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Research Report

Dissociating executive function and ADHD influences on reading ability in children with dyslexia

Noor Z. Al Dahhan [a,b], *Kelly Halverson* [a,c], *Carrie P. Peek* [a,d], *Dayna Wilmot* [a], *Anila D'Mello* [a], *Rachel R. Romeo* [a], *Olivia Meegoda* [b], *Andrea Imhof* [a,b], *Karolina Wade* [a], *Anissa Sridhar* [a], *Eric Falke* [a,e], *Tracy M. Centanni* [a,f], *John D.E. Gabrieli* [a] and *Joanna A. Christodoulou* [a,b,*]

[a] *McGovern Institute for Brain Research & Department of Brain and Cognitive Sciences, Massachussetts Institute of Technology, USA*
[b] *MGH Institute of Health Professions, Massachussetts Institute of Technology, USA*
[c] *University of Houston, Massachussetts Institute of Technology, USA*
[d] *Boston Children's Hospital, Massachussetts Institute of Technology, USA*
[e] *The Carroll School, Massachussetts Institute of Technology, USA*
[f] *Texas Christian University, Massachussetts Institute of Technology, USA*

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ABSTRACT

Developmental dyslexia (DD) and attention-deficit/hyperactivity disorder (ADHD) are two of the most common neurodevelopmental disorders among school-age children. These disorders frequently co-occur, with up to 40–50% of children with one diagnosis meeting criteria for the other, and similar percentages of children with either DD or ADHD exhibiting impaired executive functions (EF). Although both ADHD and EF deficits are common in dyslexia, there is little evidence about how ADHD and EF deficits specifically influence the brain basis of reading difficulty in dyslexia, and whether the influences of ADHD and EF on dyslexia can be disentangled. The goal of the current study was to investigate, at both behavioral and brain levels, whether reading performance in individuals with dyslexia is more strongly associated with EF or with diagnostic status of comorbid ADHD. We examined reading abilities and EF in children (8-13 years old) with typical reading ability, DD only, or both DD + ADHD. Across both groups with dyslexia, impaired EF was associated with greater impairment on measures loading onto a reading fluency, but not a reading accuracy, factor. There were no significant differences between the DD and DD + ADHD groups on measures of reading fluency or reading accuracy. During functional magnetic resonance imaging (fMRI) while performing a rhyme-matching reading task requiring phonological awareness, typically developing readers showed greater left-hemisphere reading network activation than children with DD or DD + ADHD. Children with DD and DD + ADHD did not show differential activation, but DD children with unimpaired EF showed greater activation than those with impaired EF in reading-related

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* *Corresponding author*. Department of Communication Sciences and Disorders, MGH Institute of Health Professions, 36 First Avenue, Boston MA, 02129, USA.
E-mail address: jchristodoulou@mghihp.edu (J.A. Christodoulou).

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areas. Thus, ADHD status alone had no measurable influence on reading performance or brain activation. Impaired EF in dyslexia, independent of ADHD status, was associated with greater deficits in reading fluency and greater reductions of activation in response to print in the typical left-hemisphere reading network.

1. Introduction

Developmental dyslexia (DD) and attention-deficit/hyperactivity disorder (ADHD) are two of the most prevalent neurodevelopmental disorders, with each disorder affecting approximately 5–10% of school-aged children (Boada et al., 2012; Shaywitz et al., 1990; Visser et al., 2014). DD is characterized by difficulties with accurate and/or fluent word recognition, and poor spelling and decoding abilities (Lyon et al., 2003). ADHD is characterized by persistent patterns of inattention and/or hyperactivity-impulsivity that interfere with functioning and/or development (American Psychiatric Association, 2013). DD and ADHD frequently co-occur (Carroll et al., 2005), with up to 40–50% of children with one diagnosis meeting the diagnostic criteria for the other (DuPaul et al., 2013; Willcutt et al., 2010). Individuals with DD or DD + ADHD also commonly demonstrate deficits in executive function (EF) (Daucourt et al., 2018; Doyle, 2006; Lonergan et al., 2019; Poljac et al., 2010; Willcutt et al., 2005), which describes sets of cognitive abilities necessary for setting and monitoring goals, controlling behavior, and managing complex higher-order cognitive processes (Jurado & Rosselli, 2007).

However, it is currently unclear whether the brain basis of reading disability in individuals with DD is more strongly associated with EF, with diagnostic status of comorbid ADHD, or both. Although ADHD is frequently associated with impaired EF, only about half of children and adults with ADHD demonstrate impaired EF performance (Biederman et al., 2004, 2006; Doyle et al., 2005; Fair et al., 2012; Lambek et al., 2010; Mattfeld et al., 2015; Nigg et al., 2005; Sonuga-Barke, 2005), and ADHD and EF can be dissociated both behaviorally and neurally (Mattfeld et al., 2015). Further, there is little research examining differences in reading disability in children with intact versus impaired EF as most studies examine EF on a continuous basis in relation to reading abilities. Disentangling ADHD status and EF status in relation to dyslexia has implications for theoretical (e.g., reading models) and practical (e.g., assessment, diagnosis, instruction, intervention) considerations (Boada et al., 2012). We address this gap in knowledge in the current study by delineating the relations among DD, ADHD, and EF in the neurocognitive mechanisms underlying reading impairment in DD. Using converging evidence from neuroimaging and behavioral sources can offer novel insights regarding the potentially selective or interacting effects of EF and ADHD status on reading ability in dyslexia.

EF is highly related to learning to read. Performances on EF measures, as early as kindergarten (McClelland et al., 2014), serve as concurrent and longitudinal predictors of reading achievement (Altemeier et al., 2008; Birgisdottir et al., 2015; Doyle et al., 2018; Pascual et al., 2019; van der Sluis et al., 2007). The directionality of the influence between reading and EF measures is unclear (i.e., to what degree successful reading improves EF, or strong EF drives robust reading development, or both). Correlational studies have found that children with impaired reading abilities also have weaker EF skills in verbal and visual working memory, response inhibition, and switching (or shifting) attention (Carretti et al., 2009; Cutting et al., 2009; Kibby et al., 2021, pp. 1–23; Locascio et al., 2010; Lonergan et al., 2019; Reiter et al., 2005). Even for children who have adequate decoding abilities, deficits in EF may contribute to difficulty in attaining age-appropriate levels of reading automaticity and fluency (Nguyen et al., 2020).

Current behavioral evidence supports the multiple cognitive deficit hypothesis of DD + ADHD presentation, in which children with DD and/or ADHD show significant deficits on EF measures compared to typically developing children, with similar patterns of impairments between DD-only and DD + ADHD participants (Kibby et al., 2021, pp. 1–23; Lonergan et al., 2019; McGrath et al., 2011; Pennington, 2006; Pennington et al., 2012; Willcutt et al., 2010). Intervention efforts have found that children with both reading disability and ADHD benefit from a combined treatment approach (Tamm et al., 2017). These studies support the importance of ADHD and EF in understanding variation in dyslexia and its remediation.

No functional neuroimaging study of word-level reading has disentangled the influences of ADHD and EF on reading-related activations in dyslexia. There have been a few related structural imaging studies (Kibby et al., 2009a, 2009b). The limited functional imaging studies have either not included children with dyslexia only (Mohl et al., 2015) or did not examine phonological processing for print (Langer et al., 2019). There have been many studies of functional brain differences for word reading in dyslexia, irrespective of ADHD or EF status. Meta-analyses of functional imaging studies have found differences in left-hemisphere anterior and posterior systems associated with reading disabilities (Martin et al., 2015; Richlan et al., 2009, 2011, 2013). The present study, therefore, was designed to dissociate the influences of ADHD and EF on brain functions related to word reading in dyslexia.

Two specific EFs that have been well studied in relation to reading are inhibition and switching. Inhibition involves attentional processes that actively control attention by filtering out distracting information and focusing on relevant information, regulating task appropriate behavior, and overriding inappropriate responses (Friedman et al., 2006; Miyake et al., 2000; Miyake & Friedman, 2012). Switching, also referred to as cognitive flexibility, is defined as the ability to shift between multiple tasks (Monsell, 1996). During reading, inhibition may be required to ignore task-irrelevant information, attend to relevant visual information, and ensure active speech sounds are held in working memory during reading; switching may be required to utilize different reading processes (Butterfuss & Kendeou, 2018; Doyle et al., 2018). Inhibition and switching EF processes are highly related, and exhibit shared brain bases (e.g., Hedden & Gabrieli, 2010).

Inhibition and switching are often impaired in both DD and ADHD. There is substantial evidence for impaired inhibition and switching in DD (Daucourt et al., 2018; Lonergan et al., 2019; Poljac et al., 2010) and in ADHD (e.g., Mostofsky et al., 2003; Willcutt et al., 2005; Wodka et al., 2007). Children with DD and ADHD exhibit, on average, the same degree of inhibition and switching impairments as children with DD only (Lonergan et al., 2019).

Processing speed has also been associated with reading ability (Catts et al., 2002), and is often considered as a supporting mechanism for EF. Processing speed is reduced in both DD and ADHD (Laasonen et al., 2009; McGrath et al., 2011; Shanahan et al., 2006; Willcutt et al., 2010). Indeed, among EF measures, processing speed may provide the best discrimination between dyslexia and typical reading (Booth et al., 2010).

