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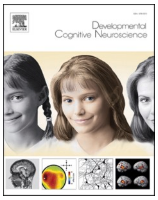

Socioeconomic dissociations in the neural and cognitive bases of reading disorders

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ABSTRACT

Childhood socioeconomic status (SES) strongly predicts disparities in reading development, yet it is unknown whether early environments also moderate the cognitive and neurobiological bases of reading disorders (RD) such as dyslexia, the most prevalent learning disability. SES-diverse 6–9-year-old children (n = 155, half with RD) completed behavioral and functional magnetic resonance imaging (fMRI) tasks engaging phonological and orthographic processing, which revealed corresponding double-dissociations in neurocognitive deficits. At the higher end of the SES spectrum, RD was most strongly explained by differences in phonological skill and corresponding activation in left inferior frontal and temporoparietal regions during phonological processing—widely considered the “core deficit” of RD. However, at the lower end of the SES spectrum, RD was most strongly explained by differences in rapid naming skills and corresponding activation in left temporoparietal and fusiform regions during orthographic processing. Findings indicate that children’s early environments systematically moderate the neurocognitive systems underlying RD, which has implications for assessment and treatment approaches to reduce SES disparities in RD outcomes. Further, results suggest that reliance on high-SES convenience samples may mask critical heterogeneity in the foundations of both typical and disordered reading development.

1. Introduction

Reading disorders (RD), including developmental dyslexia, are the most prevalent learning disability (Shaywitz, 1998), and substantial research has investigated the underlying cognitive and neurobiological mechanisms to inform interventions. While there is much evidence that socioeconomic disadvantage is associated with reduced reading skills (McLoyd, 1998; Romeo et al., 2020; Sirin, 2005; White, 1982), there is little evidence for whether and how children’s early environments may specifically influence the neurocognitive foundations of RDs. Such findings are important, because different RD mechanisms may respond preferentially to tailored instruction and potentially reduce SES disparities in reading outcomes.

Learning to read is a multi-step process that involves parsing a language’s speech sounds (phonemes), recognizing letters and letter patterns (graphemes), mapping phonemes to graphemes, blending phonemes into meaningful words, and over time, automatically recognizing words and fluently reading text for comprehension. Children who struggle with literacy acquisition may exhibit difficulty with any (or multiple) of these processes, including phonological processing, orthographic processing, language comprehension, and/or fluency (Peterson and Pennington, 2015). This leads to a variety of heterogeneous RD profiles, in which children may appear on the surface to struggle similarly, yet different “core deficits” give rise to an individual child’s

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reading difficulties. Understanding RD heterogeneity is critical for informing educational policy, screening, and interventions.

Multiple deficit models propose that, rather than a single core deficit, learning disabilities such as RD are caused by multiple, probabilistic risk factors (Pennington, 2006). One such theory, the double-deficit hypothesis (Wolf and Bowers, 1999), proposes two independent sources of reading difficulty in dyslexia: 1) deficits in phonological processing (meta-linguistic awareness of language sounds), which is critical for understanding how speech sounds combine to form words, and 2) deficits in naming speed (the rapid retrieval of names for visually-presented familiar items, such as letters), which is the foundation of fluent orthographic processing, in which groups of letters or words are processed as patterned units (Bowers et al., 1999; Bowers and Wolf, 1993). By this account, impairment in one or the other skill can result in RD, and impairments in both result in a more severe disorder. These distinct phenotypes are supported by both behavioral and neuroimaging evidence. For example, during reading, children with specific phonological deficits exhibit less activation in frontoparietal reading regions known to support phonological processing, whereas children with rapid naming deficits exhibit reduced activation in right cerebellar regions, and children with double deficits exhibit reduced activation in both regions and reduced inter-region connectivity (Norton et al., 2014). Together, these findings suggest that children with RD exhibit diverse profiles of behavioral and neurobiological deficits that differentially involve phonological and orthographic processing skills.

An additional source of variation in reading abilities is environmental. Childhood SES is consistently one of the strongest predictors of developmental reading outcomes (National Center for Education Statistics, 2021). Evidence supports many interrelated explanatory mechanisms, including differences in home literacy environments, disparities in access and use of high quality education and resources such as libraries, and myriad developmental risk factors associated with poverty, such as toxic stress and environmental toxins (for review, see Romeo et al., 2020). Despite the strong associations between SES and reading development, there is little research on the role of SES specifically on RD. This is partially because most RD studies (and especially neurobiological studies) have been conducted in high-SES "convenience samples," which may have restricted the role of environmental influences. Supporting this, RD heritability exhibits a significant gene-environment interaction, such that children from lower-SES backgrounds show *reduced* influence of genetics and *increased* influence of environment, as compared to children from higher-SES backgrounds (Friend et al., 2008). This suggests that variation in early language and literacy environments may have a disproportionate effect on RD manifestations in children from lower-SES backgrounds, as compared to their more-studied higher-SES peers.

A burgeoning literature finds that SES systematically moderates relationships between reading skills and their neurobiological foundations in readers with average and low-average skills. In three functional magnetic resonance imaging (fMRI) studies of 5–12-year-old children, SES moderated relationships between phonological skills and associated activation in all parts of the reading network, including the fusiform gyrus(Noble et al., 2006), superior temporal gyrus (Younger et al., 2019), and prefrontal cortex (Conant et al., 2017). Similarly, in two diffusion tensor imaging (DTI) studies with 4–8 year-old children, SES moderated relationships between reading skills and measures of white matter integrity in the inferior longitudinal fasciculus (Gullick et al., 2016; Ozernov-Palchik et al., 2019), a ventral tract presumed to subserve orthographic processing by connecting occipitotemporal visual processing regions (Vandermosten et al., 2012). Together, these findings suggest that children may come to rely on different neurocognitive systems to acquire literacy due to neurobiological adaptations to early environmental variations. Characterizing this heterogeneity importantly reveals how different brains learn to read, for moving from deficit models of socioeconomic disadvantage to models of adaptive functioning in context (D'Angiulli et al., 2012; Nketia et al., 2021), and for optimizing education for learners from diverse backgrounds.

