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ABSTRACT

Developmental dyslexia is a language-based reading disability, yet some have reported motor impairments, usually attributed to cerebellar dysfunction. Using fMRI we compared children with and without dyslexia during irregularly paced, left or right hand finger tapping. Neither whole-brain nor cerebellar region-of-interest analysis revealed between-group activation differences. Next, we examined seed-to-voxel intrinsic functional connectivity (iFC) using six seed regions of the motor system and found seven functional connections that differed between children with and without dyslexia. Most notably, the control group exhibited iFC between the right cerebellum seed and left SM1 during right hand tapping, but the group with dyslexia did not. However, standardized measures of reading and iFC among any of the functional connections identified in the between-group comparisons were not related when testing partial correlations. Overall, motor activity does not differ in dyslexia and altered iFC is not directly tied to reading, thereby offering little support for motor system dysfunction in dyslexia. Our results suggest that interventions targeting the motor system are not likely to benefit treatment for this common reading disability.

Keywords: connectivity, development, dyslexia, finger, motor

INTRODUCTION

Dyslexia is a learning disability characterized by slow and/or inaccurate reading of words, despite normal intelligence and/or instruction (Lyon et al. 2003). It occurs in roughly 5-12% of the population (Katusic et al. 2001). A commonly observed deficit in dyslexia is a weakness in skills collectively referred to as phonological awareness; these are needed for accurate grapheme-phoneme mapping and the successful decoding of words (Lyon et al. 2003; Peterson and Pennington 2012). Phonological awareness plays a contributing role in bringing about skilled reading in all children (Wagner and Torgesen 1987) and intensive instruction in this domain helps to improve reading ability in those with dyslexia (Alexander et al. 1991). These findings have jointly reinforced strong support of a phonological deficit theory for dyslexia. However, there are other facets of language skills and also non-language functions that are of interest in dyslexia in the quest to understand the mechanisms of this detrimental learning disability.

Some studies have focused on motor impairments in children with dyslexia, especially for tasks that are associated with cerebellar function. For example, a study by Fawcett et al. (1996) assessed children with dyslexia on a battery of motor tasks, including tests of posture, balance, muscle tone, and complex movements, and found that they performed significantly worse on all tests compared with their age-matched controls across a range of ages (10, 14 and 18 years of age on average). Also, the investigators reported that these impairments across all tasks manifested in 74% of children with dyslexia, compared to 16% of the controls (Fawcett et al. 1996). As deficits on these types of tests are indicative of abnormalities in the cerebellum, this study and others like it, as well as a brain imaging study on motor learning (described below), have led to the theory that dyslexia may be associated with abnormalities in the cerebellum (Nicolson et al. 2001).

Yet, others have raised concerns that these motor “cerebellar” impairments are not reliably identified. For example, a meta-analysis quantitatively summarizing 17 studies that compared performance of balance tasks in children, adolescents, and young adults with and without

dyslexia, revealed that effect sizes were not correlated with the degree of reading impairment; they were, however, correlated with whether the studies eliminated participants with attention-deficit-hyperactive disorder (ADHD; Rochelle and Talcott 2006). Further, a study employing a battery of cerebellar tests used by Fawcett et al. in 1996, this time in a group of children with 'pure' dyslexia (no ADHD or developmental coordination disorder) found that only 42% of these children (compared to 74% reported by Fawcett et al. 1996) performed worse than controls (Ramus et al. 2003). Further, Ramus and colleagues concluded that motor deficits (measured, for instance, with finger-to-thumb opposition movements, bead threading, and balance tasks) are restricted to a minority of those with dyslexia, a finding that is consistent across studies (Ramus 2003; White et al. 2006). As such, the evidence that motor deficits exist in children with dyslexia is mixed.

Turning to brain imaging studies of dyslexia, there is an abundance of research showing that the brain regions involved in reading and reading-related tasks (e.g. phonological processing) are altered anatomically (Eckert 2004) and functionally (Eden et al. 2016) in dyslexia. Specifically, left temporo-parietal, occipito-temporal, and inferior-frontal cortices show less gray matter volume (GMV; Linkersdorfer et al. 2012; Richlan et al. 2013) and underactivation (Maisog et al. 2008; Richlan et al. 2011) in dyslexia. By comparison, studies on brain anatomy and function of the motor system in dyslexia have been more mixed. Meta-analyses have shown reduced GMV in children with dyslexia in bilateral posterior cerebellum lobule VI (Linkersdorfer et al. 2012; Stoodley 2014) and right posterior cerebellum (Eckert et al. 2016), while another found no differences in GMV (Richlan et al. 2013). However, posterior cerebellum, and specifically lobule VI, is associated with language processing and is distinct from the anterior, motor aspect of cerebellum, offering little evidence in support of a motor system dysfunction. Rae and colleagues reported anomalies of the cerebellum (anterior and posterior extents) for brain neurochemistry (Rae et al. 1998) as well as anatomy (Rae et al. 2002). In terms of brain function, Nicolson and colleagues (1999) examined right hand finger movement sequences, both pre-learned and novel, in adults with and without dyslexia. They found that for both pre-learned and new sequences,

activation measured with positron emission photography (PET) was lower in the group with dyslexia relative to controls in right cerebellum. However, the cerebellum was not the only brain region to differ: for the new sequence task, adults with dyslexia showed greater activation in right medial prefrontal cortex and parts of bilateral temporal and parietal cortices (Nicolson et al. 1999). In a functional magnetic resonance imaging (fMRI) study, Menghini and colleagues (2006) found that for pseudorandom and repeating finger movement sequences, adults with dyslexia showed *greater* activation in right cerebellum lobule VI, right lateral premotor cortex, and bilateral inferior parietal cortex compared to controls (Menghini et al. 2006). While the notion of a motor deficit in dyslexia is considered to be controversial and the corpus of studies is small and inconsistent, further research is warranted given implications for treatment of dyslexia targeting the motor system (Reynolds et al. 2003).

In the current study we compared activity during thumb movements of the left and right hands (in separate runs) between groups of children with and without dyslexia. Based on the brain imaging studies on motor movement in dyslexia described above (Nicolson et al. 1999; Menghini et al. 2006), one might expect children with dyslexia to exhibit greater activity in regions subserving voluntary movement (e.g., premotor and parietal cortices). One might also expect activation differences in the cerebellum, although prior findings are conflicting about hyper- or hypo activity in the cerebellum in dyslexia. Therefore, our analyses focused on the whole brain as well as the cerebellum as a region-of-interest. Furthermore, given the extensive connections within the motor system, especially those between the cerebellum and cerebrum, we examined intrinsic functional connectivity (iFC) to capture correlations in these regions' brain activity over the duration of the run. Specifically, we measured background connectivity (Al-Aidroos et al. 2012; Norman-Haignere et al. 2012; Wang and Voss 2014; Gratton et al. 2016) between seed regions (located in the cerebellum or motor cortex) with the rest of the brain (seed-to-voxel iFC). Seed regions were derived from regions activated by both groups during the task to interpret the activation results in the context of functional connections. Our study was conducted in children

since studies in adults, such as those described above, leave open the possibility that any difference reported may be a consequence of having dyslexia rather than reflecting the cause of the reading disability. We matched the group with dyslexia to the control group on age, IQ, and a measure of ADHD symptoms. The ultimate goal was to determine whether there are differences in the integrity of the motor system in dyslexia.