The goal of the current study was to determine whether reading performance and reading-related brain activation in children with DD or DD + ADHD is associated with EF, with ADHD, or with both. We examined reading and EF abilities using behavioral measures in children ages 8-13 years old with typical reading ability, with DD only, or with DD + ADHD, and we collected functional neuroimaging data during a rhyme-matching reading task requiring phonological awareness from a subsample of participants. We hypothesized that typically developing readers would have higher scores (i.e., stronger skills) on all measures of EF and attention, as well as reading ability (by design), compared to children with DD and DD + ADHD. Based on the multiple cognitive deficit model, we expected to find shared neurocognitive characteristics for children with DD alone and those with comorbid ADHD compared to typical readers, presenting as differences of activation in left-hemisphere regions supporting reading. The novel question was whether the functional brain basis of reading impairment in these children with dyslexia was related to EF, to ADHD diagnosis, or both.

2. Materials and methods

We report how we determined our sample size, all data exclusions, all inclusion/exclusion criteria, whether inclusion/exclusion criteria were established prior to data analysis, all manipulations, and all measures in the study.

2.1. *Participants*

Eighty-eight children participated across three groups: typically developing (TYP; $n = 37$; ages 8.11–12.45 years), dyslexia only (DD; $n = 24$; ages 10.61–13.64 years), and dyslexia with ADHD (DD + ADHD; $n = 27$; ages 10.02–12.96 years). Participants with DD carried a prior diagnosis (e.g., DD, specific reading disorder), had a history of developmental and/or educational challenges related to reading, and also met study criteria for the DD group (see Group Designations section below for details). All participants were also assessed by a team-based neurologist specialized in ADHD to confirm or rule out a diagnosis of ADHD following an evaluation and using data from the *Conners Parent Rating Scale, 3rd Edition* (Conners-3; Conners, 2008) and the *Vanderbilt ADHD Diagnostic Parent Rating Scale* (VADPRS; Wolraich et al., 2003). Participants currently taking ADHD medications were asked to continue taking them on the day(s) of participation in the study to approximate typical school-day circumstances. Demographic characteristics by group are reported in Table 1. The typically developing reader group reflects our original recruitment strategy of enrolling students matched in age (age-matched group; $n = 17$; ages 9.82–12.45 years) and in reading ability to the group with DD (skill-matched group; $n = 20$; ages

Table 1 – Demographic characteristics of participants.

	Group		
	Typically Developing ($n = 37$)	Dyslexia ($n = 24$)	Comorbid Dyslexia/ADHD ($n = 27$)
Mean age in years (SD)	10.35 (1.15)	11.54 (.71)	11.40 (.75)
Sex			
Male	19 (51.4%)	17 (70.8%)	20 (74.1%)
Female	18 (48.6%)	7 (29.2%)	7 (25.9%)
Race/ethnicity			
White	21 (56.8%)	18 (75.0%)	23 (85.2%)
African American	5 (13.5%)	–	–
Hispanic/Latino	1 (2.7%)	–	–
Asian	2 (5.4%)	–	–
Mixed	4 (10.8%)	4 (16.7%)	2 (7.4%)
Total BSMSS	55.50 (9.23)	52.32 (7.87)	50.62 (8.31)
Maternal SES	50.21 (14.60)	45.68 (17.02)	45.12 (16.71)
ADHD Subtypes			
Hyperactive-Impulsive	–	–	4 (14.8%)
Inattentive	–	–	11 (40.7%)
Combined	–	–	12 (44.4%)
ADHD Medication	–	–	13 (52%)

Note. BSMSS = Barratt Simplified Measure of Social Status.

8.11–10.61 years). The two groups of typically developing children did not differ significantly on any behavioral or brain measure, so they were combined into a single TYP group.

Participants were recruited from a diverse urban center and surrounding areas. Legal guardians provided written informed consent, and participants completed assent forms, prior to testing based on approval of the study protocol by the Committee on the Use of Humans as Experimental Subjects (COUHES) at the Massachusetts Institute of Technology (MIT).

2.2. *Group designations*

Participants qualified for study enrollment if they were free of neurological or psychiatric disorders, were native English speakers, were enrolled in grades 3–6, and earned non-verbal cognitive ability scores in the average or higher range. Typical reader group participants also earned standard scores of 90 or higher on word reading tasks (WRMT-III and TOWRE-2 subtests) and had no educational, family, or developmental history of reading difficulties, and did not meet criteria for ADHD. DD group participants carried existing reading-related diagnoses, scored below 90 on at least two of four word reading tasks (WRMT-III and TOWRE-2 subtests), and did not meet criteria for ADHD. Comorbid group participants met the criteria of the DD group and also met ADHD diagnosis criteria based on the staff neurologist evaluation.

To determine the prevalence of EF deficits, participants with DD only or DD + ADHD were split based on their scores on the EF composite measure. Participants were categorized as unimpaired (DD-high EF) or impaired (DD-low EF) if they scored above or below, respectively, 1.5 standard deviations of the mean of the typically developing group on the EF composite measure. Similar cut-offs for designating an individual impairment have been used in prior studies of ADHD in children and adults (e.g., Biederman et al., 2006, 2004; Mattfeld et al., 2015; Nigg et al., 2005). On this basis, the resulting groups were: typically developing (TYP), unimpaired EF (DD-high EF), and impaired EF (DD-low EF) (Fig. 1).

2.3. *Behavioral assessments*

Legal copyright restrictions prevent public archiving of the various assessments and tests used in this study, which can be obtained from the copyright holders in the cited references in this section. All behavioral data can be found at: https://github.com/joanna22/Dyslexia_ADHD_EF.

2.3.1. *Measures of executive function (EF) and attention*

2.3.1.1. Inhibition and switching. On the NEPSY-II Inhibition subtest, each participant examined a series of black and white shapes or arrows and named either the shape or direction, or the alternate response, depending on the color of the shape or arrow (Korkman et al., 2007). On the NEPSY-II Switching subtest, similar instructions were given but the participant was instructed to provide the matching shape name when the color was black and the alternate response when the color was white. Raw scores were based on the number of correct responses and were then converted to age-based scaled scores ($M = 10$, $SD = 3$).

2.3.1.2. Processing speed. Processing speed was assessed using two subtests from the Wechsler Intelligence Scale for Children, 4th Edition (WISC-IV; Wechsler, 2003). On the Coding subtest, each participant was given 2 min to copy symbols that correspond to numbers using a key. On the Symbol Search subtest, each participant was given 2 min to scan groups of symbols and decide if the target symbol is present among an array of five symbols. Raw scores were calculated as correct (Coding) or correct minus incorrect (Symbol Search) responses within the time limit and converted to age-based scaled scores ($M = 10$, $SD = 3$).

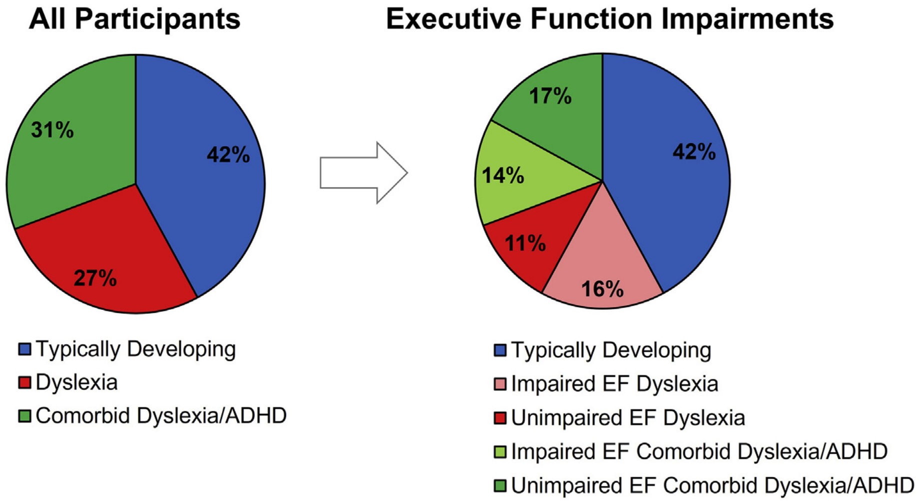

Fig. 1 – Group heterogeneity on the EF composite measure. To examine the heterogeneity of EF capacities by group, participants were separated into subgroups based on EF performance. Participants were categorized as either impaired or unimpaired on the composite EF measure if they performed below or above, respectively, 1.5 standard deviations of the mean based on performance of the age-matched control group.

2.3.1.3. Sustained attention and impulsivity. Participants completed the Gordon Continuous Performance Test (Gordon CPT; Gordon, 1983), during which each participant was instructed to view numbers on a screen and to press a button each time a predetermined number was presented. Three aspects were measured during this task: total number of correct trials, omissions, which is the number of times a participant failed to press the button when the designated number was presented, and commissions, which is the number of times a participant pressed the button when the designated number was not presented. Total scores can range from 0 (higher attention deficits) to 45 (lower attention deficits). Number of omissions is considered to be a measure of sustained attention while number of commissions is considered to be a measure of impulsivity. More omissions and commissions are indicative of greater attention deficits.