However, it remains unknown whether SES also moderates the neurobiological and cognitive bases of *atypical* reading development. If so, this could inform approaches to assessment (such as early screening), instruction, and remediation for children with RD. Supporting this possibility, in a diverse sample of 6–9-year-old children with RD, SES moderated the response to an intensive reading intervention that principally focused on orthographic processing, in contrast to interventions that focus exclusively on phonics (Romeo et al., 2018). Specifically, children from lower SES backgrounds exhibited greater reading improvements and cortical plasticity throughout canonical reading brain networks, as well as homologous right hemisphere regions. These differences in treatment response and plasticity by SES suggest that experience-related variation in RD profiles may have predisposed children from lower-SES backgrounds to disproportionately benefit. However, SES variation in RD profiles has yet to be investigated in comparison to similarly diverse typically developing readers.

The present study explored whether SES systematically moderates the cognitive and neurobiological mechanisms underlying RD. In a large, diverse sample of children with RD and SES-matched typically developing peers, we investigated cognitive and neurobiological variation in phonological and orthographic processing to reveal whether the neurocognitive bases of RD vary by children's early SES environments.

2. Methods

2.1. Participants

Participants were children ($n = 155$; 93 M/62 F) ages 6.6–9.6 years (M=7.94, SD=0.71 years) in 1st through 3rd grades (Table 1). The gender distribution of participants reflects the fact that RDs are more frequently identified in males than females. Children were recruited into one of two groups: those with a reading disorder ("RD," $n = 76$) and those who were typically developing ("TD," $n = 79$). RD and TD groups did not differ on age [$t(153) = 1.31, p = .19$] or gender (2-sided Fisher's exact test $p = .19$). Written informed consent was obtained from parents, and written assent was obtained from all child participants. All procedures were approved by the Institutional Review Board at the Massachusetts Institute of Technology.

A primary caregiver reported the child's demographics. Race/ethnicity ("select all that apply") included $n = 108$ White/Caucasian, $n = 48$ Black/African American, $n = 22$ Hispanic/Latino, $n = 10$ Asian, and $n = 3$ Native American/American Indian. Thirty participants selected more than one race/ethnicity, which are included in the counts above. Although race/ethnicity are reported for descriptive purposes, neither is used as an independent variable or covariate based on current best practices, in favor of more proximal potential explanatory factors (APA Task Force on Race and Ethnicity Guidelines in Psychology, 2019; Helms et al., 2005).

The majority of children ($n = 147$) were reported to either live with or spend significant time with two parents/caregivers, and for these children, parental education was operationalized as the average number of years of education of both parents/caregivers. For the eight children who only had significant contact with one caregiver, parental education was operationalized as the years of education of that caregiver. Parental education ranged from 10 years (partial high school) to 21 years (doctoral degree), with a mean of 15 years (some college) and standard deviation of 2.4 years. This is representative of the geographical region where the study was conducted, where 49 % of adults 25 and older hold a bachelor's degree or higher (U.S. Census Bureau, 2019). Parental education did not differ between RD and TD groups [$t(153) = 0.55, p = .59$]. A subset of parents ($n = 121$) also reported total family income, which was significantly correlated with parental education ($r = 0.24, p = .007$); however, because these data were not available for all participants, parental education was retained as the primary measure of SES. Primary analyses consider SES continuously, and secondary analyses

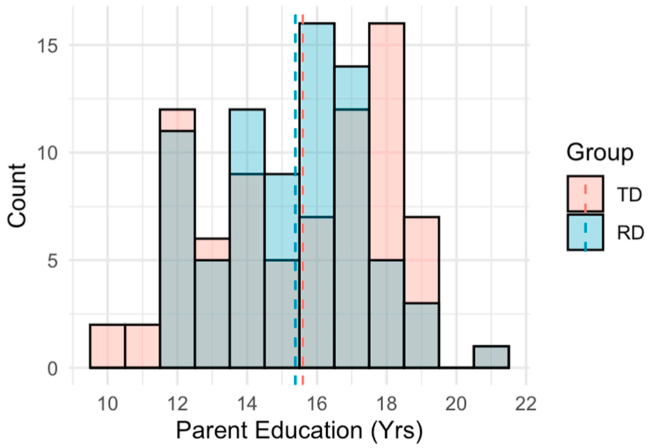

Fig. 1. Distribution of participant SES (as indexed by average parent education), split by reading group. Dashed lines represent group means, which do not significantly differ.

consider higher (≥16 years of education, n = 82) and lower (<16 years, n = 73) SES groups according to a median split.

2.2. *Inclusion criteria and group determination*

Participants were recruited through local schools and community advertisements. All children were required to be native English speakers; 33 children (21 %) were reported to either know or speak another language with moderate or greater proficiency, and another 14 children (9 %) were learning a second language (other than English) in school but were not considered bilingual.

Children in the RD group were required to have a parent- or teacher-reported history of reading difficulty or delay, and no developmental, neurological, or psychological disorders other than reading, language, or attention disorders. Language and attention disorders are highly comorbid with reading disorders (Boada et al., 2012; Pennington and Bishop, 2009), so these comorbidities were allowed. Children in the TD group were required to have a lack of reading difficulty or delay (current or prior), as well as no developmental, neurological, or psychological disorders, and no immediate family members with a reading disorder.

Additionally, children in the RD group were required to meet at least one of the following criteria: (1) a clinical diagnosis of developmental dyslexia or specific learning disability, reading subtype (n = 44, 63 %); (2) a standard score less than 90 on two of four single word reading assessments described below (n = 62, 82 %); and/or (3) an average standard score less than 90 on the four single word reading assessments (n = 57, 75 %). Half of the children in the RD group met all three criteria (n = 38, 50 %) and an additional 23 (30 %) met two criteria. Children were not required to have clinical diagnoses because lower-SES students face disparate access to neuropsychological evaluations and diagnostic services. Children in the TD group were required to *both* score 90 or greater on three of four single word reading assessments and have an average single word reading score equal to or greater than 90.

2.3. *Cognitive assessments*

All participants completed a battery of standardized assessments to measure their cognitive, reading, and language skills. Age-normed standard scores (M=100, SD=15) were used in all analyses to control for the age range of the sample. Descriptive statistics are provided in Table 1.