MATERIALS AND METHODS

Subjects

Children with dyslexia and their age-matched controls were part of a larger program of research on reading disability (Krafnick et al. 2011, 2014, Olulade et al. 2013, 2015; Evans, Flowers, Napoliello, and Eden 2014; Evans, Flowers, Napoliello, Olulade, et al. 2014; Ashburn et al. 2020). All children were right-handed (i.e., with scores above 30 on the Edinburgh Handedness Inventory Oldfield 1971), monolingual English speakers without prior diagnoses of neurological disorders. Children with and without dyslexia were recruited from comparable geographic regions within the greater Washington, DC metropolitan area and from families at comparable socioeconomic standings. Children with dyslexia came from a private school specializing in learning disabilities. Nine of the children in the control group were included in a prior study examining the motor system in children compared to adults (Turesky et al. 2018).

Children with dyslexia had a documented history of underachievement in reading. To evaluate reading proficiency, all children underwent the Woodcock-Johnson Tests of achievement (WJ III; Woodcock et al. 2001). Children with dyslexia were included if they had WJ III Word Identification (Word ID) test < 92; control children had Word ID > 92 (30_{th} percentile). WJ III test of Reading Fluency was also administered. We assessed intelligence quotient (IQ) in all participants using the Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler 1999) to ensure all children had Full-Scale IQs at or above 80.

The iFC analyses (as described below) required strict criteria for rejecting scans with head motion, leading to the elimination of 15 children with dyslexia and 16 typical readers. To match our two groups on Conners' ADHD index T-scores and chronological age, we removed another five participants. The final groups comprised 15 children in the group with dyslexia (mean age: 10.00 ± 1.3 years) and 15 children in the control group (mean age: 8.72 ± 2.0 years). Demographic information for the final sample is summarized in Table 1.

Table 1. Subject Demographics.

	Control	Dyslexia	p-value
N	15	15	
Sex (F/M)	7/8	7/8	
Age (yrs)	8.72 (2.0)	10.0 (1.3)	ns
Range (yrs)	7.1 – 13	7.4 – 12	
Edinburgh Handedness Inventory	78.6 (21)	91.3 (19)	ns
Full-Scale IQ	123 (14)	105 (12)	$p<.001$
WJ Word ID	118 (9.8)	78.1 (10)	$p<.05$
WJ Reading Fluency	122 (14)	72 (14)	$p<.05$
Conners' ADHD index	52 (8.6)	55 (7.7)	ns

MRI Task and Data Acquisition

Subjects performed visually and irregularly paced, unimanual finger tapping tasks during functional data acquisition, as used in a prior study of children and adults (Turesky et al. 2018). Subjects were instructed to press the button with their thumb in response to a circle surrounding a cross-hair, which was omnipresent throughout the run. The tasks were presented using a block design, which consisted of 4 tapping blocks interspersed with fixations. All tapping blocks were 24 seconds. Within these blocks, the timing of the stimulus presentations varied and a 100 ms tapping stimulus appeared at one of three intervals: once per 650 ms, once per 900 ms, or once per 1150 ms. Each interval was used 8 times per block and interval order was randomized and differed for each tapping block. Left and right finger tapping were performed in separate runs and each run consisted of 69 volumes (32 tapping volumes and 37 fixation volumes). For both,

subjects could view stimuli from inside the scanner using an angled mirror apparatus fastened to the head coil, which relayed projections from a screen behind the scanner.

To familiarize subjects with the tasks and scanner environment, subjects practiced each task in a mock scanner before entering the real scanner. To ensure comfort and to minimize head motion, we placed foam cushions on both sides of their heads and allowed them to use additional foam padding around their arms.

Structural MPRAGE and functional EPI images were acquired on a 3T Siemens Trio scanner. MPRAGE scans were acquired with the following parameters: TR = 1600 ms, TE = 4.38 ms, 160 axial slices, 1 mm_3 voxels, FOV = 256 mm. EPI scans were acquired with blood-oxygen-level dependent (BOLD) contrasts, using TR = 3000 ms, TE = 30 ms, 50 axial slices acquired interleaved and anterior to posterior with a 0.2 mm gap, in-plane resolution of 64 x 64 (3 mm isotropic voxels), and 192 mm FOV.

Behavior Data Analysis

We calculated two performance measures collected during the scan: (1) accuracy, defined as the percent of trials in which subjects pressed the button when prompted; and (2) response times, defined as the time between the onset of the circle around the fixation cross and the button press by the subject. Data files were lost for two subjects with dyslexia and so performance measures were calculated without them.

MRI Data Analyses

Preprocessing and Head Motion Quality Control

All preprocessing steps were performed using MATLAB 2016a (*MathWorks*) and SPM12 (https://www.fil.ion.ucl.ac.uk/spm/software/spm12/).

MPRAGE: For all subjects, images were warped into Montreal Neurological Institute (MNI) stereotaxic space to correct for inter-subject variability and segmented into gray matter, white matter and cerebrospinal fluid (CSF) masks using the VBM8 toolbox.

EPI: To reduce T1 saturation effects, we discarded the first 3 volumes from each run. Preprocessing comprised of five major steps: (1) slice time correction to account for sampling superior and inferior parts of the brain at different times, (2) realignment of scans to correct for inter-scan head motion throughout the run, (3) coregistration to the native space MPRAGE images, (4) deformation to warp EPI images into MNI space using the subject-specific transformations applied to the MPRAGE images, and (5) smoothing with 8.0 mm FWHM Gaussian kernel to improve the signal-to-noise ratio. Following preprocessing, smoothed images were overlain with the MNI template to ensure successful normalization.

We undertook several additional steps to account for in-scanner head motion, since functional connectivity in general (Van Dijk et al. 2012; Satterthwaite et al. 2013) and especially in children (Satterthwaite et al. 2012) suffers considerably from head motion artifacts. First, we removed subjects for whom ≥ 20% of the total number of scans from either their left or right hand runs were preceded by inter-scan head motion greater than 0.75 mm (25% of the voxel size) root-mean-square (RMS) displacement (i.e., $d_2 = \Delta x_2 + \Delta y_2 + \Delta z_2 + [(65\pi/180)_2 \cdot (\Delta pitch_2 + \Delta rol_2 + \Delta yaw_2)]$ (Mazaika et al. 2005). This procedure removed 16 children from the control group and 15 from the group with dyslexia. The remaining subjects (15 children in each group) did not differ on the percentage of scans removed from each subject's dataset for the left ($t(28) = -0.18$; $p > 0.05$) or right hand ($t(28) = -0.44$; $p > 0.05$; Table 2). Second, scans that were preceded by ≥ 0.75 mm inter-scan head motion were entered as regressors at the first level (please see below). Third, we performed two-sample t-tests on mean and maximum inter-scan RMS displacement (after removing scans preceded by ≥ 0.75 mm head motion; Power et al. 2012; Alaerts et al. 2014) and found no significant differences for left (mean interscan: $t(28) = -0.24$; $p > 0.05$; max interscan: $t(28) = -0.31$; $p > 0.05$) or right hand tapping data (mean interscan: $t(28) = -0.011$; $p > 0.05$; max

interscan: $t(28) = 1.65$; $p > 0.05$), as seen in Table 2. And fourth, we assessed stimulus-correlated motion using Artifact Detection Tools (ART; https://www.nitrc.org/artificat_detect; adjusted in-house) to display correlation coefficient r-values for each translation and rotation parameter, because stimulus-correlated motion has been shown to reduce sensitivity of first-level effects (Johnstone et al. 2006). A MANOVA on these Fisher r-to-z transformed values showed no significant difference between groups on these measures.

Table 2. Motion Description.

