, number of phonemes, number of syllables, and concreteness. Word rhyming was compared to a control condition of face-matching judgements, and fixation (see Al Dahhan et al., 2022 for additional details). In each trial, participants viewed two words or faces, one above the other for 4 seconds, and indicated their rhyme/match judgment via button press. The single run consisted of 40 trials of each condition, arranged in 8 20-second blocks per condition with 5 trials per block. Trials within a block were pseudorandomized once to ensure no more than three trials with the same response (yes or no) were presented sequentially. There were also eight 20-second blocks of fixation. Block order (words, faces, fixation) was pseudorandomized once to ensure the same condition was not repeated sequentially. All analyses were conducted with the Word Reading > Face Matching contrast.

Visuospatial working memory task. To isolate networks involved in visuo-spatial working memory (VSWM), children completed an adapted task from a dot matrix task from Klingberg et al. (2002). This task consisted of two VSWM conditions and two control conditions. In the VSWM conditions, red dots passed through a 4 x 4 grid and the participant was instructed to remember the path of the red dots. Then a target stimulus was presented (an empty red circle), the participant was instructed to identify if a previous dot had appeared in this location. On half of the trials, the dot was in a correct location that corresponded to one of the dots in the prior sequence, and on the other half of the trials the dot was in an incorrect location. If the target was presented in an incorrect location, it was presented in a square adjacent to a potentially correct solution. Working memory load was modulated so that either three dots (Short VSWM Condition) or five dots (Long VSWM Condition) were presented. The control conditions were identical to the VSWM conditions, except that the dots were blue and participants were instructed to watch the dots but they did not need to remember their locations. When the target stimulus appeared (an empty blue circle), the participants responded with their index finger regardless of where the circle was located. Consequently, the VSWM and control conditions were identical in the stimulus presentation, except that participants were instructed to remember the spatial locations in the VSWM conditions, and were instructed to watch the dots and wait for the target in the control condition. There were a total of six trials in each VSWM and control condition, resulting in four blocks and 24 total trials per condition. Trial and block order were randomized once and presented in this order to all

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participants. All analyses were conducted with the VSWM (Long+Short) > Control (Long+Short) contrast.

MRI image acquisition and preprocessing

All images were acquired at Athinoula A. Martinos Imaging Center at the McGovern Institute for Brain Research at MIT 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 = 1.69ms, Flip Angle = 7°, voxel size = 1mm isotropic. All BOLD images were acquired with the following parameters: TR = 2s, TE = 30ms, Flip Angle = 90°, voxel size = 3x3x3.6mm. Preprocessing was performed using fMRIPrep 21.0.2 ((Esteban et al., 2018, 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). The following descriptions of data processing are generated by fMRIPrep and are distributed under a Creative Commons license with the express purpose of being included in manuscripts.

***Anatomical data preprocessing*.** The T1-weighted image was corrected for intensity non-uniformity (INU) with N4BiasFieldCorrection (Tustison et al., 2010), distributed with ANTs 2.3.3 (Avants et al., 2009), RRID:SCR_004757), and used as T1w-reference throughout the workflow. The T1w-reference was then skull-stripped with a Nipype implementation of the antsBrainExtraction.sh workflow (from ANTs), using OASIS30ANTs as target template. Brain tissue segmentation of cerebrospinal fluid (CSF), white-matter (WM) and gray-matter (GM) was performed on the brain-extracted T1w using fast (FSL 6.0.5.1:57b01774, RRID:SCR_002823, Zhang et al., 2001). Brain surfaces were reconstructed using recon-all (FreeSurfer 6.0.1, RRID:SCR_001847, Dale et al., 1999), and the brain mask estimated previously was refined with a custom variation of the method to reconcile ANTs-derived and FreeSurfer-derived segmentations of the cortical gray-matter of Mindboggle (RRID:SCR_002438, Klein et al., 2017). Volume-based spatial normalization to one standard space (MNI152NLin2009cAsym) was performed through nonlinear registration with antsRegistration (ANTs 2.3.3), using brain-extracted versions of both T1w reference and the T1w template. The following template was selected for spatial normalization: ICBM 152 Nonlinear Asymmetrical template version 2009c [Fonov et al., 2009, RRID:SCR_008796; TemplateFlow ID: MNI152NLin2009cAsym].