Non-verbal cognition was assessed with the Matrices subtest of the *Kaufman Brief Intelligence Test, 2nd edition* (KBIT-2)(Kaufman and Kaufman, 2004). This test measures fluid reasoning by requiring children to perceive relationships and complete visuospatial analogies. Children who received a standard score below 80 (9th percentile) were excluded from the remainder of the study. Additionally, visuospatial processing speed was assessed with two subtests of the *Wechsler Intelligence Scale for Children, 4th edition* (WISC-IV)(Wechsler, 2003). The Coding subtest requires drawing symbols corresponding to keyed shapes or numerals, and Symbol Search requires marking whether a target symbol appears in a search group. Both are timed tests, and together make up the Processing Speed Index. Children's receptive vocabulary was assessed with the *Peabody Picture Vocabulary Test, 4th edition* (PPVT-4)(Dunn and Dunn, 2007).

Children's word reading skills were assessed with the Word Identification (WI) and Word Attack (WA) subtests of the *Woodcock Reading Mastery Test, 3rd edition* (WRMT-III)(Woodcock, 2011), and the Sight Word Efficiency (SWE) and Phonemic Decoding Efficiency subtest (PDE) of the *Test of Word Reading Efficiency, 2nd edition* (TOWRE-2)(Torgesen et al., 2012). WI and SWE assess the ability to recognize and read real words, while WA and PDE assess the ability to decode pseudowords. WI and WA are untimed tasks, and combine into the Basic Skills Cluster, henceforth referred to as Word Reading Accuracy. SWE and PDE assess how many words are read within 45 s, and combine into a Total Word Reading Efficiency Index, henceforth referred to as Word Reading Automaticity.

The two reading subskills assessed were phonological processing and rapid automatized naming. Phonological processing was assessed with four subtests of the *Comprehensive Test of Phonological Processing* (CTOPP)(Wagner et al., 1999). The Elision subtest measures the ability to remove phonological segments from spoken words to form other words. The Blending Words subtest measures the ability to combine sounds to form words. Elision and Blending Words together make up the Phonological Awareness (PA) composite, which indexes the awareness of and access to the phonological structure of oral language. Additionally, the Memory for Digits subtest measures the ability to repeat a sequence of numbers, and the Nonword Repetition subtest measures the ability to repeat nonwords. Together, Memory for Digits and Nonword Repetition make up the Phonological Memory (PM) composite, which indexes the ability to code information phonologically for temporary storage in working or short-term memory. The PA and PM composites were averaged to yield an overall Phonological Processing composite.

Rapid naming—the ability to recognize and rapidly name visual symbols—was assessed with three subtests of the *Rapid Automatized Naming and Rapid Alternating Stimulus Tests* (RAN/RAS)(Wolf and Denckla, 2005). The Objects and Letters subtests each present participants with 50 repetitions of five high-frequency stimuli (line drawings and letters, respectively) that children name as quickly and as accurately as possible. The 2-Set Letters and Numbers subtest present 50 repetitions of five letters and five numbers intermixed. Standard scores on all three subtests were averaged to yield an overall rapid naming composite.

2.4. *Neuroimaging data acquisition*

All structural and functional scans were acquired on a 3 T Siemens MAGNETOM TrioTim syngo MR B17 scanner equipped for echo planar imaging (EPI; Siemens, Erlangen, Germany) with a 32-channel phased array head coil. A T1-weighted MPRAGE (van der Kouwe et al., 2008) was acquired with a single shot, interleaved series with TR = 2530 ms, TE = 1.64 ms, FoV = 220 mm, and flip angle = 7.0°, yielding 176 slices with 1 mm^3 resolution. The vNav-enabled scan estimated motion throughout the T1w scan and reacquired/replaced *k*-space data unduly affected by motion (Tisdall et al., 2012). All functional images were acquired with an interleaved, descending series with TR = 2000 ms, TE = 30 ms, FoV = 192 mm, flip angle = 90°, producing 32 slices with 3 mm^3 resolution. Before each scan, six dummy volumes were acquired and discarded to reach equilibrium, and online prospective acquisition correction (PACE)(Thesen et al., 2000) was implemented to reduce the effect of motion artifacts on functional data. Subjects wore insert earphones designed to muffle the external scanner noise while clearly

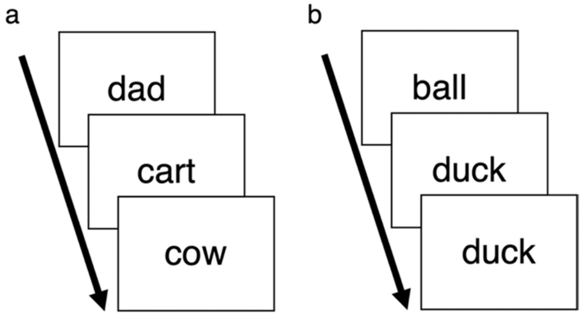

Fig. 2. Schematic of functional MRI tasks. For both tasks, participants saw a series of printed words. (a) For the phonological task, participants were instructed to press a button when two words in a row started with the same first sound, so "cart" followed by "cow" would prompt a button press. (b) For the orthographic task, participants were instructed to press a button when the same word appeared twice in a row, so "duck" followed by "duck" would prompt a button press.

transmitting the sounds necessary for some functional tasks, and indicated button presses with their right index finger.

2.5. Neuroimaging tasks

Participants completed two separate functional MRI tasks, one tapping phonological processing and one tapping orthographic processing. In each task, participants saw a series of short, one- or two-syllable words (3–7 letters long, $M = 4.7$, $SD = 1.1$) familiar to first and second graders. Words were presented one at a time, in lowercase font, in black text centered on a light gray background. Words divided into two separate lists per task, and list order was alternated across participants. As words were presented, participants performed a one-back matching task for either the beginning phoneme or the word orthography (see below). All of the children practiced the tasks to mastery on a computer with a different set of stimuli before the scanning session began. (Fig. 1).

The phonological task (Fig. 2a) had two conditions: printed words (text condition) and auditory spoken words (speech condition). Only the text condition is analyzed here for comparison with the orthographic task. Participants were instructed to "press the button when two words in a row start with the same first sound." For example, "goat/green" and "cake/king" start with the same first sound, but "boat/leaf" do not. Ten percent of correct phonological matches did not have matching letters (e.g., cake/king). There were no instances of adjacent words that had the same letter but different phonemes (e.g., cake/circle). Written words were presented for 2200 ms, with a 300-ms presentation of "+ " between words to maintain fixation. To disregard anticipatory responses and allow for slower responses by RD participants, button presses were counted from 500 to 3000 ms after stimulus onset. Blocks (20 s) contained 8 trials of the same condition. Four blocks of 8 trials (20 s) per condition were pseudorandomly distributed (along with four rest blocks) throughout a run, such that a block was never followed by a block of the same condition. Each participant completed two runs, totaling 64 text trials, with 20 (31 %) randomly distributed "yes" trials indicating a phonological match. The contrast of interest was text > rest.