2.3.1.4. ADHD rating scales. ADHD symptomatology was indexed using the Conners-3 (Conners, 2008) and the Vanderbilt ADHD Diagnostic Parent Rating Scale (VADPRS; Wolraich et al., 2003). Conners-3 includes symptoms of ADHD from the *Diagnostic and Statistical Manual of Mental Disorders, Fourth Edition, Text Revision* (DSM-IV-TR), and includes related areas such as EF and social problems. Conners-3 provides an index probability score indicating how similar a child is to the clinical ADHD sample, with higher scores indicating greater attentional deficits. The VADPRS includes the 18 DSM-IV ADHD symptoms rated on a 4-point scale indicating how frequently each ADHD symptom occurs. The VADPRS also includes a set of performance items that assesses functional impairments rated on a 5-point scale across academic and social domains. VADPRS average performance, which is the number of functional impairments reported divided by the number of performance criteria answered, was used in our analyses.

2.3.2. *Measures of reading and related skills*

Raw scores for measures of reading and related skills were converted to age-based standardized scores.

2.3.2.1. Phonological memory. Phonological memory was assessed using the Memory for Digits subtest from the Comprehensive Test of Phonological Processing, 2nd Edition (CTOPP-2; Wagner et al., 2013). Each participant was asked to listen to a string of digits that increased in length incrementally from two to nine digits, and then to repeat them back in the correct order. Raw scores were based on the number of correct responses and were then converted to scaled scores ($M = 10$, $SD = 3$).

2.3.2.2. Rapid naming. Rapid naming was assessed using the numbers, letters, and 2-set subtests from the Rapid Automatized Naming and Rapid Alternating Stimulus Tests (RAN/RAS; Wolf & Denckla, 2005). Each participant was asked to name numbers, letters, or alternating stimuli (numbers and letters), respectively, as accurately and quickly as possible. Raw scores were based on the number of seconds needed to name all the items and were converted to standard scores ($M = 100$, $SD = 15$).

2.3.2.3. Word recognition. Untimed and timed single word reading were assessed. On the Word Identification subtest from the Woodcock Reading Mastery Tests, 3rd Edition (WRMT-III; Woodcock, 2011), each participant was asked to read aloud single words that increased in difficulty. Raw scores were the number of words read correctly and were converted to a standard score ($M = 100$, $SD = 15$). On the Sight Word Efficiency subtest from the Test of Word Reading Efficiency, 2nd Edition (TOWRE-2; Torgesen et al., 2012), each participant was shown a list of words and asked to read the words aloud as quickly as possible. Raw scores were based on the number of words read correctly within the 45-s time limit and were converted to standard scores ($M = 100$, $SD = 15$). As designed, performance on inclusion criteria for single word reading were lower for disordered groups compared to the typically developing reader group: WRMT-III Word Identification: $F(2, 87) = 52.41$, $p < .001$; TOWRE-2 Sight Word Efficiency: $F(2, 87) = 45.98$, $p < .001$ (see Table 2).

2.3.2.4. Decoding ability. Decoding skills were assessed using untimed and timed measures. Untimed decoding skills were assessed using the Word Attack subtest (WRMT-III; Woodcock, 2011). Each participant was asked to read pseudowords of increasing difficulty. Timed decoding skills were assessed using the Phonemic Decoding Efficiency (TOWRE-2; Torgesen et al., 2012). Each participant was shown lists of pseudowords and asked to read them aloud as quickly as possible. Raw scores for both measures were based on the number of items read correctly (within the 45-s time limit for PDE) and were then converted to standard scores ($M = 100$, $SD = 15$). As expected, performance on inclusion criteria for decoding was lower for disordered groups compared to typically developing peers: WRMT-III Word Attack: $F(2, 87) = 45.71$, $p < .001$; TOWRE-2 Phonemic Decoding Efficiency: $F(2, 87) = 81.44$, $pp < .001$.

2.3.2.5. Text reading. Oral reading fluency was assessed using the Gray Oral Reading Tests, 5th Edition (GORT-5; Wiederholt & Bryant, 2012). Each participant was asked to read passages of increasing length and complexity. Rate, accuracy, fluency, and comprehension scores were calculated. Rate was based on the amount of time it took the participant to read the passage. Accuracy was based on the number of errors the participant made while reading the passage. Comprehension was based on the number of questions the participant answered correctly after reading each passage. Raw scores were converted to scaled scores for each index ($M = 10$, $SD = 3$), with rate and accuracy combined to obtain the fluency score. The Reading Fluency subtest from the Woodcock–Johnson Tests of Achievement, 3rd Edition (WJ-III; Woodcock et al., 2001) was used to measure each participant's ability to rapidly read simple sentences and indicate whether they were true or false within a 3-min time limit. Raw scores, based on correct minus incorrect responses, were converted to standard scores ($M = 100$, $SD = 15$).

2.3.2.6. Sentence memory. For the Sentence Memory subtest from the Wide Range Assessment of Memory and Learning, 2nd Edition (WRAML-2; Sheslow & Adams, 2003), each

Table 2 – Descriptive statistics of groups on measures of executive function, attention, reading ability, and related skills.

	Group			Group Differences (all p's < .01)
	Typically Developing (TYP) ($n = 37$)	Developmental Dyslexia (DD) ($n = 24$)	Comorbid Dyslexia/ADHD (DD + ADHD) ($n = 27$)	
	M (*SD*)	*M* (*SD*)	*M* (*SD*)	
Measures of Executive Function and Attention				
EF Composite	11.12 (1.86)	8.04 (1.90)	8.84 (1.88)	TYP > DD = DD + ADHD
Conners-3 ADHD index	.52 (.93)	2.91 (3.75)	10.91 (3.82)	TYP < DD < DD + ADHD
VADPRS Average Performance	.49 (.31)	.52 (.34)	1.22 (.65)	TYP = DD < DD + ADHD
Gordon CPT Trials Correct	41.8 (5.16)	36.76 (9.00)	37.74 (5.63)	TYP > DD = DD + ADHD
Gordon CPT Number of Omissions	3.20 (5.16)	8.24 (9.00)	7.26 (5.63)	TYP < DD = DD + ADHD
Gordon CPT Number of Commissions	2.94 (4.99)	4.57 (3.96)	5.87 (5.15)	TYP = DD = DD + ADHD
Measures of Reading Ability and Related Skills				
CTOPP-2 Memory for Digits	11.59 (2.70)	8.54 (2.80)	7.96 (2.86)	TYP > DD = DD + ADHD
RAN/RAS Numbers	111.24 (10.18)	92.50 (12.94)	96.15 (11.35)	TYP > DD = DD + ADHD
RAN/RAS Letters	108.41 (9.98)	92.88 (12.41)	95.96 (10.39)	TYP > DD = DD + ADHD
RAN/RAS 2-set	110.56 (11.04)	94.00 (12.17)	97.19 (11.68)	TYP > DD = DD + ADHD
WRMT-III Word Identification[a]	113.68 (12.92)	83.21 (14.47)	87.41 (11.15)	TYP > DD = DD + ADHD
WRMT-III Word Attack[a]	108.14 (9.99)	85.13 (14.35)	83.15 (11.20)	TYP > DD = DD + ADHD
TOWRE-2 Sight Word Efficiency[a]	111.30 (11.09)	84.67 (16.28)	86.93 (9.53)	TYP > DD = DD + ADHD
TOWRE-2 Phonemic Decoding Efficiency[a]	110.43 (10.25)	81.21 (14.75)	79.22 (7.59)	TYP > DD = DD + ADHD
WJ-III Reading Fluency	115.70 (25.40)	88.71 (20.42)	92.48 (14.03)	TYP > DD = DD + ADHD
GORT-5 Rate	13.14 (3.68)	6.67 (3.43)	7.67 (2.24)	TYP > DD = DD + ADHD
GORT-5 Accuracy	10.41 (2.65)	5.83 (2.34)	5.70 (1.75)	TYP > DD = DD + ADHD
GORT-5 Fluency	11.97 (3.09)	6.13 (2.98)	6.56 (1.63)	TYP > DD = DD + ADHD
GORT-5 Comprehension	11.81 (3.32)	7.38 (2.68)	7.56 (1.69)	TYP > DD = DD + ADHD
WRAML-2 Sentence Memory	12.56 (2.05)	10.58 (3.23)	9.78 (3.00)	TYP > DD = DD + ADHD
KBIT-2 Matrices[a]	117.62 (13.93)	98.92 (11.55)	107.15 (12.46)	TYP > DD = DD + ADHD

Note. CPT = Continuous Performance Test; CTOPP-2 = Comprehensive Test of Phonological Processing, 2nd Edition; EF = Executive Functioning; GORT-5 = Gray Oral Reading Test, 5th edition; KBIT-2 = Kaufman Brief Intelligence Test, 2nd edition; RAN/RAS = Rapid Automatized Naming and Rapid Alternating Stimulus Tests; TOWRE-2 = Test of Word Reading Efficiency, 2nd Edition; VADPRS = Vanderbilt ADHD Diagnostic Parent Rating Scale; WISC-IV = Wechsler Intelligence Scale for Children- 4th Edition; WJ-III = Woodcock–Johnson, 3rd edition; WRAML-2 = Wide Range Assessment of Memory and Learning, 2nd Edition; WRMT-III = Woodcock Reading Mastery Tests, 3rd Edition; TYP = typically developing; DD = developmental dyslexia; DD + ADHD = comorbid dyslexia/ADHD.