Each subject's dataset included one B0 inhomogeneity fieldmaps. A deformation field to correct for susceptibility distortions was estimated based on fMRIPrep's fieldmap-less approach. The deformation field is that resulting from co-registering the EPI reference to the same-subject T1w-reference with its intensity inverted (Huntenburg, 2014; Wang et al., 2017). Registration is performed with antsRegistration (ANTs 2.3.3), and the process regularized by constraining deformation to be nonzero only along the phase-encoding direction, and modulated with an average fieldmap template (Treiber et al., 2016).

Functional data preprocessing. For each of the BOLD runs found per subject (across all tasks and sessions), the following preprocessing was performed. First, a reference volume and its skull-stripped version were generated using a custom methodology of fMRIPrep. Head-motion

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parameters with respect to the BOLD reference (transformation matrices, and six corresponding rotation and translation parameters) are estimated before any spatiotemporal filtering using mcflirt (FSL 6.0.5.1:57b01774, Jenkinson et al., 2002). The estimated fieldmap was then aligned with rigid-registration to the target EPI (echo-planar imaging) reference run. The field coefficients were mapped on to the reference EPI using the transform. BOLD runs were slice-time corrected to 0.959s (0.5 of slice acquisition range 0s-1.92s) using 3dTshift from AFNI (Cox & Hyde, 1997, RRID:SCR_005927). The BOLD reference was then co-registered to the T1w reference using bbregister (FreeSurfer) which implements boundary-based registration (Greve & Fischl, 2009). Co-registration was configured with six degrees of freedom.

Several confounding time-series were calculated based on the preprocessed BOLD: framewise displacement (FD), DVARS and three region-wise global signals. FD was computed using two formulations following Power (absolute sum of relative motions, Power et al., 2014) and Jenkinson (relative root mean square displacement between affines, Jenkinson et al., 2002). FD and DVARS are calculated for each functional run, both using their implementations in Nipype (following the definitions by Power et al., 2014). The three global signals are extracted within the CSF, the WM, and the whole-brain masks. Additionally, a set of physiological regressors were extracted to allow for component-based noise correction (CompCor, Behzadi et al., 2007). Principal components are estimated after high-pass filtering the preprocessed BOLD time-series (using a discrete cosine filter with 128s cut-off) for the two CompCor variants: temporal (tCompCor) and anatomical (aCompCor). tCompCor components are then calculated from the top 2% variable voxels within the brain mask. For aCompCor, three probabilistic masks (CSF, WM and combined CSF+WM) are generated in anatomical space. The implementation differs from that of Behzadi et al. in that instead of eroding the masks by 2 pixels on BOLD space, the aCompCor masks are subtracted from a mask of pixels that likely contain a volume fraction of GM. This mask is obtained by dilating a GM mask extracted from the FreeSurfer's aseg segmentation, and it ensures components are not extracted from voxels containing a minimal fraction of GM. Finally, these masks are resampled into BOLD space and binarized by thresholding at 0.99 (as in the original implementation). Components are also calculated separately within the WM and CSF masks. For each CompCor decomposition, the k components with the largest singular values are retained, such that the retained components' time series are sufficient to explain 50 percent of variance across the nuisance mask (CSF, WM, combined, or temporal). The remaining components are dropped from consideration. The head-motion estimates calculated in the correction step were also placed within the corresponding confounds file. The confound time series derived from head motion estimates and global signals were expanded with the inclusion of temporal derivatives and quadratic terms for each (Satterthwaite et al., 2013). Frames that exceeded a threshold of 0.9 mm FD or 3.0 standardized DVARS were annotated as motion outliers.