The orthographic task (Fig. 2b) had four conditions: real words, false fonts, shape sequences, and abstract shapes, plus rest. False fonts and shape sequences were character-by-character substitutions of the letters in the real word stimuli, such that they had high and low similarity to Roman letters, respectively; the abstract shapes were symmetric Fourier descriptor curves. Only the real word condition is analyzed here for comparison with the phonological task. Participants were instructed to "press the button when you see the same thing twice in a row." Words were presented for 1200 ms with a "+ " presented for 300 ms between stimuli to maintain fixation. To disregard anticipatory responses, button presses were counted from 300 to 1500 ms after stimulus onset. Blocks (20 s) contained 8 trials of the same condition. Four blocks of 11 trials (16.5 s each) per condition were pseudorandomly distributed (along with four rest blocks) throughout a run such that a block was never followed by another block of the same condition. Each participant completed two runs, such that in total, they experienced 88 real word trials, with 20 (22 %) randomly distributed "yes" trials indicating a visual/orthographic match. The contrast of interest was real words > rest.

2.6. Neuroimaging analysis

Anatomical images were reconstructed and manually corrected with Freesurfer v6.0 to ensure appropriate parcellation and segmentation (Fischl, 2012). Functional images were preprocessed with fMRIPrep v1.4.1, including bias-field correction, brain extraction, normalization to the ICBM 152 nonlinear template, tissue segmentation, and motion correction procedures (Esteban et al., 2019). Normalized and extracted functional images were spatially smoothed using a 6-mm FWHM Gaussian kernel. Functional volumes with > 1 mm framewise displacement were excluded, which is a threshold previously shown to be appropriate for young children (Siegel et al., 2014). Participants with < 70 % surviving volumes across two runs of the full task or < 80 % surviving volumes of the conditions of interest were excluded from analysis for that task. Motion was not correlated with any demographic variables or task performance on conditions of interest. The final sample size was n = 91 (out of 104 attempted scans) for the phonological task and n = 95 (out of 120 attempted scans) for the orthographic task, and 79 participants had usable data on both tasks. Subject-level general linear models (GLMs) were estimated with custom Nipype pipelines (Gorgolewski et al., 2011) with FSL v5.0.9 (Jenkinson et al., 2012). GLMs controlled for the six motion regressors, framewise displacement, and excluded volumes as indicated by fMRIPrep.

Three regions of the left hemisphere associated with language and reading functions were selected a priori as regions of interest (ROIs) and were constructed from anatomical parcellations of the Desikan-Killiany atlas in subject space (Desikan et al., 2006): 1) left inferior frontal ROI comprised pars opercularis and pars triangularis parcellations, which are known to support multiple aspects of language processing including phonological processing (Kovelman et al., 2011; Poldrack et al., 1999) 2) the left temporo-parietal ROI comprised superior temporal and supramarginal parcellations, which also support phonological processing (Pugh et al., 2001; Temple et al., 2001) and 3) the left ventral occipital region consisted of the fusiform parcellation, which supports orthographic processing (Boros et al., 2016; Paz-Alonso et al., 2018). For each task and contrast of interest, the average activation across each entire ROI was extracted for statistical analysis.

2.7. Statistical analysis

All analyses were conducted in R (v. 4.0.2). Results were FDR-corrected for multiple comparisons at the level of each analysis.

To examine group effects on cognitive assessments, four multivariate regressions models were estimated with independent variables of reading group (categorical TD/RD) and SES (continuous parent education), and dependent variables of standard (age-normed) scores on assessments of (1) word reading accuracy, (2) word reading automaticity, (3) phonological processing, and (4) rapid naming. All models controlled for participant gender, and the timed measures (automaticity and rapid naming) additionally controlled for nonverbal processing speed. Age was not covaried because age-normed standard scores were used. A first set of models evaluated only main effects with no interaction term, FDR-corrected for 8 effects of interest (4 assessed domains, 2 predictors). Main effects were evaluated without interaction terms so that they are not conditioned on an interaction. Next, group*SES interaction terms were added, and the models were again FDR corrected for 4 effects of interest (4 assessed domains, 1 interaction each). Significant interactions were interpreted by investigating effects of SES in