	Control	**Dyslexia**	**p-value**
L. % movement scan	3.23 (5.7)	3.64 (6.7)	ns
L. mean interscan displacement (mm)	0.138 (0.058)	0.142 (0.047)	ns
L. max interscan displacement (mm)	0.469 (0.16)	0.484 (0.11)	ns
L. stim correlated motion (dim. pool)	0.0729 (0.051)	0.0782 (0.068)	ns
R. % movement scan	3.44 (4.9)	2.61 (5.2)	ns
R. mean interscan displacement (mm)	0.151 (0.047)	0.151 (0.046)	ns
R. max interscan displacement (mm)	0.604 (0.11)	0.516 (0.17)	ns
R. stim correlated motion (dim. pool)	0.0520 (0.048)	0.0964 (0.073)	ns

Task-Evoked Activation Analyses

All task-evoked activation analyses were performed in SPM12. For each subject, first-level statistics were performed by first applying a temporal high pass filter of 128 seconds, and then modeling each condition (left and right hand tapping) with a convolution of the canonical hemodynamic response function and our experimental block design. Fixation was treated as baseline, rather than as a distinct condition. We used an autoregressive (AR 1) model to reduce serial correlations from biorhythms and unmodeled neuronal activity. To account for head motion

as a confound of the button press and for changes in the global mean signal, we created a multiple regression model comprising the RMS displacement *from origin*, a logical vector to indicate whether a particular scan was preceded by ≥ 0.75 mm motion, and the global mean signal at each time point. This procedure generated within-subject beta maps for left and right hand tapping separately.

To identify within-group activations, we performed one-sample t-tests on children with and without dyslexia for left and right hand tapping. To identify between-group activation differences, we performed two-sample t-tests for control > dyslexia and dyslexia > control contrasts using left and right hand tapping data. We applied SPM's EPI.nii template as an explicit mask. All clusters output from these second-level analyses were reported as significant using an *FDR* cluster-level correction of $p < 0.05$ and a height threshold of $p < 0.001$.

Region-of-Interest (ROI) Analysis in the Cerebellum

Since the cerebellum was of special interest, we conducted an ROI analysis specifically in those regions of the cerebellum involved in our motor tasks. To this end, we first identified those voxels that were active during each task (left and right hand tapping) in both groups (control and dyslexia) and then generated group overlap ROIs for the cerebellum. Percent signal changes (PSCs) were extracted from subjects' first level left hand tapping data for the left ROI and right hand tapping data for the right ROI using MarsBaR 0.44 (http://marsbar.sourceforge.net/index.html), and then averaged for each hand. Accordingly, PSCs from all subjects were extracted from the same two ROIs. Identifying regions based on overlapping activation of the two groups prevented bias toward either group (defining ROIs by independent sources would have introduced bias in favor of the control group). Normality of the data was assessed using the D'Agostino-Pearson omnibus normality test. PSCs were normally distributed for both groups' for left and right hand tapping data, except for the dyslexia group's right hand tapping data ($K_2 = 6.64$; $p < 0.036$). Therefore, between-group comparisons were performed using parametric t-tests (two-tailed).

Seed-to-Voxel Intrinsic Functional Connectivity (iFC) Analyses

For the functional connectivity analyses, we constructed seed regions from the activation maps, consistent with earlier work (Rehme et al. 2013). Seed regions were derived by overlaying the activation results from the groups with and without dyslexia, similar to the group overlap ROI procedure described above for the cerebellum. This time, primary sensory motor cortex (SM1) and supplementary motor area (SMA) were included, resulting in three seed regions in each hemisphere. Then, 6 mm spheres were built around the centers of mass for these ROIs, located as follows: left cerebellum anterior lobe (x = -18, y = -56, z = -17), right cerebellum anterior lobe (x = 13, y = -55, z = -15), left SM1 (x = -37, y = -22, z = 60), right SM1 (x = 38, y = -22, z = 61), left SMA (x = -2.6, y = -2.5, z = 61), and right SMA (x = 2.3, y = -1.8, z = 60).

All iFC analyses were performed using CONN 15h/16a (https://www.nitrc.org/projects/conn; Whitfield-Gabrieli and Nieto-castanon 2012). To maximize signal-to-noise, all unsmoothed functional data (following preprocessing and motion quality control steps detailed earlier) were denoised, which involved simultaneous regression of temporal confounding factors and temporal filtering. Temporal confounding factors included the six rigid body head position parameters, a logical vector to indicate scans that were preceded by inter-scan head motion ≥ 0.75, and block conditions (fixation, left hand tapping, right hand tapping) convolved with the canonical hemodynamic response function. CONN also implements the CompCor method (Behzadi et al. 2007; Chai et al. 2012), in which five principal components were estimated from the subject-specific white matter and CSF masks generated in the VBM segmentation step above. We did not use temporal derivatives, as they decreased the signal-to-noise ratio. We used a band-pass filter of 0.008-0.090 Hz for our iFC analysis for which block-to-block discrimination is not necessarily desired (please see https://www.nitrc.org/projects/conn forum for a discussion of block-to-block discrimination); our low-pass threshold is consistent with that of previous background iFC studies (Rehme et al. 2013; You et al. 2013) and a range similar to this one has been advocated for reducing iFC measures related to motion (Satterthwaite et al.

2013). These steps produced denoised, residual BOLD time series for every gray matter voxel for every subject.

Seed time series were computed by averaging denoised BOLD time series corresponding to the voxels within the seed; for a given seed (e.g., left cerebellum), these voxels may have differed by subject because each seed was masked with subject-specific gray matter masks (from the MPRAGE segmentation step above). Maps generated for the right cerebellum, left SM1, and left SMA seeds were based on right hand tapping data; and maps generated for the left cerebellum, right SM1, and right SMA seeds were based on left hand tapping data.

Bivariate correlations were computed from time series data from the full runs for each hand. Here, the first-level analysis was performed using weighted GLM, HRF weighting, and bivariate correlation parameters. This resulted in single-subject *r*-maps in which the value of each voxel represents the correlation coefficient of that voxel's denoised time series with the seed time series. These maps were subsequently transformed into z-maps using Fisher's r-to-z transform.

Generation of within-group brain maps used one-sample t-tests for each group and seed separately. A positive iFC value at a given voxel indicated that that voxel's denoised time series was correlated with the time series of the seed. A negative iFC value at a given voxel indicated that that voxel's time series was anti-correlated with the time series of the seed. Generation of between-group brain maps used two-sample t-tests for controls > dyslexia and dyslexia > controls contrasts for each seed separately. All clusters output from these second-level analyses were reported significant using an *FDR* cluster-level correction of $p < 0.05$ and a height threshold of $p < 0.001$.

To differentiate positive and negative within-group iFC and to examine inter-subject variability in the between-group results, we extracted single-subject iFC measures from all resulting between-group clusters for both contrasts (control > dyslexia and dyslexia > control) using the REX toolkit (https://www.nitrc.org/rex).

Finally, we examined brain-behavior relationships *post hoc* using Pearson correlations and partial correlations (controlling for effect of group) on iFC estimates from those clusters that differed between the groups. There were two behavioral measures, Word Identification and Reading Fluency standard scores.

Reporting and Visualization of MRI Results

Significant clusters' peak voxel MNI stereotaxic coordinates and voxel extents were reported using SPM12 and CONN 15h/16a, converted into Talairach anatomical space (Talairach and Tournoux 1988) using the *icbm2tal* algorithm (Lancaster et al. 2007) included in GingerALE 2.3.6, and labelled as anatomical regions according to the Talairach Client 2.4.3 (http://talairach.org/client.html). Any peak coordinate greater than 11 mm from gray matter according to the Talairach Client was investigated using the Talairach Applet (http://www.talairach.org/applet.html), and a visual determination of its anatomical location was made.