The BOLD time-series were resampled into standard space, generating a preprocessed BOLD run in MNI152NLin2009cAsym space. All resamplings can be performed with a single interpolation step by composing all the pertinent transformations (i.e. head-motion transform matrices, susceptibility distortion correction when available, and co-registrations to anatomical

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and output spaces). Gridded (volumetric) resamplings were performed using antsApplyTransforms (ANTs), configured with Lanczos interpolation to minimize the smoothing effects of other kernels (Lanczos, 1964). Non-gridded (surface) resamplings were performed using mri_vol2surf (FreeSurfer).

Inclusion criteria. N = 60 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).

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, and squared expansion terms. We also included ACompCor terms that explained 50% of variance in a combined white matter and cerebrospinal fluid mask, one-hot encoded vectors for any non-steady state volume, as well as cosine regressors that acted as high-pass filters (128 seconds). For every task contrast of interest, we computed subject-level effect size maps, which were the basis of our second-level models. We ran second-level models (group-wise and correlation analyses) 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. Effect-size maps were converted to t-statistics and normalized to z-statistics. All reported group comparisons are thresholded at an FDR corrected $p < .05$, and correlation analyses are thresholded at an uncorrected $p < .001$.

Results

Descriptive statistics across all variables used for study inclusion and group classification are presented in **Table 1.** Additional demographics across the three participant groups 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

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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. [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 Test 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

Behavioral differences between RD-Only and RD+MD Groups

We conducted *t*-test comparisons to examine differences in sample characteristics and cognitive skills between the RD-Only Group and RD+MD Group (**Table 3**). There were no significant differences between 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

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timed word reading fluency, all measures of math skill, and all measures of EF (processing speed, auditory working memory, and visuospatial working memory).

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	.713	0.09
Grade	5.50	0.63	5.43	0.77	0.39	.699	0.10
Sex (1=M, 2=F)	1.40	0.50	1.54	0.51	-1.14	.259	-0.28
Socioeconomic Status[1]	56.94	8.04	51.54	11.89	2.04	.045 *	0.52
Nonverbal Cognition[2]	107.67	10.87	102.70	11.01	1.85	.069	0.45
Reading and Related Skills							
Phonological Awareness[3]	8.28	2.43	7.73	2.85	0.82	.414	0.20
Word Reading Efficiency[4]	83.97	8.27	78.56	10.07	2.35	.022 *	0.58
Basic Reading Skills Cluster[5]	82.70	9.90	79.75	9.86	1.21	.232	0.30
Mathematics							
Math Facts Fluency Composite[6]	97.77	11.70	76.51	8.70	8.52	<.001 ***	2.09
Math Calculation Skills Cluster[7]	97.45	8.83	76.12	8.82	9.88	<.001 ***	2.44
Executive Function							
Processing Speed[8]	97.17	12.21	87.11	13.11	3.17	.002 **	0.74
Auditory Working Memory Index[8]	93.62	14.23	84.57	10.34	2.99	.004 **	2.58
Visuospatial Working Memory Span[9]	6.29	1.23	5.44	1.34	2.23	.030 *	0.65
Visuospatial Working Memory Errors[9]	11.33	6.41	17.07	7.61	-2.78	.008 **	-0.81
fMRI tasks							
Word Reading Task Accuracy	83.22	16.75	77.50	19.63	0.99	.330	0.31
Word Reading Response Time (sec)	1.86	0.28	1.80	0.32	0.63	.536	0.20
VSWM Task Accuracy	82.14	14.20	71.88	23.39	1.75	.088	0.52
VSWM Response Time (sec)	0.91	0.15	0.94	0.17	-0.72	.477	-0.22

Note. [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.