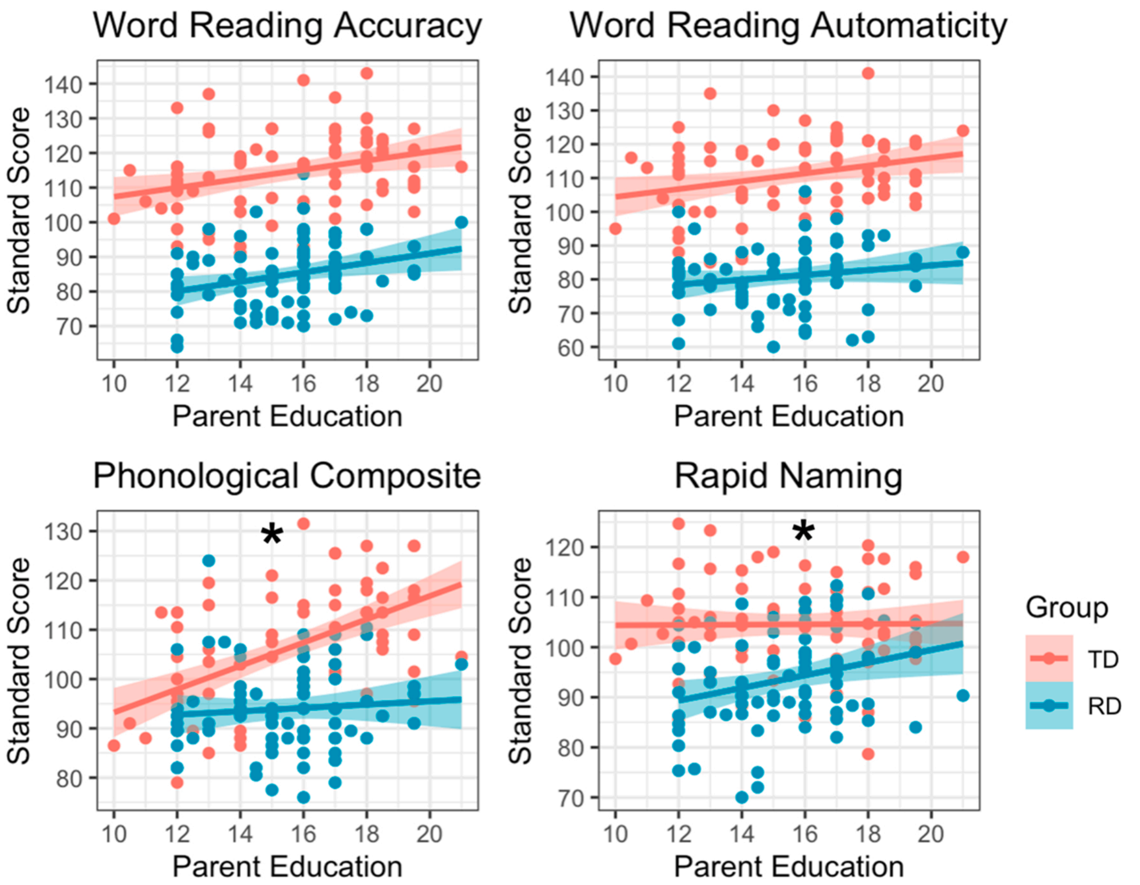

Fig. 3. Performance on standardized assessments as a function of parent education and reading group (TD = Typically Developing; RD = Reading Disability). Asterisks indicate significant interactions after FDR correction. Results of multiple regression models are shown in Table 2.

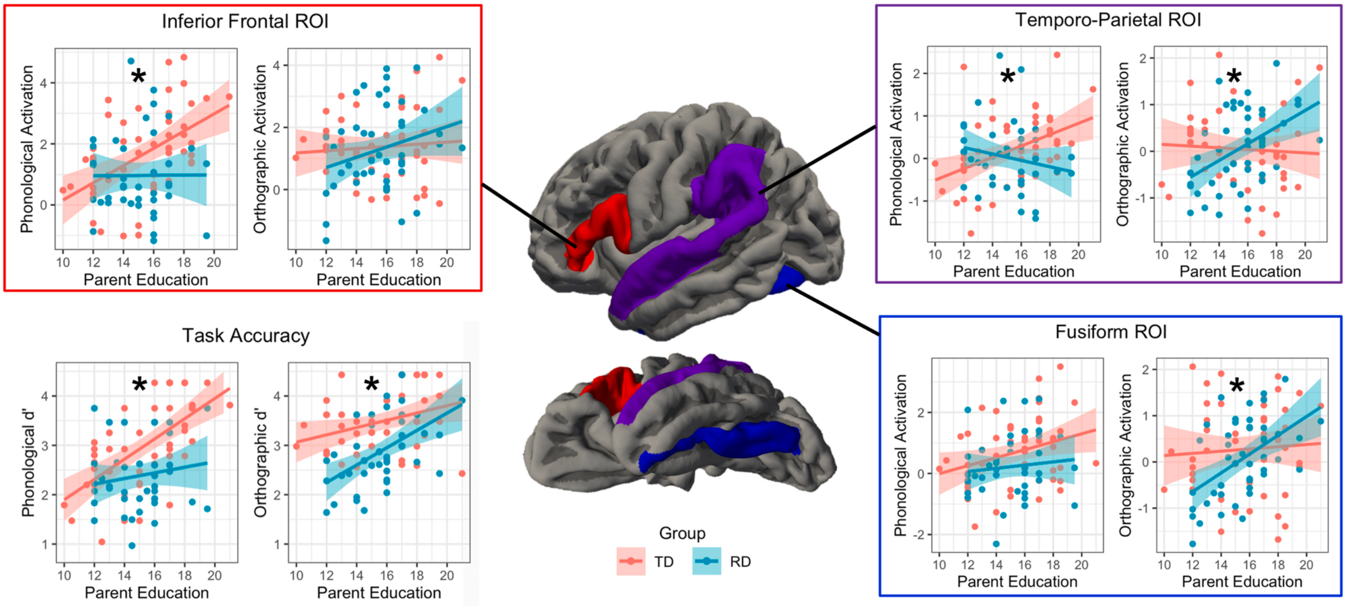

Fig. 4. Task performance and ROI activation as functions of parent education and reading group (TD = Typically Developing; RD = Reading Disability). All pairs of plots show response to the phonological task on the left, and the orthographic task on the right. Plots in the bottom left display task accuracy as measured by the discriminability/sensitivity index (*d*′). All other plots display mean activation across three a priori, anatomically defined, left hemisphere ROIs: inferior frontal (red), temporoparietal (purple), and fusiform (blue). Asterisks indicate significant interactions after FDR correction. Results of multiple regression models are shown in Table 3.

Table 1
Participant demographics and standardized assessment scores.

Measure	Typically Developing (TD)	Reading Disability (RD)	TD-RD Group Difference	Correlation with SES
Gender	43 M, 36 F	50 M, 26 F	n.s.	n.s.
Age (years)	8.01 (0.72)	7.86 (0.70)	n.s.	n.s.
Parental Education (years)	15.59 (2.73)	15.38 (2.10)	n.s.	N/A
Nonverbal Reasoning	114.53 (15.74)	103.33 (13.68)	4.73 (<0.001)	0.46 (<0.001)
Nonverbal Processing Speed	100.78 (14.08)	93.74 (12.29)	3.27 (0.001)	n.s.
Symbol Coding	9.83 (3.02)	8.42 (3.12)	2.84 (0.005)	n.s.
Symbol Search	10.38 (2.75)	9.32 (2.24)	2.60 (0.01)	0.19 (0.04)
Receptive Vocabulary	118.69 (17.05)	108.41 (13.29)	4.16 (<0.001)	0.52 (<0.001)
Word Reading Accuracy	114.65 (11.57)	84.75 (9.89)	17.27 (<0.001)	0.21 (0.02)
Word Identification (real words)	114.92 (11.62)	84.54 (10.46)	17.12 (<0.001)	0.19 (0.03)
Word Attack (pseudowords)	112.28 (11.39)	86.48 (11.00)	14.29 (<0.001)	0.21 (0.02)
Word Reading Automaticity	110.92 (11.49)	80.88 (9.67)	17.37 (<0.001)	n.s.
Sight Word Efficiency (real words)	112.14 (11.09)	83.95 (10.80)	15.98 (<0.001)	n.s.
Phonemic Decoding Efficiency (pseudowords)	108.54 (11.77)	80.08 (9.88)	16.14 (<0.001)	0.18 (0.04)
Phonological Processing	106.47 (11.58)	93.94 (9.11)	7.44 (<0.001)	0.35 (<0.001)
Phonological Awareness	111.08 (13.53)	96.59 (10.73)	7.31 (<0.001)	0.35 (<0.001)
Elision	12.47 (2.74)	8.55 (2.08)	9.95 (<0.001)	0.32 (<0.001)
Blending Words	11.22 (2.53)	10.26 (2.29)	2.46 (0.02)	0.27 (<0.01)
Phonological Memory	101.87 (12.30)	91.37 (10.75)	5.60 (<0.001)	0.29 (<0.001)
Digit Memory	11.03 (2.57)	9.17 (2.44)	4.57 (<0.001)	0.28 (<0.001)
Nonword Repetition	9.59 (2.39)	7.95 (1.73)	4.88 (<0.001)	0.23 (0.01)
Rapid Naming	104.55 (9.32)	93.61 (9.63)	7.16 (<0.001)	n.s.
Objects	99.05 (14.04)	90.35 (12.58)	4.03 (<0.001)	n.s.
Letters	104.67 (10.42)	94.39 (11.49)	5.81 (<0.001)	n.s.
Letters/Numbers 2-set	109.94 (11.03)	95.95 (11.76)	7.61 (<0.001)	n.s.