Cortical motor regions (e.g., SM1, SMA, etc.) were labelled by overlaying thresholded brain maps on the Human Motor Area Template (HMAT; (Mayka et al. 2006); http://lrnlab.org/). This template was derived by implementing the ALE method on 126 fMRI or PET studies involving motor control, and it demarcates the motor areas into 3 main divisions (SM1, medial premotor cortex – MPMC, and lateral premotor cortex – LPMC) and subdivisions (primary motor and somatosensory cortices for SM1, SMA and pre-SMA for MPMC, and PMv and PMd for LPMC). For our reporting, we differentiated the subdivisions of MPMC and LPMC, but not SM1, because most of the effects in this region registered in a single cluster. This is different from activations in MPMC and LPMC, which often registered in one but not both subdivisions. All results were visualized using the Mango software package (http://rii.uthscsa.edu/mango/) with the Colin brain template in MNI space (Holmes et al. 1998). All voxels at surface depth ≤ 10 voxels are visualized at the surface.

RESULTS

Behavioral Results

Group averages for in-scanner head motion and performance (accuracy and response times) are summarized in Tables 2 and 3, respectively. No significant differences between children with and without dyslexia were observed for head motion nor for performance.

Table 3. In-Scanner Performance.

	Control	Dyslexia	p-value
L. accuracy (% correct)	0.88 (0.1)	0.85 (0.08)	ns
L. response time (ms)	324 (40)	328 (35)	ns
R. accuracy (% correct)	0.88 (0.1)	0.84 (0.1)	ns
R. response time (ms)	334 (55)	341 (44)	ns

Task-Evoked Activation Analyses

Within-Group Maps

Whole-brain activation maps for the groups with and without dyslexia during tapping compared to the fixation baseline are depicted in Figure 1 and activation peaks are described in Table 4.

Control Group

In the control group, left hand thumb tapping induced activation in right SM1 (extending into right PMd), left SMA (extending into right SMA and anteriorly into bilateral pre-SMA), left anterior cerebellum, right claustrum (extending into right PMv), right midbrain (extending into right thalamus), and right inferior occipital gyrus.

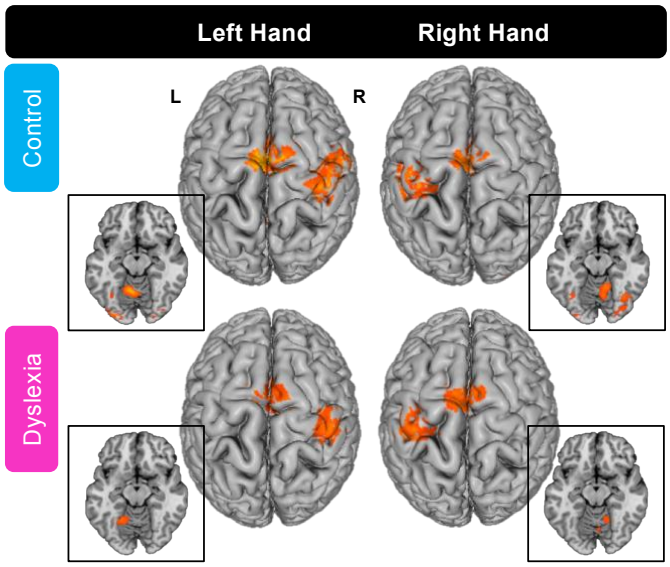
Right-hand thumb tapping was associated with activation in left primary sensorimotor cortex (SM1), left supplementary motor area (SMA; extending into right SMA and bilateral pre-SMA),

right anterior cerebellum, left posterior cerebellum, left thalamus (extending into right thalamus), and left inferior occipital gyrus.

Group with Dyslexia

In the group with dyslexia, left hand thumb tapping was associated with activation in right SM1, left SMA (extending into right SMA and bilateral pre-SMA), right PMv (though the peak was located in right insula, not precentral gyrus), left anterior cerebellum, right thalamus, and right lingual gyrus.

Right hand thumb tapping showed activation in left SM1, left SMA (extending into bilateral pre-SMA), right anterior cerebellum, left thalamus, and right middle occipital gyrus.



[Figure 1: Whole-brain activation maps for finger tapping in the control group and the group with dyslexia. For both groups, left and right finger tapping relative to fixation baseline elicited activations in cortical and subcortical (not shown) brain areas (*FDR* cluster-level corrected threshold of $p < 0.05$). All axial slices in insets are at z = -15 (MNI). L, left hemisphere; R, right hemisphere. Please see Table 4 for peak locations.**]**

Table 4. Activation peaks for within-group contrasts for left and right hand tapping.

Anatomical region	Functional motor region	BA	Peak MNI coordinate			k	Z
			x	y	z		
Control							
Left Hand Tapping							
R. Postcentral Gyrus	R. SM1	3	36	-20	51	2173	5.50
L. Medial Frontal Gyrus	L. SMA	6	-4	-6	69	2268	5.81
L. Ant. Cerebellum			-9	-56	-10	3748	6.57
R. Claustrum			34	16	9	386	4.43
R. Midbrain			9	-24	-9	425	4.05
R. Inferior Occipital Gyrus		18	27	-93	-4	1639	5.07
Right Hand Tapping							
L. Precentral Gyrus	L. SM1	4	-30	-24	57	1629	5.57
L. Medial Frontal Gyrus	L. SMA	6	-4	-8	62	1262	5.67
R. Ant. Cerebellum			14	-54	-20	4908	5.22
L. Post. Cerebellum			-40	-64	-24	503	4.22
L. Thalamus			-10	-22	2	760	4.70
L. Inferior Occipital Gyrus		18	-32	-94	-4	1211	5.23
Dyslexia							
Left Hand Tapping							
R. Postcentral Gyrus	R. SM1	3	40	-24	58	1079	4.77
L. Medial Frontal Gyrus	L. SMA	6	-4	0	58	1787	4.64
R. Insula	R. PMv	13	50	-2	9	184	3.68
L. Ant. Cerebellum			-21	-56	-16	646	4.46

R. Thalamus			16	-20	8	198	4.25
R. Lingual Gyrus		17	24	-96	3	419	4.64
Right Hand Tapping							
L. Postcentral Gyrus	L. SM1	3	-38	-26	63	1154	4.76
L. Medial Frontal Gyrus	L. SMA	6	-9	-2	64	1268	4.73
R. Ant. Cerebellum			15	-56	-15	503	3.82
L. Thalamus			-9	-21	9	539	4.46
R. Middle Occipital Gyrus		18	39	-92	0	249	4.40

Between-Group Maps

No significant between-group differences were observed for control > dyslexia or dyslexia > control contrasts.

Region-of-Interest (ROI) Analysis in the Cerebellum

We compared average percent signal change (PSC) in left and right cerebellar ROIs between the two groups. No between-group differences were observed for left ($t(28) = 1.34$, $p > 0.05$) or right hand ($t(28) = 0.737$, $p > 0.05$) tapping.

Seed-to-Voxel Intrinsic Functional Connectivity (iFC) Analyses

Within-Group Maps

We performed bivariate correlation analyses to identify brain areas exhibiting functional connectivity with any of the six seed regions. For brevity we do not report on significant self-connections, which are connections that are close to the seed (e.g., if, when using a left cerebellum seed, a cluster emerges with peak coordinate in left cerebellum); however, full lists of

within-group iFC results are provided in Table S1. Additionally, unless otherwise specified, iFC estimates are positive.