Neurocognitive differences between RD-Only and RD+MD Groups

First, we examined the neurocognitive bases of phonological word reading and visuospatial working memory across all participants (RD-Only, RD+MD, and Other). **Figure 1** visualizes 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

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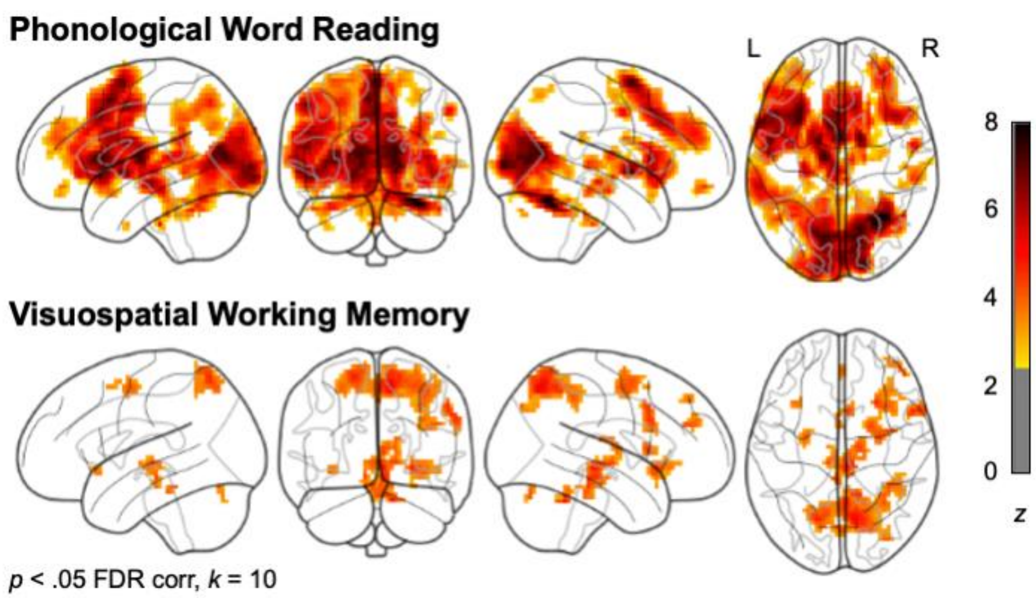
expected, the word reading task engaged a left-lateralized network of frontal, temporo-parietal and occipital regions in the perisylvian language network. The VSWM task engaged the bilateral superior parietal and temporal lobes, and primarily right-lateralized frontal regions, as well as bilateral subcortical regions.

Figure 1

Experimental task > control condition contrasts for all participants



We then examined how comorbid RD+MD might be associated with neurocognitive differences during phonological processing and VSWM using two complementary approaches. We began by conducting two sample *t*-tests between the RD-Only versus RD+MD groups (**Table 4, Figure 2**). There were no differences in the Phonological Word Reading > Face Matching contrast between RD-Only (N = 18) and RD+MD groups (N = 18), even at a reduced threshold of p < .001 uncorrected. However, the VSWM > Control contrast revealed significant group differences. The RD-Only Group (N = 20) demonstrated significantly greater activation of the bilateral occipital cortex than the RD+MD Group, whereas RD+MD Group (N = 21) showed greater activation than the RD-Only Group in a small cluster in right primary motor cortex. Decoding via 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 group.