[a] Indicated measures used for group designation criteria.

participant repeated meaningful sentences. Raw scores were based on the total number of points received for each sentence and were then converted to scaled scores ($M = 10$, $SD = 3$).

2.3.2.7. Non-verbal cognitive ability. Participants were administered the Matrices subtest from the Kaufman Brief Intelligence Test, 2nd Edition (KBIT-2; Kaufman & Kaufman, 2004) to obtain an estimate of non-verbal cognitive abilities. Each participant was shown incomplete visual patterns, with five possible pieces to complete the patterns, and asked to point to the piece that would best complete the pattern. Raw scores were based on the number of correct items and were converted to standard scores ($M = 100$, $SD = 15$).

2.4. *Measure of Socioeconomic Status*

Participants' socioeconomic status (SES) was measured using the Barratt Simplified Measure of Social Status (BSMSS; Barratt, 2006), which documents parental occupation and education. BSMSS scores can range from 8 (lower SES) to 66 (higher SES). SES was calculated by a composite of maternal occupation and maternal education. Maternal factors were chosen to represent SES because they are considered to have a stronger relationship with cognitive development than paternal factors in children (Mercy & Steelman, 1982).

2.5. *fMRI experimental design*

A sub-sample of participants completed a neuroimaging study to examine group differences on an fMRI task. The number of recruited participants was determined first by willingness to participate in the neuroimaging study (70 out of 88 participants), and then by the number of useable functional scans after screening for motion artifacts (36 out of 70 participants). This resulted in a sub-sample of 36 children with useable functional scans: TYP ($n = 15$; ages 9.00–12.24 years), DD ($n = 13$; ages 10.61–13.64 years), and DD + ADHD ($n = 8$; ages 10.22–12.96 years).

2.5.1. *fMRI paradigm*

An fMRI task was used to elicit reading-specific activations. The task included a target condition of word-rhyming judgements, a control condition of face-matching judgements, and fixation. For the word-rhyming task, participants judged whether two words did or did not rhyme. For the face-matching task, participants judged whether two faces were or were not identical. For both judgement tasks, participants viewed two words or faces, one above the other, accompanied by directions (‘rhyme?’ for words; ‘same?’ for faces) and indicated responses (yes or no) via button press. The button box was held in the right hand with the index finger over the button used to indicate ‘yes’ responses and the middle finger over the button used to indicate ‘no’ responses. The single run consisted of 40 trials of each condition, arranged in 8 blocks per condition with 5 trials per block. Prior to each block, instructions specifying the next task (‘rhyme?’ for words; ‘same?’ for faces) were shown for 2 sec. Each trial was presented for 4 sec, for a total of 20 sec per block (excluding directions). The proportion of trials was equal for ‘yes’ and ‘no’ intended responses. 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-sec blocks of fixation. Block order (words, faces, fixation) was pseudorandomized once to ensure the same condition was not repeated sequentially. The total duration of the run was 8 min and 32 sec. The task was presented via PsychoPy (Peirce, 2007). The PsychoPy code and stimuli used for this study can be found at: https://github.com/joanna22/Dyslexia_ADHD_EF.

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., ‘crane’, ‘brain’). Word stimuli pairs were further balanced for written frequency, verbal frequency, number of letters, number of phonemes, number of syllables, and concreteness.

Face stimuli were selected from the FEI face database to create visually similar pairs. This database was developed by the Artificial Intelligence Laboratory of FEI in São Bernardo do Campo in São Paulo, Brazil and includes 200 individuals between the ages of 19 and 40 years old photographed between 2005 and 2006 (Thomaz & Giraldi, 2010). Photos were in color, with individuals facing forward with neutral expressions, against a white background, and cropped to show the head. Stimuli pairs were matched for gender, hair color, hair style, glasses, and eye color. The trials consisted of half male and half female pairs and were balanced for race/ethnicity (Caucasian, Black, Asian, Hispanic). A total of 60 unique faces were used (20 for matched conditions, 40 for mismatched conditions).

2.5.2. *MRI image acquisition*

Prior to the MRI session, all participants had a preparation session (at least 30 min) with a mock scanner in order to become familiar with the MRI environment, practice lying down in the scanner, staying still and minimizing head movements, going through the task on the mirror system, and becoming accustomed to the various MRI sounds. Participants also practiced the fMRI task during the mock scanner session to optimize task familiarity and comfort. During this time, participants listened to the task directions and practiced responding via button press on a computer. The practice task included two trials of each condition, and data collection began once the participant reached mastery (100% correct) on the practice task.

The MRI session consisted of a T1-weighted anatomical scan, 4 functional MRI (fMRI) scans, a diffusion weighted imaging scan, and a resting state scan as part of a larger study. Participants spent approximately 45 min in the scanner. Imaging data was acquired using a Siemens 3-T Magnetom Trio system (Erlangen, Germany) fitted with a 32-channel receive-only head coil with participants lying supine. High resolution T1-weighted whole-brain structural scans were performed on each participant using a 3D MP-RAGE sequence (Repetition Time, TR = 2530 msec; echo time, TE = 1.6 msec; flip angle, FA = 7°; field-of-view, FOV = 256 × 256 mm; matrix size 256 × 256 mm; 1 mm iso-voxel resolution; 176 volumes). Functional images were acquired axial oblique with 32 horizontal slices (3.3 mm thick) covering the whole brain. Functional data were collected using T2*-weighted echo-planar image (EPI) volumes sensitive to blood oxygen-level dependent (BOLD) contrast (Kwong et al., 1992; Ogawa et al., 1990) acquired in an interleaved fashion (TR = 2000 msec, TE = 30 msec, FA = 90°, FOV = 192 × 192mm, matrix size 64 × 64, 3.0 mm iso-voxel resolution, 192 volumes). The conditions of our ethics approval do not permit public archiving of raw imaging files. Readers seeking access to the data should contact the lead author. Access will be granted to named individuals in accordance with ethical procedures governing the reuse of sensitive data. Specifically, requestors must complete a formal data sharing agreement.

2.5.3. *fMRI preprocessing and analyses*

Preprocessing and analyses were performed using statistical parametric mapping software (SPM8; Wellcome Department of Cognitive Neurology, London, UK). During preprocessing, data were realigned to the first functional volume and spatially normalized using the mean functional volume to the Montreal Neurological Institute (MNI) template. Normalized images were smoothed using a Gaussian filter (6-mm full width at half maximum) to decrease spatial noise. Analysis included individual and group level statistics. For the individual level analysis, the stimuli were modeled as box-car functions aligned with the onset of each stimulus, the width of which corresponded to the duration of each stimulus. The expected BOLD responses to the stimuli were obtained by convolving a canonical hemodynamic response function with the modeled stimuli. A high-pass filter with a cutoff of 128s was used on both the data and the model to reduce the impact of physiological noise. Outlier image volumes in the BOLD time series were identified based on either the mean intensity of image volume greater than 3 standard deviations from the mean intensity of the time series or the largest voxel movement of the image volume greater than .5 mm, based on scan-to-scan movement. Data from 34 participants were removed from fMRI analyses due to excessive head motion (>3 mm) during scanning (4 TYP, 11 DD, and 19 DD + ADHD). Image volumes were masked by a binary image created from the functional time series. Outlier images were included as nuisance regressors in the first-level analysis per person. The number of outlier images differed among the age-matched control group ($M = 19.00$, $SD = 8.10$), the skill-matched control group ($M = 41.25$, $SD = 29.68$), the DD group ($M = 22.08$, $SD = 11.99$), and the DD + ADHD group ($M = 20.13$, $SD = 9.39$; $F(3, 35) = 3.19$, $p = .04$). This group difference was specifically driven by the skill-matched control group who significantly differed from the other three groups, $p < .05$; this finding is expected given the higher rate of movement for younger children in fMRI studies (e.g., Byars et al., 2002; Yerys et al., 2009). A random effects model, corrected for the between-group differences in number of outlier images, was used for a second-level analysis to characterize group level effects. Brain regions were identified using a threshold of $p < .001$ cluster-level FDR corrected for multiple comparisons and using a cluster extent threshold of 10 voxels or more.

To investigate activation differences between the impaired reader groups during the fMRI rhyme-matching task relative to the face-matching task, we examined regions of the left-hemisphere reading network demonstrating significant differences between the TYP group and the combined DD and DD + ADHD groups. Six areas of the reading network were chosen from the fMRI rhyme-matching task relative to face-matching task from a cluster of 125 contiguous voxels (5 mm sphere radius) based on the area of peak activation: the angular gyrus, supramarginal gyrus, inferior frontal gyrus, superior temporal gyrus, middle temporal gyrus, and fusiform gyrus (Table 4). Beta weights in these regions of interest (ROIs) were extracted to evaluate activation differences between groups, and how activations in the ROIs correlated with EF performance. Beta weights in these ROIs for each participant can be found at: https://github.com/joanna22/Dyslexia_ADHD_EF.