Control Group

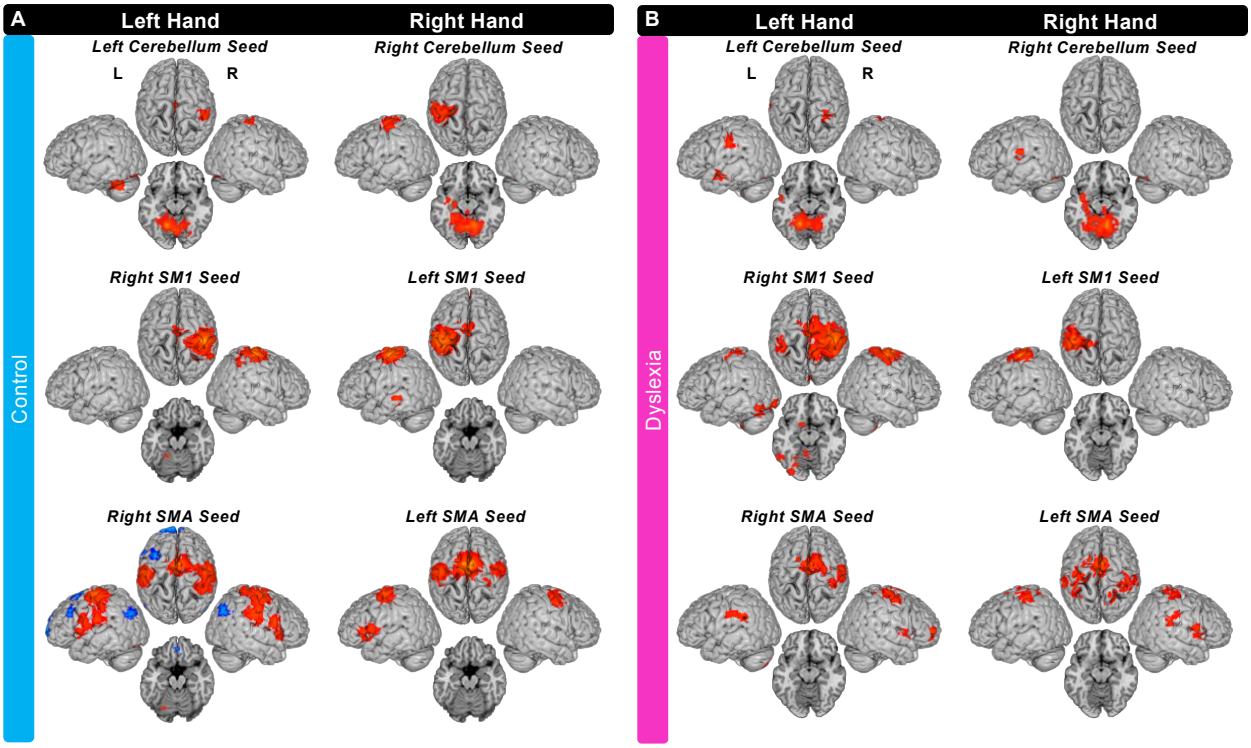
For the left hand tapping run, the controls exhibited iFC between the left cerebellum seed and right SM1, between the left cerebellum seed and right SMA (extending into left SMA); between the right SM1 seed and left anterior cerebellum; between the right SMA seed and left SM1 (extending into PMd), between the right SMA seed and left PMv (two separate clusters), and between the right SMA seed and left lentiform nucleus. The controls also exhibited negative iFC between the right SMA seed and right MTG, between the right SMA seed and left MTG, and between the right SMA seed and left IFG.

For right hand tapping, the controls exhibited iFC between the right cerebellum seed and left SM1 (though the anatomical location was left inferior parietal lobule and not postcentral gyrus; extending into PMd); between the left SM1 seed and left SMA (extending into right SMA and bilateral pre-SMA) and between the left SM1 seed and left MTG; between the left SMA seed and right SM1 and between the left SMA seed and right PMd (extending into PMv; Figure 2A).

Group with Dyslexia

For the left hand tapping run, the group with dyslexia exhibited iFC between the left cerebellum seed and left SM1, between the left cerebellum seed and right SM1, and between the left cerebellum seed and left MTG. There was also iFC between the right SM1 seed and left SM1 (two separate clusters), between the right SM1 seed and left anterior cerebellum, and between the right SM1 seed and left fusiform gyrus. Lastly, there was iFC between the right SMA seed and right SM1 (two separate clusters with the more lateral extending into PMd) and between the right SMA seed and left STG.

For the right hand tapping run, the group with dyslexia exhibited iFC between the right cerebellum seed and left superior temporal gyrus (STG), but not between this seed and any motor regions (as defined by HMAT; please see methods for details). There was no iFC between the left SM1 seed and other regions. Lastly, the group with dyslexia exhibited iFC between the left SMA seed and right SM1, between the left SMA seed and left SM1 (though the anatomical peak was outside pre/postcentral gyrus), between the left SMA seed and left PMv, between the left SMA seed and right STG, and between the left SMA seed and right inferior parietal lobule (Figure 2B).



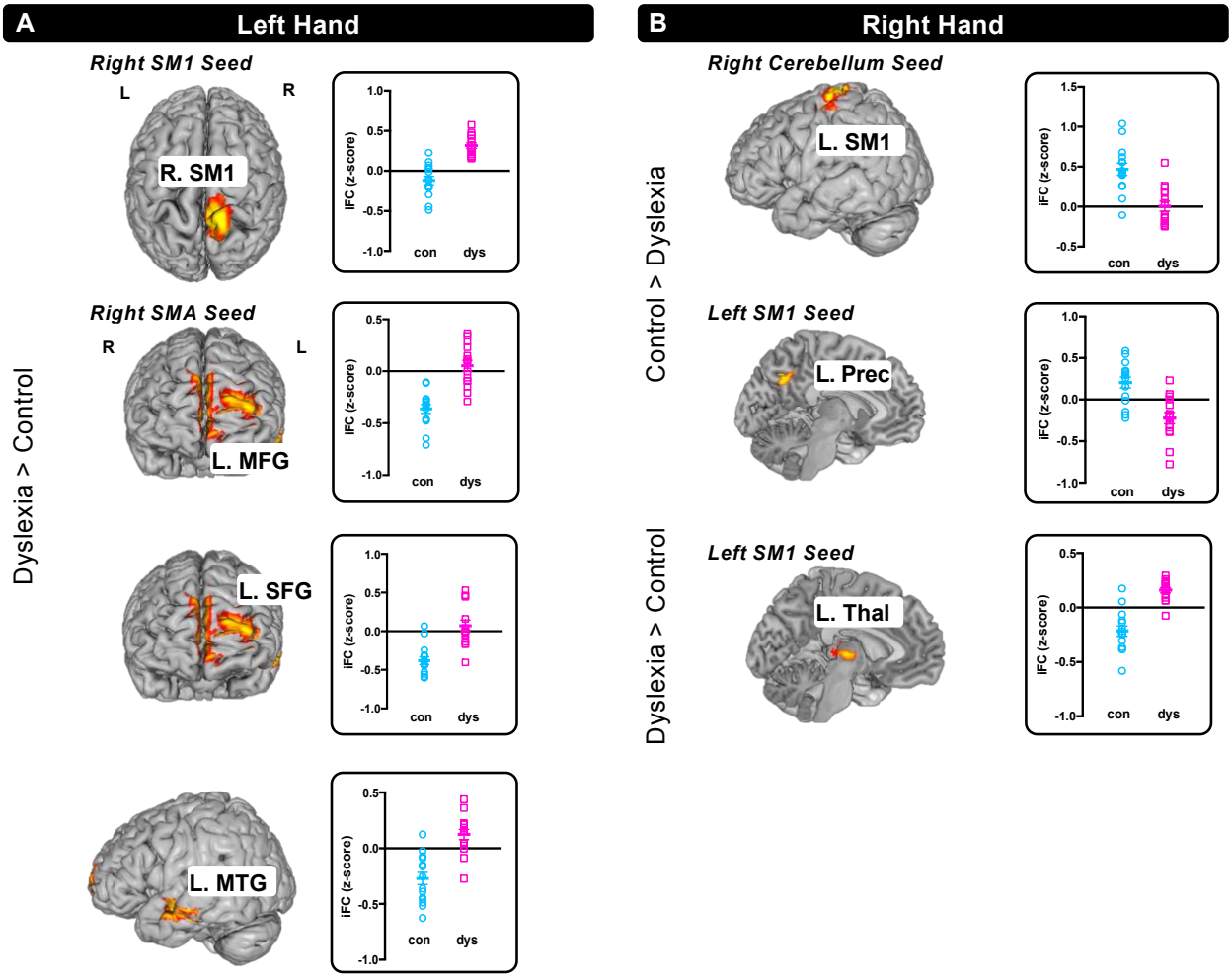
[Figure 2: Seed-to-Voxel Intrinsic Functional Connectivity for (A) the control group and (B) the group with dyslexia. IFC with seeds in left cerebellum, right SM1, and right SMA used left finger tapping data; and iFC with seeds in right cerebellum, left SM1, and left SMA used right finger tapping data. Axial slices are z = -15 (MNI) for cerebellum seeds and z = -20 (MNI) for SM1 and SMA seeds. All maps were thresholded with *FDR* cluster-level correction of $p < 0.05$. L, left