each group separately. Interactions were further probed by dividing participants into higher and lower-SES groups by median split, and estimating logistic regressions predicting reading group as a function of phonological processing and rapid naming, controlling for gender and processing speed, FDR-corrected for 4 effects of interest (2 assessed domains, 2 predictors).

Table 2
Main Effects and Interactions for Cognitive Tasks.

Effect	Coefficient Estimate	p-value	FDR adjusted p-value
Word Reading Accuracy			
Group	**29.53**	**< 0.001**	**< 0.001**
SES	**1.33**	**< 0.001**	**< 0.001**
Group*SES	-0.07	0.93	0.93
Word Reading Automaticity			
Group	**28.62**	**< 0.001**	**< 0.001**
SES	**0.89**	**0.01**	**0.01**
Group*SES	0.29	0.70	0.93
Phonological Processing			
Group	**12.02**	**< 0.001**	**< 0.001**
SES	**1.65**	**< 0.001**	**< 0.001**
Group*SES	**2.00**	**0.002**	**0.01**
RAN/RAS			
Group	**9.41**	**< 0.001**	**< 0.001**
SES	0.27	0.37	0.37
Group*SES	**-1.54**	**0.01**	**0.03**

In-scanner task performance was operationalized by the discriminability/sensitivity index d', a measure of the ability to successfully detect a phonological or orthographic match and ignore non-matches. A loglinear correction (Hautus, 1995) was applied to extreme values (0 % and 100 % hit and false alarm rates). Multivariate regressions models were estimated for each task with d' and reaction time (hits only) as the dependent variables, and group and SES as independent variables, controlling for participant age and gender. Models predicting reaction time also control for nonverbal processing speed. As above, a first set of models evaluated only main effects with no interaction term, FDR-corrected for 8 effects of interest (2 tasks, 2 outcome measures, 2 predictors), and second set of models evaluated group*SES interactions, FDR corrected for 4 effects of interest (2 tasks, 2 outcome measures, 1 interaction).

Finally, multivariate regressions models were estimated for each task, with the 3 ROI activations as the dependent variables, and group and SES as independent variables, controlling for participant age and gender. A first set of models evaluated only main effects with no interaction term, FDR-corrected for 12 effects of interest (3 ROIs, 2 tasks, 2 predictors), and second set of models evaluated group*SES interactions, FDR corrected for 6 effects of interest (3 ROIs, 2 tasks, 1 interaction).

3. Results

3.1. Cognitive assessments

Performance on cognitive measures is displayed in Fig. 3. By design, TD children scored higher than children with RD on both word reading assessments, including word reading accuracy (b=29.53, adjusted $p < .001$) and word reading automaticity (b=28.62, adjusted $p < .001$). Additionally, TD children scored higher than children with RD on phonological processing (b=12.02, adjusted $p < .001$) and rapid naming (b=9.41, adjusted $p < .001$) assessments. Additionally, a main effect of SES indicated that children from higher-SES backgrounds exhibited higher scores on measures of word reading accuracy (b=1.33, adjusted $p < .001$), word reading automaticity (b=0.89, adjusted $p < .001$), and phonological processing (b=1.65, adjusted $p < .001$), although SES was not associated with rapid naming after controlling for group (b=0.27, adjusted $p = .37$).

No group by SES interactions were found for either word reading accuracy (b=−0.07, adjusted $p = .93$) or word reading automaticity (b=0.29, adjusted $p = .93$). However, group by SES interactions were significant for phonological processing (b=2.00, $p = .01$) and rapid naming (b=−1.54, adjusted $p = .03$). Notably, these interactions were in opposite directions, such that TD (versus RD) children exhibited stronger effects of SES on phonological processing, while RD (versus TD) children exhibited stronger effects of SES on rapid naming (asterisks in Fig. 3). Effectively, this meant that higher-SES children showed greater TD-RD differences in phonological processing, while lower-SES children showed greater TD-RD differences in rapid naming.

To confirm this effect, participants were divided into higher and lower-SES groups by median split. Logistic regressions controlling for gender and nonverbal processing speed indicated that for children from higher-SES backgrounds, group (TD or RD) was most strongly explained by phonological processing (b=0.23, adjusted $p < .001$), with only a marginal contribution of rapid naming (b=0.09, adjusted $p = .05$). However, for children from lower-SES backgrounds, group status was significantly explained by rapid naming (b=0.19, adjusted $p < .001$),

Table 3
Main Effects and Interactions for fMRI Tasks.