3. Results

3.1. Demographic characteristics

The TYP, DD, and DD + ADHD groups did not differ on sex ($F(2, 87) = 2.14$, $p = .12$) or SES ($F(2, 80) = .14$, $p = .87$). The groups differed on age ($F(2, 87) = 15.68$, $p < .001$), as expected, because the TD group consisted of both age-matched and skill-matched participants. SES scores ranged from 18 to 66 ($M = 52.22$; $SD = 11.86$). Fifteen participants had mothers who were full-time homemakers. For these participants, paternal occupation was substituted and combined with maternal education in order to calculate SES. Maternal education and occupation scores were significantly correlated with one another ($r = .32$; $p = .003$), which supported combining these two measures into a single composite score. Furthermore, 84% of participants optionally reported their annual gross family income, which ranged from less than $20,000 to more than $120,000. Income was significantly correlated with maternal occupation ($r = .38$; $p = .001$), maternal education ($r = .43$; $p = .000$), and total BSMSS scores ($r = .45$; $p = .000$), which

Table 3 – Descriptive statistics of groups on measures of executive function, attention, reading ability, and related skills.

	Group			Group Differences (all p's < .01)
	Typically Developing ($n = 37$)	DD-high EF ($n = 29$)	DD-low EF ($n = 22$)	
	M (*SD*)	*M* (*SD*)	*M* (*SD*)	
Measures of Executive Function and Attention				
EF Composite	11.12 (1.86)	9.73 (1.13)	6.61 (1.10)	TYP > DD-high EF > DD-low EF
Conners-3 ADHD index	.52 (.93)	2.91 (3.75)	10.91 (3.82)	TYP < DD-high EF < DD-low EF
VADPRS Average Performance	.49 (.31)	.85 (.55)	.99 (.81)	TYP < DD-high EF < DD-low EF
Gordon CPT Trials Correct	41.8 (5.16)	38.65 (6.06)	35.50 (8.41)	TYP = DD-high EF < DD-low EF
Gordon CPT Number of Omissions	3.20 (5.16)	6.35 (6.06)	9.50 (8.41)	TYP = DD-high EF < DD-low EF
Gordon CPT Number of Commissions	2.94 (4.99)	4.54 (3.54)	6.31 (6.00)	TYP = DD-high EF < DD-low EF
Measures of Reading Ability and Related Skills				
CTOPP-2 Memory for Digits	11.59 (2.70)	9.14 (2.85)	7.00 (2.21)	TYP > DD-high EF > DD-low EF
RAN/RAS Numbers	111.24 (10.18)	97.36 (10.92)	89.63 (12.13)	TYP > DD-high EF > DD-low EF
RAN/RAS Letters	108.41 (9.98)	97.96 (9.94)	89.05 (11.37)	TYP > DD-high EF > DD-low EF
RAN/RAS 2-set	110.56 (11.04)	99.21 (10.38)	90.68 (11.94)	TYP > DD-high EF > DD-low EF
WRMT-III Word Identification	113.68 (12.92)	87.75 (12.89)	85.21 (12.01)	TYP > DD-high EF = DD-low EF
WRMT-III Word Attack	108.14 (9.99)	85.46 (11.87)	84.74 (13.06)	TYP > DD-high EF = DD-low EF
TOWRE-2 Sight Word Efficiency	111.30 (11.09)	88.54 (14.20)	81.89 (10.72)	TYP > DD-high EF = DD-low EF
TOWRE-2 Phonemic Decoding Efficiency	110.43 (10.25)	83.21 (11.66)	78.05 (10.09)	TYP > DD-high EF = DD-low EF
WJ-III Reading Fluency	115.70 (25.40)	97.11 (17.47)	81.89 (13.84)	TYP > DD-high EF > DD-low EF
GORT-5 Rate	13.14 (3.68)	7.61 (2.95)	6.42 (2.01)	TYP > DD-high EF = DD-low EF
GORT-5 Accuracy	10.41 (2.65)	6.07 (2.12)	5.53 (1.98)	TYP > DD-high EF = DD-low EF
GORT-5 Fluency	11.97 (3.09)	6.71 (2.61)	5.84 (1.80)	TYP > DD-high EF = DD-low EF
GORT-5 Comprehension	11.81 (3.32)	8.04 (2.35)	7.00 (1.83)	TYP > DD-high EF = DD-low EF
WRAML-2 Sentence Memory	12.56 (2.05)	10.93 (3.47)	9.42 (2.24)	TYP > DD-high EF = DD-low EF
KBIT-2 Matrices Standard Score	117.62 (13.93)	107.75 (12.94)	97.37 (10.62)	TYP > DD-high EF > DD-low EF

Note. CPT = Continuous Performance Test; CTOPP-2 = Comprehensive Test of Phonological Processing, 2nd Edition; GORT-5 = Gray Oral Reading Test, 5th edition; EF = Executive Functioning; KBIT-2 = Kaufman Brief Intelligence Test, 2nd edition; RAN/RAS = Rapid Automatized Naming and Rapid Alternating Stimulus Tests; TOWRE-2 = Test of Word Reading Efficiency, 2nd Edition; VADPRS = Vanderbilt ADHD Diagnostic Parent Rating Scale; WISC-IV = Wechsler Intelligence Scale for Children- 4th Edition; WJ-III = Woodcock–Johnson, 3rd edition; WRAML-2 = Wide Range Assessment of Memory and Learning, 2nd Edition; WRMT-III = Woodcock Reading Mastery Tests, 3rd Edition; TYP = typically developing; DD = developmental dyslexia; DD + ADHD = comorbid dyslexia/ADHD; DD-high EF = dyslexia unimpaired EF; DD-low EF = dyslexia impaired EF.

Table 4 – MNI coordinates of peak activation for each group for rhyme-matching relative to face-matching.

Brain Areas	Peak MNI Coordinates			T value
	x	y	z	
TYP > DD & DD + ADHD				
L Supramarginal Gyrus	−63	−27	30	2.38
L Superior Temporal Gyrus	−51	−9	−38	2.02
L Inferior Frontal Gyrus	−52	11	2	2.37
L Lingual Gyrus	−27	−57	4.8	1.88
L Fusiform Gyrus	−42	−42	−17	2.08
L Parahippocampal Gyrus	−24	3	−20	2.67
R Middle Temporal Gyrus	57	−15	−9.6	2.04
R Cuneus	6	−81	29	1.99
DD & DD + ADHD > TYP				
L Middle Temporal Gyrus	−39	−69	19	3.87
R Supramarginal Gyrus	63	−27	30	2.87
R Fusiform Gyrus	33	−18	−31	3.08
DD > DD + ADHD				
No Significant Difference.	–	–	–	–
DD + ADHD > DD				
No Significant Difference.	–	–	–	–
DD-high EF > DD-low EF				
L Angular Gyrus	−51	−66	30	3.30
R Superior Temporal Gyrus	66	−18	−2.4	3.23
L Inferior Frontal Gyrus	−60	9	30	3.02
L Fusiform Gyrus	−21	−3	−45	3.70
L Supramarginal Gyrus	−48	−48	44	3.87
DD-low EF > DD-high EF				
R Supramarginal Gyrus	57	−30	41	3.19
L Middle Temporal Gyrus	−63	−63	−6	3.41

Note. L: left hemisphere; R: right hemisphere; $P < .001$ uncorrected; cluster corrected FDR <.05; TYP = typically developing; DD = developmental dyslexia; DD + ADHD = comorbid dyslexia/ADHD; DD-high EF = dyslexia unimpaired EF; and DD-low EF = dyslexia impaired EF.

justifies using BSMSS scores as an index of SES (Table 1). There were no significant differences across groups on BSMSS scores ($F(2, 80) = 2.45$, $p = .093$).

Performance on standardized reading and cognitive measures by group are presented in Table 2. A one-way ANOVA with Bonferroni post-hoc comparisons indicated that the TYP group had significantly higher scores on nonverbal cognition (KBIT-2 Matrices) than both the DD and DD + ADHD groups, $F(2, 87) = 15.91$, $p < .0001$, with no significant difference between these latter two groups, $p = .076$.

In the DD + ADHD sample ($n = 27$), 15% of participants were of the hyperactive-impulsive subtype, 41% were of the inattentive subtype, and 44% were of the combined subtype. In total, 48% of participants in the DD + ADHD group were on psychostimulant medication for ADHD symptoms on a regular basis, and were asked to continue to take their ADHD medication for the study.