hemisphere; R, right hemisphere. Table 5 provides the full list of brain areas with iFC to these seeds.]

Between-Group Differences

Figure 3 shows the results by seed regions during (A) left hand and (B) right hand tapping, as well as the individual iFC measures extracted from significant clusters shown for each group. For left hand tapping there were no functional connections that were *weaker* in the group with dyslexia. Instead the group with dyslexia exhibited *greater* iFC in four functional connections: between the right SM1 seed and a more medial cluster in right SM1; and between the right SMA seed and three left hemisphere regions, the medial frontal gyrus (MFG), the SFG, and the MTG (Figure 3A).

For right hand tapping, the group with dyslexia compared with the controls exhibited *weaker* iFC between the right cerebellum seed and left SM1 (BA 3); this functional connection was observed in the control group in the within-group results (as described above), but not in the group with dyslexia. Also, the group with dyslexia exhibited relatively *weaker* iFC between the left SM1 seed and left precuneus, yet relatively *greater* iFC between the left SM1 seed and left thalamus (Figure 3B; Table 5).



[Figure 3: Seed-to-Voxel iFC differences between the control group and the group with dyslexia (A) left hand tapping and (B) right hand tapping. (A) There were four iFCs that were relatively greater in the group with dyslexia and none that were relatively less during left hand tapping. (B) There was one iFCs that was relatively greater in the group with dyslexia and two that were relatively less during right hand tapping. All maps $p < 0.05$ *FDR* cluster-level corrected. Individual iFC measures extracted from significant clusters are depicted to the right of the brain map for differentiating positive and negative within-group iFC and showing inter-subject variance. L, left hemisphere; R, right hemisphere; SM1, primary sensorimotor cortex; SMA, supplementary motor area; MFG, medial frontal gyrus; SFG, superior frontal gyrus; MTG, middle temporal gyrus; Prec, precuneus; Thal, thalamus.**]**

Table 5. iFC peaks for between-group comparisons for cerebellum, SM1, and SMA seeds.

Contrast / Seed	Anatomical region	Functional motor region	BA	Peak MNI coordinate x	y	z	k	Z
Please see Supplemental Figure 1 for within-group iFC peaks								
Control > Dyslexia								
Right Hand Tapping								
R. CB seed	L. Postcentral Gyrus	L. SM1	3	-32	-22	70	121	3.65
L. SM1 seed	L. Precuneus		31	-6	-62	32	108	3.85
Left Hand Tapping								
ns								
Dyslexia > Control								
Left Hand Tapping								
R. SM1 seed	R. Postcentral Gyrus*	R. SM1	5	8	-38	82	124	4.38
R. SMA seed	L. Medial Frontal Gyrus		10	0	66	2	142	4.30
	L. Middle Temporal Gyrus		21	-56	-4	-16	86	4.00
	L. Superior Frontal Gyrus		9	-14	64	14	99	3.92
Right Hand Tapping								
L. SM1 seed	L. Thalamus			-4	-18	2	95	5.09

*Peak coordinate reported not within gray matter by Talairach Client. Anatomical Label determined by visual inspection of Colin brain template in Mango.

Brain-Behavior Relationships

Finally, to determine if there were relationships between the strength of these seven functional connections and reading ability, we performed Pearson correlations and partial correlations *post hoc* between individual iFC estimates extracted from clusters that were significant in the between-group comparisons and measures of reading: the Word Identification and the Reading Fluency subtests of the Woodcock-Johnson Tests of Achievement (Woodcock et al. 2001). Because the data were binomially distributed for reading scores (according to group), we controlled for the effect of group using partial correlations. No brain-behavior partial correlations were significant after Bonferroni correction for multiple tests (i.e., 14 tests).

DISCUSSION

This is the first study to investigate activity and functional connectivity of the motor system in children with dyslexia and age-matched controls. For either group, visually paced, unimanual finger tapping with either hand engaged those regions widely reported previously to be activated (Witt et al. 2008), namely SM1 contralateral to the side of movement, bilateral SMA, and anterior cerebellum ipsilateral to the side of movement. Between-group comparisons did not reveal any differences in the group with dyslexia compared to controls. An ROI analysis focused on the cerebellum due to its purported role in dyslexia (Nicolson et al. 1999) did not reveal between-group differences either. When examining (seed-to-voxel) intrinsic functional connectivity (iFC) using three seed regions in both hemispheres (cerebellum, SM1 and SMA), both groups overall exhibited functional connections between cerebral cortical regions, as well as between the cerebellum and the cerebral cortex. Between-group comparisons revealed seven differences in iFC. The most notable of these was between the seed in the right cerebellum and left SM1 during right hand tapping, the only between-group difference that was consistent with and supported by the within-group results. Specifically, for the within-group maps, left and right hand finger tapping was associated with a functional connection between the cerebellum and SM1 for both groups, except for the group with dyslexia during right hand tapping, and this manifested as relatively weaker functional connectivity when comparing the two groups. While the two groups differed in seven functional connections, none of the iFC estimates amongst these regions, correlated (partial correlation) with reading ability (accuracy or fluency). Overall, these findings suggest normal activity during motor processing, with some differences in intrinsic functional connectivity that were not directly tied to reading.

Functional Anatomy of Motor Movements During Finger Tapping

Several studies have examined motor system activation in typically developing children (Rivkin et al. 2003; Vandermeeren et al. 2003; Mostofsky et al. 2006; De Guio et al. 2012; Roessner et al.

2012, 2013; Turesky et al. 2018) with many more studies having been conducted in adults (please see Witt et al. 2008, for a meta-analysis). As in the present study, previous studies in children have reported activation of SM1, SMA, and cerebellum. Overall, our groups of children with and without dyslexia, showed patterns of activation during finger tapping that are consistent with previous studies in typically developing children and with the functional anatomy underlying finger tapping in general.

While there are no prior studies in children on functional connectivity during a motor task, the motor system in children (age range: 5-8 years) has been loosely characterized as part of a resting-state (i.e., awake, no task) study on intrinsic functional connectivity of the entire brain (de Bie et al. 2012). Using an independent component analysis (ICA), the study revealed several resting-state networks, including two sensorimotor networks, one of which encompassed bilateral SM1, bilateral SMA, and bilateral cerebellum, the same regions amongst which we found functional connectivity.