Table 4

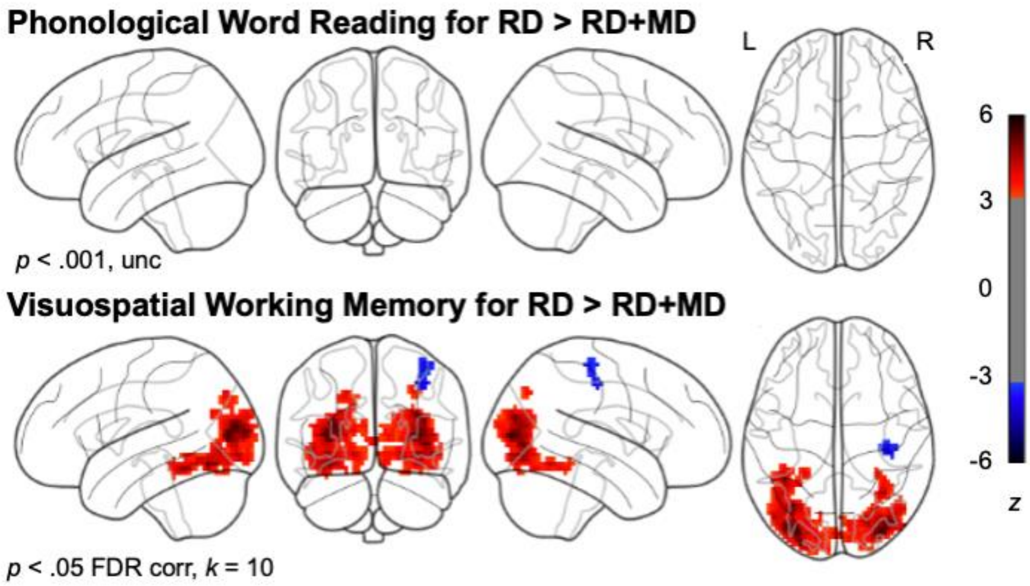
RD-Only vs. RD+MD group differences in brain activation during phonological word reading and visuospatial working memory fMRI tasks

			MNI coordinates		
Location of cluster	Mean T	Volume (mm)	*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

Figure 2

Experimental task > control condition comparison for RD-Only > RD+MD.



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Notably, there were no significant differences between RD and RD+MD Groups 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, we continued to see significant differences for RD > RD+MD in the bilateral occipital cortex when controlling for all of the above variables; RD+MD > RD activation in right primary motor cortex did not survive when controlling for SES or task accuracy. For the phonological word reading task, we failed to see any group differences when each nuisance regressor was included, even at a reduced threshold.

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 & 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 vulnerability in math, but did not clearly meet the criteria for MD. To maximize our sample of RD participants across a full spectrum of math ability, we examined brain-behavior correlations across all RD-Only, RD+MD and Other participants.

We conducted whole-brain regression analyses using each participant's average score across all four behavioral single word reading tasks (ReadAvg) and average score across all four math tasks (MathAvg) as covariates. This continuous analysis specifically tested H1, which suggested that math skill would be correlated with brain activation related to phonological processing, 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 analyses were thresholded at a more lenient $p < .001$ (uncorrected).

During the Word Reading task, reading skill was positively associated with right frontal activation, and negatively associated with activation across bilateral superior parietal and occipito-temporal regions. Math skill was positively associated with bilateral clusters in the inferior/superior parietal cortex, as well as additional right supplementary motor, occipito-parietal and occipito-temporal clusters. During the VSWM task, reading skill was negatively associated with activation of the bilateral orbitofrontal cortex, a region frequently implicated in working memory (Owen et al., 2005). Math skill was positively associated with bilateral occipito-temporal engagement during VSWM. Notably, these associations between math skill and occipito-temporal activation are consistent with the RD-Only v. RD+MD group comparison, supporting the interpretation that poor math ability was associated with less robust activation of visual processing regions.