	Phonological Task			Orthographic Task		
Effect	Coefficient Estimate	p-value	Adjusted p-value	Coefficient Estimate	p-value	Adjusted p-value
Task Accuracy						
Group	**-55**	**0.001**	**0.001**	**0.68**	**< 0.001**	**< 0.001**
SES	**0.16**	**< 0.001**	**< 0.001**	**0.11**	**< 0.001**	**0.001**
Group*SES	**0.15**	**0.03**	**0.04**	**-0.15**	**0.02**	**0.03**
Task Reaction Time						
Group	.00	0.91	0.91	-0.03	0.17	0.20
SES	-0.01	0.07	0.12	-0.01	0.10	0.13
Group*SES	0.00	0.84	0.84	**0.00**	**0.01**	**0.03**
Activation in Inferior Frontal Region						
Group	**.64**	**0.03**	**0.08**	0.08	0.77	0.81
SES	**0.19**	**0.001**	**0.02**	0.08	0.13	0.19
Group*SES	**0.28**	**0.03**	**0.04**	-0.14	0.22	0.26
Activation in Temporo-Occipital Region						
Group	.16	0.35	0.44	-0.04	0.81	0.81
SES	0.07	0.08	0.16	0.06	0.11	0.19
Group*SES	**0.21**	**0.01**	**0.03**	**-0.19**	**0.01**	**0.03**
Activation in Fusiform Region						
Group	.41	0.08	0.16	0.17	0.37	0.44
SES	**0.11**	**0.02**	**0.08**	**0.09**	**0.02**	**0.08**
Group*SES	0.07	0.51	0.51	**-0.19**	**0.02**	**0.04**

with no additional contribution of phonological processing (b=0.04, adjusted $p = .26$). These results did not change with additional controls of vocabulary or nonverbal cognition (fluid reasoning).

3.2. *fMRI task performance*

Behavioral task performance is displayed in the bottom left of Fig. 4. Participants performed more accurately on the orthographic task than the phonological task [mean d' orthographic $= 3.15$, phonological $= 2.72$; two-sample $t(182.55) = 3.53$, $p < .001$); paired $t(78) = 4.13$, $p < .001$. Main effects of group indicated that children with RD were significantly less accurate on both the phonological task (b=0.55, adjusted $p = .001$) and the orthographic task (b=0.68, adjusted $p < .001$). Additionally, main effects of SES indicated that higher-SES was significantly associated with better performance on both the phonological task (b=0.16, adjusted $p < .001$) and the orthographic task performance (b=0.11, adjusted $p < .001$). There were no main effects of group or SES on reaction time for either task (all $|b|<0.03$, all adjusted $p > .11$).

Similar to the behavioral assessments, group by SES interactions were significant for performance on both tasks, such that TD children exhibited stronger effects of SES on phonological task accuracy (b=0.15, adjusted $p = .04$), while children with RD exhibited stronger effects of SES on orthographic task accuracy (b=−0.15, adjusted $p = .04$).

3.3. *Brain activation*

Mean activations in the three left hemisphere ROIs are displayed Fig. 4, and whole brain activation maps are shown in Supplementary Figure 1. There were no significant main effects of group; however, TD children exhibited marginally more activation than RD children during the phonological task in the inferior frontal region (b=0.64, unadjusted $p = .03$, adjusted $p = .08$). Main effects of SES indicated that children from higher-SES backgrounds exhibited greater activation during the phonological task in the inferior frontal region (b=0.26, adjusted $p = .04$), and marginally greater activation during both tasks in the fusiform region (phonological: b=0.11, $p = .02$, adjusted $p = .08$; orthographic: b=0.09, $p = .02$, adjusted $p = .08$).

Group by SES interactions were significant for the phonological task in the inferior frontal region (b=0.28, adjusted $p = .04$) and the temporoparietal (b=0.21, adjusted $p = .03$) regions, and for the orthographic task in the temporoparietal (b=−0.19, adjusted $p = .03$) and the fusiform (b=0.19, adjusted $p = .04$) regions (asterisks in Fig. 4). As above, these interactions were in opposite directions, such that TD (versus RD) children exhibited stronger effects of SES on phonological activation in inferior frontal and temporoparietal regions, while RD (versus TD) children exhibited stronger effects of SES on orthographic activation in temporoparietal and fusiform regions. Effectively, this means that higher-SES children showed greater TD-RD differences in inferior frontal and temporoparietal regions during phonological processing, while lower-SES children showed greater TD-RD differences in the same temporoparietal region plus fusiform regions during orthographic processing.

4. Discussion

This study investigated whether the neurocognitive foundations of RD vary by children's socioeconomic environment. In 155 SES-diverse children with and without RD, we found expected main effects of reading group status and SES on reading-related cognitive measures, as well as a double dissociation in both cognitive skills and associated brain activation. Specifically, for children from *higher-SES* backgrounds, RD was most strongly associated with both phonological processing skill and activation in left inferior frontal and temporoparietal regions during a phonological task. However, for children from *lower-SES* backgrounds, RD was most strongly associated with both rapid naming skills and activation in left temporoparietal and fusiform regions during orthographic processing. These findings suggest that aspects of children's early SES environments systematically moderate the cognitive and neurobiological systems underlying RD, which has both empirical and translational implications.

Consistent with a multiple deficit view, children with RD exhibited reduced accuracy on both phonological and orthographic tasks (Peterson and Pennington, 2015; Wolf and Bowers, 1999). Surprisingly, for fMRI activation, a main effect of RD group was only found in the inferior frontal region during the phonological task. However, when the sample is limited to only the higher-SES half of participants (i.e., akin to a "convenience sample"), significant group effects for phonological activation was found in all three ROIs. However, the lower-SES half of participants do not show this pattern, and instead exhibit a unique group effect for orthographic processing in the fusiform ROI. This suggests that representationally biased convenience samples may indicate brain activation patterns of "core deficits" that are not characteristic of all children with RD.

This SES dissociation in the neurocognitive profiles of RD is consistent with a growing literature finding that SES systematically moderates relationships between reading skills and their neurobiological foundations. Specifically, the finding that lower-SES children with RD exhibit a larger difference in orthographic brain functioning is consistent with evidence from diffusion imaging studies that children from lower-SES (versus higher-SES) backgrounds exhibit stronger brain-behavior relationships between reading skills and structural ventral white matter tracts (Ozernov-Palchik et al., 2019), which may suggest that they rely more on visuospatial processing for reading achievement (Gullick et al., 2016). This broadly suggests that variation in children's early experiences may influence the precise pattern of neurocognitive functions they harness to achieve literacy, and in parallel, which functions are most affected by reading disorders.