Dyslexia, Motor Movement, and the Cerebellum

Two studies have compared brain activity in groups with and without dyslexia during a finger movement task, both conducted in adults (Nicolson et al. 1999; Menghini et al. 2006). The first employed a right hand, multi-digit motor sequence task with two conditions, pre-learned and novel motor sequences. For the pre-learned sequence, the group with dyslexia exhibited relatively weaker activation in right cerebellum and left cingulate gyrus; no areas were more active in the group with dyslexia. For the novel sequence task, the group with dyslexia again exhibited relatively weaker activation in the same right cerebellum region, demonstrating a difference in the cerebellum that was identified in two motor tasks, independent of whether they were pre-learned or novel. Greater activation was also observed in the group with dyslexia compared to the control group during the novel sequence in bilateral angular gyrus and left STG, as well as an area labelled as medial area 9 (BA 9; Nicolson et al. 1999). The authors focused mostly on the

cerebellum findings, arguing that these provide brain-based evidence for their early behavioral findings that were indicative of cerebellar abnormalities (Fawcett et al. 1996). The investigators used two paradigms that differed in a motor learning component, with the expectation that there would be greater activation in the cerebellum performing the pre-learned sequence relative to the new sequence in each group. However, this was not the case in the controls. Further, that there were differences between the two groups in the cerebellum for both sequences indicated a more general motor deficit.

In the study by Menghini et al. (2006), adults performed two types of motor sequence tapping: a random sequence, and a repetition of a specific sequence with the expectation that subjects would be implicitly learning this repeated sequence over the course of the experiment. When combining random and repeated sequences, both groups exhibited activation in bilateral cerebellum lobule VI, bilateral premotor cortex, left superior parietal lobule, and bilateral inferior parietal cortex. The control group also showed activation in left basal ganglia, left SMA, and right superior parietal lobule, while the group with dyslexia did not show activation in any additional brain areas. When comparing the groups with each other, the group with dyslexia exhibited *greater* activation in right cerebellum lobule VI, right lateral premotor area, and bilateral inferior parietal cortex compared with typical readers; there were no regions where the group with dyslexia showed less activation (Menghini et al. 2006). As such, the results of a right cerebellum difference in dyslexia between the two studies had opposite outcomes. Turning to studies examining brain anatomy in dyslexia for further background, one meta-analysis reported less GMV in dyslexia in the right cerebellum (Eckert et al. 2016), and two others less GMV bilaterally (Linkersdorfer et al. 2012; Stoodley 2014), while yet another found no differences in GMV at all (Richlan et al. 2013). These inconsistencies do not offer much help in the interpretation of the conflicting results from the two functional brain imaging studies. Taken together there are few studies of the motor system in dyslexia and no consistent evidence in support of aberrant function or anatomy.

Given these prior studies, our findings of no differences in activation between children with and without dyslexia during a finger movement task may not be surprising. However, research reporting worse performance in dyslexia compared with typical readers on a variety of cerebellum-specific (Fawcett et al. 1996), as well as simpler (Wolff et al. 1984; Wolff 2002), motor tasks, might lead one to expect differences in the motor system, especially the cerebellum. As such, it is worth considering the task employed and the methods used in the present study. Our task involved externally triggered motor movement, which is the most common approach to activating the motor system associated with finger movements (Witt et al. 2008); and irregular pacing, as used here, elicits greater activation than regular pacing in cerebellum, SM1, and SMA (Lutz et al. 2000). This task has previously been shown to elicit activation of the motor system in many studies, including one from our own lab (Turesky et al. 2018), and indeed elicited robust activation in the current study (including the cerebellum) for both groups and during the use of either hand. Despite this, we did not observe any significant differences between the controls and the group with dyslexia anywhere in the brain, even when using an ROI analysis focused on the cerebellum. Since we studied children, it is also possible that the activation differences in dyslexia reported in the above studies on adults reflect neuroplastic (possibly compensatory) processes that are a consequence of prolonged experience with dyslexia. However, this assertion would be a more compelling explanation for all studies, if the two conducted in adults (Nicolson et al. 1999; Menghini et al. 2006) had similar results. Finally, it should be noted that the notion of dysfunction of the motor system, especially the cerebellum, in dyslexia has not enjoyed much support and has been criticized on theoretical grounds, as well concerns around “cerebellar treatment” for this reading disability (Zeffiro and Eden 2001; McPhillips 2003; Richards et al. 2003; Singleton and Stuart 2003; Snowling and Hulme 2003; Stein 2003; Rack et al. 2007). Our results also do not offer any further evidence in support of an altered motor system in dyslexia that would motivate treatment targeting the motor system. As noted by others in this debate, such an approach would not likely

lead to a positive outcome, and could detract from the language-based literacy instruction that has shown efficacy.

Dyslexia and Brain-Based Disconnections

As part of our study, we examined functional connections between target seed regions placed in those areas activated during the finger tapping task (cerebellum, SM1, and SMA, specific for each hand) and the rest of the brain. The purpose was to provide context for any differences in activation between the two groups, and while brain activity was not different, the group with dyslexia lacked the functional connection between right cerebellum and left SM1 for right hand tapping (resulting in a between-group difference). Motor cortex projects to the anterior cerebellum as part of the cortico-cerebellar loop, passing through the pontine nucleus in the brainstem along its efferent segment and through the thalamus as part of its afferent segment (Kelly and Strick 2003; for a review, see Ramnani 2006). Our findings may suggest a disruption of this loop, limited to the right cerebellar with left cerebral connection. It is somewhat difficult to substantiate this observation with prior work, which has shown anatomical anomalies in bilateral cerebellum (Linkersdorfer et al. 2012; Stoodley 2014) and in right, but not left, precentral gyrus, the location of primary motor cortex (Krafnick et al. 2014). However, studies of anatomical connectivity using diffusion tensor imaging (DTI) provide an interesting lens by which to consider our results. Vandermosten and colleagues (2012) examined regions where white matter structure (i.e., functional anisotropy) correlated with reading and found (using probabilistic fiber tracking) that a large portion was within the left corona radiata (Vandermosten et al. 2012). Interestingly, the x- and y- bounding coordinates of the cluster contain our peak coordinates for SM1 (anterior boundary: x = -24, y = -12, z = 30; posterior bound: x = -32, y = -24, z = 22; our SM1 cluster: x = -32, y = -22, z = 70), suggesting that the part of corona radiata affected in dyslexia may contain corticofugal M1 fibers going to the pontine nucleus (one segment of the cortico-cerebellar loop) or afferent fibers from thalamus to M1 (another segment of the cortico-cerebellar loop), both of

which would affect cortico-cerebellar iFC. Notably, the coordinates from this meta-analysis fall very near the left insula, which Paulesu and colleagues (1996) suggested acts as an anatomical bridge between inferior frontal and tempero-parietal regions that is dysfunctional in dyslexia (Paulesu et al. 1996). Overall, this adds to the body of evidence for a disruption in this region in children with dyslexia.

Furthermore, an emperical DTI study in adolescents with dyslexia exhibited greater anatomical connectivity in thalamocortical tracts between thalamus and SM1 bilaterally compared with age-matched typical readers (Fan et al. 2014). In our study, the group with dyslexia exhibited relatively *greater* iFC between the left SM1 seed and left thalamus, which fits with this study and that by Vandermosten described above, given that the corona radiata contains afferent fibers from thalamus to M1. However, we did not find functional connectivity between these two regions in the within-group map of the control group (or the group with dyslexia), which makes it difficult to gauge the nature of this result. Whether the iFC differences we observed are related to these white matter tracts specifically would need to be tested in future studies. Future studies would also need to address whether our observations can be explained specifically in the context of the motor system, or reflect general brain dysfunction underlying language that are reflected in structures that serve the motor systems, making the cerebellum an innocent bystander (Zeffiro and Eden 2001). We explored this issue briefly in a *post-hoc* analysis designed to test for brain-behavioral relationships between iFC and measures of word reading accuracy or reading fluency, but we found no such correlations. Broadly, this is consistent with previous behavioral literature, showing no correlations between measurements of motor and reading deficits (Rochelle and Talcott 2006) or ability (White et al. 2006). Lastly, many of the subjects in the present study were included in a report using a reading task, which revealed no differences between the children with and without dyslexia in the cerebellum (Ashburn et al 2020). Overall, the lack of a brain-behavior relationship and differences in brain activity dovetail with what others have argued earlier, that

the motor differences (whether brain or behavioral) may be epiphenomenal but are not a defining feature of dyslexia (Ramus 2003).