Figure 3

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

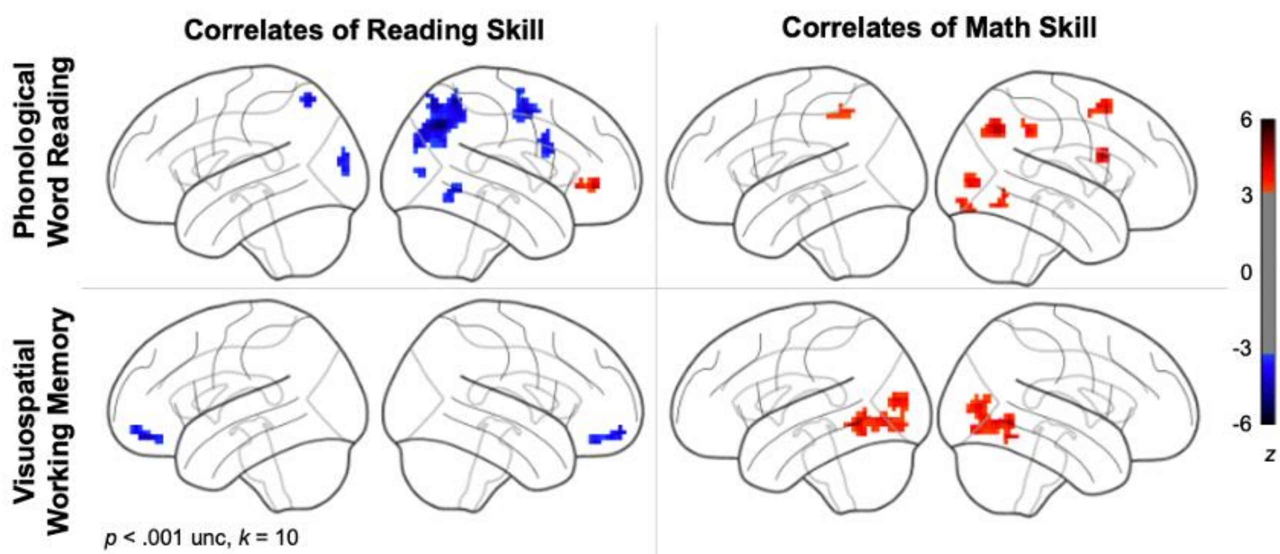

Table 5

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

			MNI coordinates		
Location of cluster	Mean T	Volume (mm)	*x*	*y*	*z*
Word reading task correlation with reading skill, controlling for math skill					
R superior parietal lobule	-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
R middle/inferior temporal gyrus	-3.48	842	56.5	-57.5	-6.5
L superior parietal lobule	-3.53	713	-21.5	-66.5	58.3
L middle lateral occipital cortex	-3.46	616	-30.5	-93.5	18.7
R medial frontal cortex	3.53	616	14.5	44.5	-2.9
R middle frontal/precentral gyrus	-3.48	518	47.5	-0.5	51.1
R middle lateral occipital cortex	-3.22	356	44.5	-81.5	7.9
Word reading task correlation with math skill, controlling for reading skill					
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
R inferior/superior parietal lobule	3.40	713	35.5	-42.5	40.3
R superior frontal/supplementary motor area	3.43	680	11.5	8.5	58.3
R inferior occipital cortex	3.33	616	32.5	-90.5	-13.7
R inferior occipital/inferior temporal cortex	3.37	486	53.5	-60.5	-6.5
L inferior/superior parietal lobule	3.21	454	-45.5	-51.5	51.1
VSWM task correlation with reading skill, controlling for math skill					
L frontal pole	-3.63	1912	-33.5	53.5	-17.3
R frontal pole	-3.50	1814	29.5	62.5	-13.7
R frontal pole	-3.59	324	29.5	41.5	-20.9
VSWM task correlation with math skill, controlling for reading skill					
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
L superior occipital cortex/calcarine gyrus	3.42	518	-15.5	-90.5	11.5
R fusiform gyrus	3.58	421	35.5	-57.5	-13.7

Note. Whole brain analysis, $p < .001$ uncorrected. L = left hemisphere, R = right hemisphere. Clusters do not survive FDR correction.

Discussion

This study examined behavioral and neurocognitive factors associated with co-occurring math difficulties (MD) in a sample of impaired readers, ages 9–13. Leading theories have pointed to phonological processing and working memory (EF) 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 greater phonological impairment than that seen in RD-Only. There were no statistically significant differences on behavioral or neuroimaging measures of

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phonological awareness between the two groups of children. In contrast, we found that RD+MD co-occurrence was associated with worse EF performance than that seen in RD-Only. Furthermore, the RD+MD Group exhibited significantly reduced activation in the visual cortex during a visuospatial working memory task. These results point to difficulties with EF in general and visuo-spatial working memory in particular as differentiating RD children with vs. without co-occurring MD.