3.2. *Behavioral group characteristics on EF, attention, reading ability, and related skills*

3.2.1. *Measures of EF and attention*

Performance among the four EF measures (WISC-IV Coding, WISC-IV Symbol Search, NEPSY-II Inhibition, NEPSY-II Switching) were moderately to strongly correlated with one another across all participants: WISC-IV Coding and WISC-IV Symbol Search: $r = .53$, $p < .001$; NEPSY-II Inhibition and NEPSY-II Switching: $r = .72$, $p < .001$; WISC-IV Coding and NEPSY-II Inhibition: $r = .61$, $p < .001$; WISC-IV Coding and NEPSY-II Switching: $r = .71$, $p < .001$; WISC-IV Symbol Search and NEPSY-II Inhibition: $r = .52$, $p < .001$; WISC-IV Symbol Search and NEPSY-II Switching: $r = .48$, $p < .001$). EF measures were combined into meaningful factors based on principal axis factoring (PAF). PAF was chosen in order to select the fewest number of factors which could account for the correlations among the EF measures. This analysis extracted one factor, defined as the EF composite score: NEPSY-II Switching, NEPSY-II Inhibition, WISC-IV Coding and WISC-IV Symbol Search (listed in order of strength in relation to factor) (Table 2).

Group differences were evaluated on the EF composite score (Table 2; Fig. 2). A MANOVA with the EF composite score as the dependent variable and group as a between-subjects factor revealed a significant main effect of group, $F(2, 80) = 21.23$, $p < .001$. Subsequent univariate ANOVAs revealed that the TYP group performed significantly better than the DD and DD + ADHD groups ($p = .000$). The DD and DD + ADHD groups did not significantly differ from one another ($P = .31$). Similar results were found after controlling for the effect of non-verbal cognitive ability.

Group differences were evaluated for attention focusing on ADHD symptomatology via questionnaires and performance on a continuous performance task (CPT) (Table 2). ANOVAs revealed significant group effects on the Conners-3 ADHD index, $F(2, 83) = 95.68$, $p = .001$, and Conners-3 ADHD index probability, $F(2, 83) = 96.26$, $p < .0001$. These group effects were examined with Bonferroni post hoc tests, which revealed that the TYP group had significantly better scores than both the DD group ($p = .040$) and DD + ADHD group ($p < .001$) on both the Conners-3 ADHD index and the Conners-3 ADHD index probability, and that the DD group had significantly better scores ($p < .001$) than the DD + ADHD group on both tests. Thus, the DD + ADHD group had the greatest attentional difficulties and the TYP group had the least attentional difficulties on both attention measures (Table 2).

Similarly, an ANOVA revealed a significant group effect on the VADPRS, $F(2, 83) = 23.09$, $p < .0001$. Bonferroni post hoc results indicated that the DD + ADHD group had significantly greater attentional deficits on the VADPRS compared to both the TYP ($p < .001$) and DD groups, ($P < .001$). There was no significant difference in performance between the TYP and DD groups, ($p = 1.00$).

For the Gordon CPT, an ANOVA with total trials performed correctly, total omissions and total commissions as the within-subjects factor, and group as the between-subjects factors revealed that there were no significant group effect, $F(2, 76) = 2.66$, $p = .076$.

3.2.2. *Measures of reading ability and related skills*

Group differences were evaluated for the measures of reading ability and related skills (Table 2). A MANOVA with measures of reading ability and related skills as dependent variables and group as a between-subjects factor revealed a significant main effect of group, Wilk's $\lambda = .26$, $F(2, 83) = 61.40$, $p < .001$. Subsequent univariate ANOVAs revealed that the TYP group

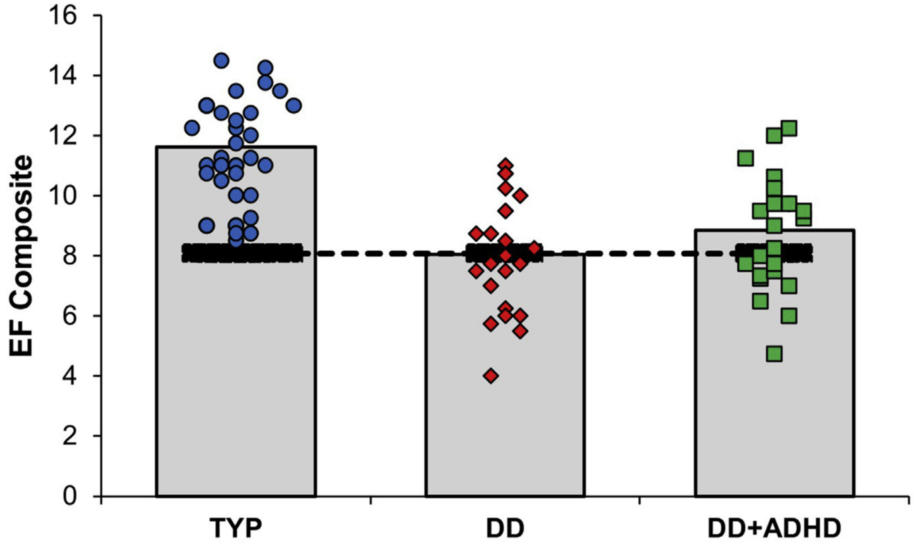

Fig. 2 – Group performance on the EF composite measure. The graph indicates standardized scores on the *y*-axis and group distribution on the *x*-axis. The dotted line indicates 1.5 standard deviations below the mean for the typically developing group, which is the cut-off used to determine impaired and unimpaired participants on each task. The spread scatter plots and bar graphs depict distribution of participant performance and group means, respectively. *Note.* TYP = typically developing; DD = developmental dyslexia; DD + ADHD = comorbid dyslexia/ADHD.

performed significantly better than the DD and DD + ADHD groups across all measures (CTOPP-2 Memory for Digits: $F(2, 87) = 15.96$, $p < .001$; RAN/RAS Numbers: $F(2, 87) = 24.21$, $P < .001$; RAN/RAS Letters: $F(2, 87) = 18.24$, $p < .001$; RAN/RAS 2-set: $F(2, 86) = 17.95$, $p < .001$; GORT-5 Rate: $F(2, 87) = 36.82$, $p < .001$; GORT-5 Accuracy: $F(2, 87) = 42.88$, $p < .001$; GORT-5 Fluency: $F(2, 87) = 46.87$, $p < .001$; GORT-5 Comprehension: $F(2, 87) = 26.94$, $p < .001$; WRAML-2 Sentence Memory: $F(2, 86) = 8.76$, $p < .001$; and WJ-III Reading Fluency: $F(2, 87) = 15.21$, $p < .001$). The DD and DD + ADHD groups did not significantly differ from one another on any of these measures (all p's > .05). Similar results were found after controlling for nonverbal cognitive ability.

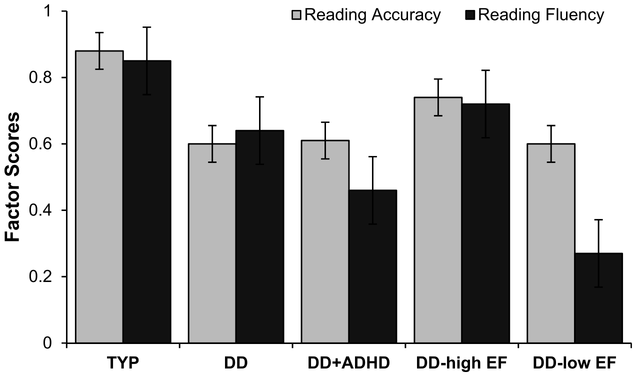

Fig. 3 – Group performance on Reading Accuracy and Reading Fluency composite scores, which were factors extracted from the principal axis factoring analysis. *Note.* TYP = typically developing; DD = developmental dyslexia; DD + ADHD = comorbid dyslexia/ADHD; DD-high EF = dyslexia unimpaired EF; and DD-low EF = dyslexia impaired EF.

Reading measures were combined into meaningful factors based on PAF. This analysis extracted two factors (Table 2; Fig. 3). The first factor (Reading Accuracy) included primarily measures of reading accuracy: GORT-5 Rate, GORT-5 Accuracy, GORT-5 Comprehension, WRMT-III Word Identification, WRMT-III Word Attack, and WRAML-2 Sentence Memory (listed in order of strength in relation to factor). The second factor (Reading Fluency) included primarily measures of reading or naming fluency: TOWRE-2 Sight Word Efficiency, TOWRE-2 Phonemic Decoding Efficiency, WJ-III Reading Fluency, RAN 2-set, RAN letters, RAN numbers (listed in order of strength in relation to factor).

The TYP group had significantly higher scores for both Reading Accuracy and Reading Fluency factors than both the DD-high EF and DD-low EF groups (all p's < .05). The DD and DD + ADHD groups did not significantly differ from one another on either factor (Reading Accuracy: $p = 1.00$; Reading Fluency: $p = .684$). Critically, the DD-high EF group had significantly higher scores on the Reading Fluency factor than the DD-low EF group ($p = .044$), but these two groups did not differ significantly on the Reading Accuracy factor ($p = .85$).