There are several reasons why varying SES environments may give rise to these differences. RD has a higher genetic influence for children from higher-SES backgrounds, but there is a higher influence of environment for children from lower-SES backgrounds (Friend et al., 2008). On average, higher-SES environments are associated with many factors known to support literacy development, including greater exposure to literacy activities and supportive materials in the home, as well as increased access to books, libraries, and high-quality literacy instruction (Hutton et al., 2021; Pace et al., 2017; Phillips and Lonigan, 2009; Romeo et al., 2020). Thus, higher-SES children who struggle to read despite strong environmental support may be more susceptible to genetic predispositions for phonological processing difficulties, while children from lower-SES backgrounds may be more influenced by variation in literacy-related experiences, such as exposure to print. Another possibility considers adaptive approaches to environmental differences. On average, children from higher-SES backgrounds are exposed to greater quantity and complexity of language (Rowe and Weisleder, 2020), which may selectively advantage linguistic skills such as phonological processing. Indeed, language skills are more strongly associated with SES than visuospatial and other nonverbal skills (Farah et al., 2006; Noble et al., 2007), which is consistent with present findings of a main effect of SES on phonological processing, but not rapid naming. Thus, children from lower-SES backgrounds may disproportionately harness *relative strengths* in nonverbal domains to acquire literacy in an adaptive fashion. As such, they may exhibit optimal response to interventions with a strong focus on orthographic skills in addition to phonological ones (Romeo et al., 2018). Either account has translational implications for both early screening and instructional approaches. In terms of screening, relative deficits in orthographic and/or visuospatial processing may be an overlooked warning sign for RD in readers from diverse backgrounds. Similarly, training orthographic processing skills (e.g., recognizing common orthographic patterns, word visualization and visual search, knowledge of morphology and spelling) (O'Brien et al., 2011) may be important treatment targets with the potential to reduce socioeconomic achievement gaps in reading acquisition.

These findings should be interpreted within the scope of the present study, which may constrain generalizations (Simons et al., 2017). Participants were recruited to represent diversity in parental education, yet this is only one component of SES, which traditionally indexes both financial and sociocultural status. Notably, parental education is a common proxy for SES, tends to be the strongest predictor of children's educational outcomes (Duncan and Magnuson, 2012), and was significantly correlated with family income in the subset of participants with available income data (78 %). However, financial hardship independent of educational resources may uniquely influence brain and cognitive development. Further, this study did not measure any adverse experiences that are often correlated with SES—such as individual or community level stressors, racial/ethnic/linguistic discrimination, and access to high-quality education—which may also influence task performance and/or brain activation. Future studies should examine the potential influence of multiple dimensions of adverse experiences (Sheridan and McLaughlin, 2016).

Additionally, the nature of the study design required purposeful sampling of students with both strong and weak reading skills across the entire SES spectrum; thus, one may argue that the strong readers from lower SES backgrounds are a "niche" sample that may not generalize to broader groups of lower SES students. However, we argue that this group represents an important demonstration of resilience, and understanding their neurocognitive approaches to reading are critical for overcoming deficit narratives about lower SES learners. Other limitations are that all participants were native English speakers, so it is unclear how these results may generalize to children learning to read other languages, and especially those with writing systems that differ in orthographic depth or script type. Finally, while rapid naming involves orthographic processing, it is not an explicit measure of orthographic processing; however, given that the rapid naming results mirrored those of the orthographic fMRI task, it is likely that a pure behavioral measure of orthographic processing would exhibit similar patterns.

In conclusion, this study finds that the neurocognitive foundations of reading disorder vary according to children's early socioeconomic environments. Whereas phonological processing and its brain-based underpinnings are commonly recognized as the "core deficit" of dyslexia, the present findings indicate that other reading-related skills may be more implicated in children from less advantaged backgrounds. It is important to note that this does not suggest that children with RD from lower-SES backgrounds do not have phonological difficulties, but that this may not be the hallmark for all struggling readers, and that effective prevention and intervention must consider individual variation in RD profiles and how these may be influenced by a multitude of environmental factors. On a larger scale, this suggests that representationally biased research samples may mask theoretically and translationally important heterogeneity in neurobiological factors underlying reading development, and that research findings based on exclusively advantaged samples may not generalize to all struggling readers. It is vital that reading difficulties be understood in context for the most effective translation of research to practice in support of struggling learners.

CRediT authorship contribution statement

R.R.R., J.D.E.G., and J.A.C. designed the study aims; T.K.P. and J.A.C. developed the protocol and tasks; R.R.R., T.K.P., H.A.O., K.K.H., and J.A.C. collected, processed, and curated the data; R.R.R. analyzed the data under supervision of J.D.E.G. and J.A.C.; R.R.R. wrote the original paper draft; and all authors edited and provided comments on the paper.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

All data and code is available on OSF in the link provided in the attached file.

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Open practices statement

All numerical data, analytic code, and results (R markdown) for the present study are publicly accessible https://osf.io/zk8f3/. There is not a preregistration for this study.

All continuous measures are represented as mean (standard deviation). “Group Difference” reports a two-tailed t-test statistic and p-value, and “Correlation with SES" reports a zero-order pearson correlation and p-value; p-values for all cognitive assessments are FDR corrected for multiple comparisons, and n.s. = not significant. Nonverbal Reasoning = KBIT-2 Matrices; Nonverbal Processing Speed = WISC-IV Processing Speed Index; Receptive Vocabulary = PPVT-4; Word Reading Accuracy = WRMT-III Basic Skills Index; Word Reading Automaticity = TOWRE-2 Total Word Reading Efficiency Index; Phonological Processing = Average of CTOPP Phonological Awareness and Phonological Memory Indices; Rapid Naming = Average of RAN/RAS Objects, Letters, and 2-Set Letters/Numbers subtests.Table 2.

Results of multiple regression models estimating the effects of group (TD or RD) and SES on standardized assessments of reading skills and reading subskills. Coefficients are unstandardized b values. Main effects are estimated in models without an interaction term. FDR adjustments are made for multiple outcome measures (see Methods), and significant effects are bolded. Corresponding scatterplots are shown in Fig. 3. (Table 3).

Results of multiple regression models estimating the effects of group (TD or RD) and SES on accuracy/reaction time of in-scanner tasks and functional activation in the three regions of interest during the specified task. Coefficients are unstandardized b values. Main effects are estimated in models without an interaction term. FDR adjustments are made for multiple outcome measures (see Methods), and significant/marginally significant effects are bolded. Corresponding scatterplots are shown in Fig. 4.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.dcn.2022.101175.

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