Conclusion

While dyslexia is associated with difficulties in reading due to language-based deficits in phonological processing, there has been a small and controversial body of literature focusing on deficits in motor function. Here, we found no differences in brain activity in the motor system between children with and without dyslexia during finger movements. However, our results indicate possible compromise in some connections within the motor system, most notably a functional disconnection between right cerebellum and left SM1 during right hand finger tapping. However, as none of these showed a relationship with standardized measures of reading ability, our results do not support the hypothesis that the motor system, specifically the cerebellum, has a critical role in dyslexia. Our results indicate that treatments targeting the motor system are not justified and will likely not be beneficial for improving reading skills in children with this common learning disability.

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Supplemental Table 1. iFC peaks for within-group contrasts for cerebellum, SM1, and SMA seeds.

Group	Anatomical region	Functional motor region	BA	Peak MNI coordinate			k	Z
Seed				x	y	z		
Control								
Left Hand Tapping								
L. CB seed	R. Postcentral Gyrus	R. SM1	2	42	-30	66	170	3.82
	L. Medial Frontal Gyrus[#]	R. SMA	6	2	-14	56	96	3.75
	L. Ant. Cerebellum			-18	-58	-16	2142	6.88
	L. Ant. Cerebellum			-54	-56	-32	113	4.49
R. SM1 seed	R. Paracentral Lobule	R. SMA	5	4	-24	58	148	4.17
	L. Ant. Cerebellum			-22	-48	-22	77	3.78
	R. Precentral Gyrus	R. SM1	4	38	-22	64	2091	6.74
R. SMA seed	L. Postcentral Gyrus	L. SM1	3	-46	-12	60	1040	5.35
	L. Insula	L. PMv	13	-40	4	12	1268	5.18
	L. Precentral Gyrus	L. PMv	4	-62	2	16	120	4.69
	L. Lentiform Nucleus			-20	-4	-6	68	4.25
	R. Middle Temporal Gyrus		39	56	-68	32	162	-4.09
	L. Middle Temporal Gyrus		39	-50	-66	28	162	-3.91
	L. Inferior Frontal Gyrus		9	-58	22	26	60	-3.80
	L. Cingulate Gyrus		31	-4	-42	38	242	-5.10
	L. Medial Frontal Gyrus		10	0	66	2	1465	-4.82
	R. Precentral Gyrus		6	68	8	18	1209	4.77

	L. Middle Frontal Gyrus		6	-32	12	58	93	-4.54
	L. Post. Cingulate Gyrus		31	-12	-64	20	111	-3.86
	L. Post. Cerebellum			-24	-74	-16	54	4.27
	L. Medial Frontal Gyrus	R. SMA	6	0	-4	62	4255	6.95
Right Hand Tapping								
R. CB seed	L. Inferior Parietal Lobule[≠]	L. SM1	40	-40	-26	44	619	4.39
	L. Sub-Gyral Temporal Lobe		21	-38	-6	-16	176	4.01
	R. Ant. Cerebellum			10	-54	-14	2639	6.48
L. SM1 seed	L. Medial Frontal Gyrus	L. SMA	6	-8	-4	58	506	5.07
	L. Middle Temporal Gyrus		21	-60	-28	-6	82	4.72
	L. Medial Frontal Gyrus[#]		9	2	56	22	206	4.36
	L. Precentral Gyrus	L. SM1	4	-38	-20	60	2297	6.72
L. SMA seed	R. Postcentral Gyrus	R. SM1	3	26	-20	66	65	3.89
	R. Precentral Gyrus	R. PMd	4	52	-6	44	340	4.84
	L. Precentral Gyrus		44	-58	16	0	246	4.42
	L. Medial Frontal Gyrus	L. SMA	6	-2	-2	62	3667	7.79
Dyslexia								
Left Hand Tapping								
L. CB seed	L. Postcentral Gyrus	L. SM1	2	-66	-18	30	98	4.19
	R. Postcentral Gyrus	R. SM1	2	28	-32	76	49	4.17
	L. Middle Temporal Gyrus		21	-52	-4	-18	49	4.11
	L. Post. Cerebellum			-26	-54	-48	135	4.26

	L. Ant. Cerebellum			-18	-54	-18	1849	7.25
R. SM1 seed	L. Postcentral Gyrus	L. SM1	3	-34	-18	52	88	4.30
	L. Postcentral Gyrus	L. SM1	2	-38	-32	68	58	4.05
	L. Ant. Cerebellum			-6	-52	-12	47	3.89
	L. Fusiform Gyrus		37	-60	-60	-18	394	4.70
	L. Subcallosal Gyrus		34	-12	4	-20	55	4.72
	R. Post. Cerebellum*			32	-44	-56	125	5.42
	L. Post. Cerebellum			-20	-58	-50	153	4.36
	L. Post. Cerebellum*			-26	-44	-54	134	4.11
	L. Post. Cerebellum			-34	-88	-18	138	4.00
	L. Post. Cerebellum			-10	-74	-42	100	3.84
	R. Lingual Gyrus		18	14	-84	6	352	4.64
	R. Precentral Gyrus	R. SM1	4	38	-20	60	3006	6.39
R. SMA seed	R. Postcentral Gyrus	R. SM1	2	52	-22	60	176	4.07
	R. Postcentral Gyrus	R. SM1	3	36	-30	58	90	3.88
	L. Superior Temporal Gyrus		13	-58	-38	26	121	4.31
	R. Middle Frontal Gyrus		10	46	48	2	126	4.70
	R. Precentral Gyrus		44	54	4	0	124	4.33
	L. Post. Cerebellum			-34	-78	-50	116	5.13
	L. Medial Frontal Gyrus#	R. SMA	6	2	-2	58	1404	6.70
Right Hand Tapping								
R. CB seed	L. Postcentral Gyrus		43	-58	-16	16	126	4.60
	L. Superior Temporal Gyrus		38	-36	0	-16	314	4.40

	Midline Pons*			0	-16	-28	57	4.09
	R. Post. Cerebellum			12	-60	-14	2425	6.67
L. SM1 seed	L. Precentral Gyrus	L. SM1	4	-38	-22	60	1102	7.03
L. SMA seed	R. Postcentral Gyrus	R. SM1	3	42	-26	56	553	4.47
	L. Inferior Parietal Lobule	L. SM1	40	-52	-24	52	60	3.78
	L. Insula	L. PMv	13	-40	4	14	68	4.28
	R. Superior Temporal Gyrus		22	58	8	-4	159	4.45
	R. Inferior Parietal Lobule		40	60	-22	26	56	4.24
	L. Medial Frontal Gyrus	L. SMA	6	-2	-4	60	2546	6.85

*Peak coordinate reported not within gray matter (11mm cube) by Talairach Client. Anatomical Label determined by visual inspection of Colin brain template in Mango.

⊀Inconistence between anatomical and functional regions

#Inconsistence between +/- x-coordinate and Talairach Client R/L identification