For the TYP group, higher EF composite scores were associated with significantly better performance for measures of both Reading Fluency ($r = .46$, $p = .006$) and Reading Accuracy ($r = .47$, $p = .005$). However, for the DD-high and DD-low groups, stronger EF composite scores were associated with significantly better performance on measures of Reading Fluency (DD-high EF: $r = .51$, $p = .013$; DD-low EF: $r = .48$, $p = .044$) but less so with Reading Accuracy (DD-high EF: $r = .30$, $p = .09$; DD-low EF: $r = .17$, $p = .43$), and lower risk of attentional problems (Conners-3 ADHD index: DD-high EF: $r = .19$, $P = .35$; DD-low EF: $r = -.17$, $p = .50$; VADPRS Average Performance: DD-high EF: $r = .41$, $p = .04$; DD-low EF: $r = .21$, $p = .40$).

3.3. *Group differences on neuroimaging measures on rhyme-matching relative to face-matching*

A sub-sample including 36 children participated in neuroimaging data collection aiming to examine group differences on an fMRI rhyme-matching phonological task: TYP ($n = 15$), DD ($n = 13$), and DD + ADHD ($n = 8$). There were no significant differences on any of the behavioral measures of EF, attention, reading ability, and related skills between each larger sample and this smaller subset of participants (all p's > .05).

In-scanner task performance on the word-rhyming task was examined with a MANOVA with measures of accuracy (total items correct) and reaction time as dependent variables and group as a between-subjects factor. These analyses revealed a significant main effects of group for accuracy, $F(2, 35) = 36.453$, $p < .0001$ and for reaction time, $F(2, 35) = 21.76$, $p < .0001$. Similar results were found after controlling for the effects of non-verbal cognitive ability. Bonferroni post hoc analyses revealed significantly better accuracy and faster reaction times for the TYP group than both the DD and DD + ADHD groups on the word-rhyming task ($p < .001$); no significant differences were found between the DD and DD + ADHD groups for accuracy ($p = 1.00$) or reaction time ($p = 1.00$) on the word-rhyming task. There were, however significant differences between the two EF groups, such that the DD-high EF group was significantly more accurate, $F(2, 35) = 47.03$, $p < .0001$, and faster, $F(2, 35) = 17.33$, $p = .001$, than the low-EF group on the word-rhyming task.

We compared brain activations across groups during the fMRI rhyme-matching task relative to face-matching (Table 4, Fig. 4). A contrast of rhyme-matching greater than face-matching revealed that the TYP group showed greater activation than the DD and DD + ADHD groups and the DD-high EF and DD-low EF groups in the left hemisphere reading network, including the middle and superior temporal gyri, supramarginal gyrus, angular gyrus, inferior frontal gyrus, and fusiform gyrus (Table 3, Fig. 4; $p < .001$ uncorrected; cluster corrected FDR <.05). The DD-high EF group exhibited significantly greater activation than the DD-low EF group in the left inferior frontal gyrus, middle temporal gyrus, superior temporal gyrus, cerebellum, precuneus, and lateral occipital cortex (Fig. 4). In contrast, the DD and the DD + ADHD groups did not significantly differ from one another ($p > .05$).

To further investigate the activation differences between the impaired reader groups during the fMRI rhyme-matching task relative to face-matching, we examined regions of the reading network demonstrating significant differences between the TYP group and the combined DD and DD + ADHD groups. We extracted beta weights from each resulting region of interest (ROI) to examine how the activations correlated with EF performance based on the contrast of TYP Group versus combined DD and DD + ADHD groups (Fig. 4). Combining DD-only and DD + ADHD groups, better EF performance significantly correlated with greater activations in the left angular gyrus ($r = .48$, $p = .037$) and left fusiform gyrus ($r = .46$, $P = .047$), and lesser activations in the left superior temporal gyrus ($r = -.52$, $p = .023$).

4. Discussion

The goal of the current study was to use behavioral and neuroscience evidence to disentangle the influences of EF and ADHD on reading impairment in children with dyslexia.

Behaviorally, impaired EF had a significant association with impaired reading fluency (but not reading accuracy), but

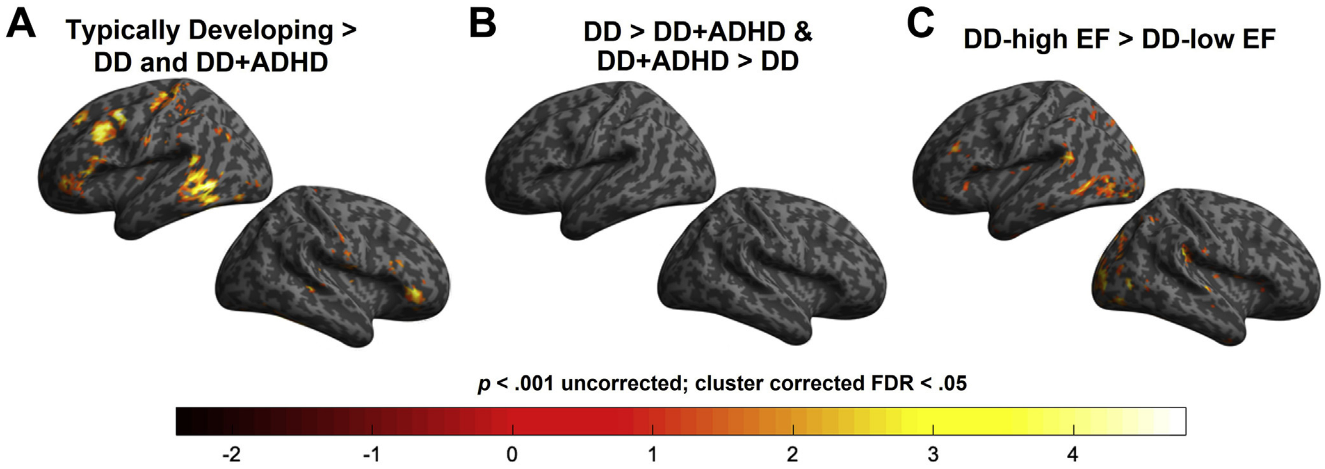

Fig. 4 – Group comparisons among the typically developing (TD), impaired, and unimpaired executive function groups on the for rhyme-matching relative to face-matching tasks. Dyslexia and comorbid dyslexia/ADHD participants were combined and separated into subgroups based on executive functioning (EF) performance on the independently obtained measures of EF collected outside of the scanner. Participants were categorized as unimpaired or impaired if they scored above or below, respectively, 1.5 standard deviations of the mean typically developing performance. Uncorrected height threshold of $P < .001$, whole-brain cluster corrected for multiple comparisons, corrected $P < .05$. *Note.* TYP = typically developing; DD = developmental dyslexia; DD + ADHD = comorbid dyslexia/ADHD; DD-high EF = dyslexia unimpaired EF; and DD-low EF = dyslexia impaired EF.

an additional ADHD diagnosis was not associated with differences in reading performance. There were no significant differences on any behavioral measure of reading, reading-related skills, or EF between children with dyslexia only compared to children with both dyslexia and ADHD. When the children with dyslexia were divided into children with better or worse EF scores, irrespective of ADHD diagnosis, the children with worse EF had lower performance on measures of reading fluency, but not reading accuracy.

Novel and parallel insights were discovered in relation to functional activation in the left-hemisphere reading work. Children with dyslexia had reduced activation throughout brain regions associated with dyslexia, and these activations were further reduced in children with both dyslexia and EF deficits. ADHD diagnosis alone, however, had no measurable influence on brain activation beyond EF. These findings offer novel evidence clarifying the separable roles of ADHD and EF status on the brain basis of reading disability, and point to the importance of EF on brain differences associated with reading disability.

4.1. *Co-Occurrence of ADHD and EF deficits in developmental dyslexia*

The sample of children with dyslexia in this study was similar to other studies in observing high rates of comorbid ADHD and high rates of EF deficits. Over half (54%) of the children with dyslexia also qualified for a diagnosis of ADHD. The presence or absence of the ADHD diagnosis was determined by a pediatric neurologist following an individual session with each child (across all groups) and parent questionnaires. Children with ADHD had worse scores on both the Conners Parent Rating Scale (Conners, 2008) and the Vanderbilt ADHD Diagnostic Parent Rating Scale (Wolraich et al., 2003) than the typically reading children and the children with dyslexia only. Thus, the ADHD measures converged on a distinction between children with dyslexia who did or did not have an additional diagnosis of ADHD, and also confirmed the absence of ADHD in the typically developing group.

The children with dyslexia also had a high rate of EF deficits as measured by inhibition, switching, and processing speed measures. Overall, the children with dyslexia had significantly lower scores than typically reading children on all measures of EF, which is consistent with other studies reporting EF deficits in dyslexia (Kibby et al., 2021; Shanahan et al., 2006; Varvara et al., 2014; Willcutt et al., 2001). Using a cut-off of 1.5 standard deviations below the mean of typically reading children, 38% of children with dyslexia had a deficit on inhibition and switching and 29% of children with dyslexia had a deficit on processing speed measures.

Critically, among children with dyslexia, the diagnosis of ADHD was unrelated to the deficits in EF. The rates of both kinds of EF deficits (inhibition-switching and processing speed) were similar in children with dyslexia whether or not they were also diagnosed with ADHD. There were no significant differences on any of the four individual EF measures or the composite EF measure between children with dyslexia only versus children with both dyslexia and ADHD. These findings are consistent with a meta-analysis showing that dyslexia alone and dyslexia with ADHD show similar EF impairments across measures of inhibition, switching, and auditory working memory (Lonergan et al., 2019).