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 the criteria for impaired math skill, and over 20% demonstrating a possible vulnerability in math. We found that only 35% of participating RD 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.

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 a single learning difficulty 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 IQ, 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 significantly out-performed the RD+MD Group in timed reading, and all behavioral measures of EF (processing speed, auditory working memory, and visuo-spatial 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).

No evidence for phonological processing difficulties underlying RD+MD

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

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RD-Only groups. Aligned with our present findings, phonological awareness in a group of 2nd graders predicted variance in reading only and not math skill (Child et al., 2019).

The phonological word reading fMRI task also revealed no statistically significant group differences in brain activation, even at a lenient, exploratory threshold. Regression analyses with the full reading-impaired 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 bilateral superior parietal and occipito-temporal activation. This finding extends prior research revealing reduced temporoparietal engagement in impaired readers during phonology tasks (Hoeft et al., 2006; Shaywitz et al., 1998; Temple et al., 2001). In contrast, math skill (controlling for reading) was positively associated with numerous, primarily right-lateralized, small 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). Other clusters observed in the right supplementary motor and occipito-temporal regions may require additional investigation to better understand their association to both math and reading.

Behavioral differences in EF and working memory

Our second hypothesis was that co-occurring RD+MD was related to EF difficulties. As predicted, we observed 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 work 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. Math difficulties, independent of RD, are frequently associated with EF difficulties. For instance, poor math skills have been repeatedly linked to deficits in multiple aspects of EF, particularly visuospatial working memory (David, 2012; Geary, 2004; Mammarella et al., 2018). RD, independent of MD, has also been associated with poor EF (Alt et al., 2022; Reiter et al., 2005). Akin to the present study, nearly half of children with RD also demonstrated low EF abilities, independent of ADHD diagnoses (Al Dahhan et al., 2022).

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 deficits 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

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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 comorbidity therefore requires attention in future research. Furthermore, challenges in working memory may underlie areas other than reading and math, potentially impacting writing, attention, content-area learning, and other academic and non-academic domains, warranting further study.

Neurocognitive differences in visuospatial processing during working memory task

In addition to behavioral differences in EF, we predicted that co-occurring math difficulties were associated with activation differences underlying visuospatial working memory. 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 the bilateral visual cortex. This finding was replicated in a complementary whole-brain regression analysis: greater math skill was associated with greater engagement of the 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 cause 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, 2022). 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).

Both reading and math depend on accurate visual perception and the ability to discriminate between similar forms. Children's ability to match visual figures can explain similar variability in both reading and math outcomes (Cui et al., 2019). Behavioral studies have further associated poor visuo-spatial abilities with co-occurring reading and math difficulties. Compared to typically developing controls, both children with RD-Only and children with 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). Visuospatial skills in children with RD, such as recalling and reproducing complex figures, can discriminate between those with and without co-occurring math difficulties (Helland & Asbjørnsen, 2003).

The visuospatial processing differences frequently reported in RD seem to be relatively

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independent from the language-based or phonological difficulties that are often considered a core deficit (Helland & Asbjørnsen, 2003; Kristjánsson & Sirgudadóttir, 2022). 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). To date, however, there has been limited evidence of visual processing differences at the neurocognitive level in RD+MD.

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. This result demonstrates that recruitment of the visual cortex varies substantially across children with RD. Deficits in visual processing may therefore not be at the core of all RD, but may represent an additive challenge for many impaired readers that is associated with increased RD+MD risk.

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). We also note that the whole brain correlation analyses with math and reading skill did not survive FDR correction and therefore should be interpreted cautiously.

Conclusion

Children with RD frequently struggle with co-occurring MD. The present study aimed to identify the behavioral and neurocognitive factors associated with MD in a sample of children with RD. We found that 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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