4.2. *Distinction between Reading Accuracy and Reading Fluency*

Children with dyslexia are commonly challenged by both reading accuracy (decoding) and reading fluency demands. The partial separability of these two aspects of reading has been noted as a “double deficit” that occurs in many children with dyslexia (Wolf & Bowers, 1999). When we applied a data-driven approach to all the reading and reading-related measures in our study, we found that two factors accounted for much of the variance in scores. One factor (that we termed Reading Accuracy) encompasses six measures of performance with words, sentences, or passages in which children are instructed to perform at their own comfortable rate. A second factor (Reading Fluency) loaded on six measures of performance with text, words, pseudowords, numbers, and letters in which children were instructed to perform as quickly as possible. Thus, the data-driven analyses aligned well with the generally noted distinction between accuracy and fluency difficulties in dyslexia.

4.3. *EF deficits, but not ADHD, influence reading fluency*

By design (inclusion/exclusion criteria), the typical reader group had significantly better scores than the dyslexia group on all ten reading and reading-related measures. The additional diagnosis of ADHD, however, had no significant effect on reading performance on any of the ten measures among children with dyslexia. Thus, ADHD per se does not appear to worsen reading disability in dyslexia.

In contrast, the addition of an EF deficit in dyslexia did worsen reading disability in dyslexia, regardless of ADHD diagnostic status. However, this effect of impaired EF was specific to poor reading fluency and not reading accuracy. For the Reading Fluency composite of timed reading and reading-related measures, impaired EF in children with dyslexia was associated with worse performance. Children with dyslexia and intact EF had lower Reading Fluency scores than typically reading children, but children with both dyslexia and impaired EF had the lowest Reading Fluency scores of all. Alternatively, Reading Accuracy performance was nearly equivalent in children with dyslexia who had intact or impaired EF (although both groups performed below typically reading children). Thus, impaired EF was specifically associated with poor reading fluency performance in children with dyslexia. More generally, these findings are consistent with behavioral evidence that EFs contribute to the comorbidity between ADHD and dyslexia (Kibby et al., 2021, pp. 1–23).

The present study employed canonical measures of EF, but these findings can also be interpreted in terms of mechanisms of attentional control that underlie EF processes (Bavelier & Green, 2019). Indeed, the relation of executive functions to attentional control was noted in the early definitions of EF (Baddeley, 1996) as related to the Supervisory Attentional System (SAS) (Norman & Shallice, 1986). Longitudinal studies have found that attentional mechanisms underlie reading acquisition, especially reading fluency (Bertoni et al., 2019;

Carroll et al., 2016; Franceschini et al., 2012; Gori et al., 2016). For example, visual-spatial attention in pre-reading kindergarteners has been found to be an important predictor of future reading skills (for a review, see Eimer, 2014; Franceschini et al., 2012), and there is evidence for an association between reading ability and visual-spatial ability across development (White et al., 2019). Children enrolled in intervention programs targeting attentional mechanisms demonstrate significant improvements on reading skills, particularly on reading fluency, and also improvements on phonological awareness, such as auditory-phonological short-term memory (Bertoni et al., 2021; Franceschini & Bertoni, 2019; Franceschini et al., 2012, 2017; Gori et al., 2016; Pasqualotto et al., 2022; Peters et al., 2019, 2021). The specific importance of EF dysfunction for reading fluency impairment and reduced brain activation is consistent with findings noting the association between deficits in attention and reading, especially reading fluency (Bertoni et al., 2019; Carroll et al., 2016; Franceschini et al., 2012; Gori et al., 2016). Future studies ought to examine directly the relations between attentional control, EF, and brain functions in dyslexia.

4.4. *Neuroimaging evidence for the importance of EF in the reading network of the brain*

The neuroimaging evidence was consistent with the behavioral evidence that EF, but not the additional diagnosis of ADHD, was related to reading impairment. Children with dyslexia, regardless of ADHD status, exhibited reduced activation in the major regions of the left-hemisphere reading network including the middle and superior temporal gyri, supramarginal gyrus, angular gyrus, inferior frontal gyrus, and fusiform gyrus. These reductions of activation are consistent with many prior studies of dyslexia and reading (Gabrieli, 2009; Paulesu et al., 2014). There were no significant differences in activation between the children with dyslexia only versus the children with both dyslexia and ADHD, which is consistent with the idea that ADHD per se does not alter the brain basis of reading impairment in dyslexia. There were, however, significant differences in brain activation when children with dyslexia were divided by their EF status. Children with both dyslexia and impaired EF exhibited reduced activations in the left inferior frontal gyrus, middle temporal gyrus, superior temporal gyrus, cerebellum, precuneus, and lateral occipital cortex relative to children with DD and unimpaired EF.

Although functional neuroimaging studies have not disentangled the influences of EF and ADHD in dyslexia, prior findings are consistent with the present study. One study compared boys with ADHD only and boys with both dyslexia and ADHD (Mohl et al., 2015). Hypoactivation in left-hemisphere reading-related areas occurred only in the boys with both dyslexia and ADHD. This finding supports the idea that reduced activations in left-hemisphere reading-related areas do not occur more generally in ADHD, but rather are specific to (male) children with ADHD who also have dyslexia. Also, there is structural neuroimaging evidence indicating the frontal lobes may mediate the comorbidity between ADHD and dyslexia (Jagger-Rickels et al., 2018; Kibby et al., 2020), which is consistent with the known importance of the frontal lobes in EF.

5. Limitations

Several limitations were present in this study. First, the analyses were conducted on relatively small samples, especially for the neuroimaging. At the same time, all the neuroimaging results aligned precisely with the larger behavioral analyses (i.e., significant reductions of activation in dyslexia, significant reductions of activation in children with both dyslexia and EF deficits, and no significant difference between children with dyslexia who did or did also have ADHD). The limited number of participants prohibited analysis of ADHD subtypes of the inattentive type, hyperactive-impulsive type, and combined type. Likewise, the small sample was limited in racial and ethnic diversity across groups. Second, children with ADHD on stimulant medications were encouraged to maintain their regular dosage so that their performance would be similar to their everyday reading performance in school. This, however, prohibited examination of the role of medication in the findings. Third, although the children completed multiple measures of reading, reading-related abilities, and EF, a more complete evaluation may reveal specific associations between particular EF abilities, attentional capacities, and reading abilities. On the other hand, there is evidence that EF impairments in inhibition, switching, and updating of working memory are all similarly related to reading impairment in dyslexia (Daucourt et al., 2018). Fourth, a larger sample and additional measures will be needed to consider how the present findings relate to other subtypings of dyslexia, such as children with dyslexia who have phonological versus surface dyslexia (Peterson et al., 2014) or who do or not have elevated visual crowding for print (Joo et al., 2018).

6. Conclusions

The present study revealed strong dissociations between the influences of EF and ADHD on the brain and behavioral bases of dyslexia. Impaired EF in children with dyslexia was associated with reduced brain activation in multiple regions of the left-hemisphere reading network relative to typically reading children as well as children with dyslexia but unimpaired EF. In parallel, impaired EF in children was associated with reduced behavioral reading fluency relative to typically reading children as well as children with dyslexia but unimpaired EF. ADHD clinical status had no independent influence on brain function or reading fluency. These findings motivate the importance of characterizing EF in children with dyslexia, and consideration of supportive interventions that target EF in those children who have both impaired EF and dyslexia.

Credit author statement

Noor Z. Al Dahhan: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Visualization; Roles/Writing - original draft. **Kelly Halverson:** Data curation; Investigation; Methodology; Project administration; Resources. **Carrie P. Peek:** Data curation; Formal analysis; Investigation; Methodology; Project administration; Resources. **Dayna Wilmot:** Data curation; Investigation;

Methodology; Project administration; Resources. **Anila D'Mello:** Investigation; Project administration. **Rachel R. Romeo:** Investigation; Project administration. **Olivia Meegoda:** Investigation; Project administration. **Andrea Imhof:** Data curation; Investigation; Project administration. **Karolina Wade:** Investigation; Project administration. **Anissa Sridhar:** Investigation; Project administration **Eric Falke:** Project administration. **Tracy Centanni:** Investigation; Methodology; Project administration; Resources. **John D. E. Gabrieli:** Conceptualization; Funding acquisition; Investigation; Methodology; Project administration; Resources; Supervision; Roles/Writing - original draft. **Joanna A. Christodoulou:** Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Supervision; Roles/Writing - original draft.

Data availability statement

The data and analysis code used to support the findings of this study have been deposited in a Github repository (https://github.com/joanna22/Dyslexia_ADHD_EF).

Registration statement

No part of the study procedures or analysis was pre-registered prior to the research being conducted.

Ethics approval statement

The Committee on the Use of Humans as Experimental Subjects (COUHES) at the Massachusetts Institute of Technology (MIT) approved this study and the study conforms to recognized standards from the US Federal Policy for the Protection of Human Subjects.

Declaration of competing interest

The authors declare no conflicts of interest.

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