

Research Report

Decoding the role of the cerebellum in the early stages of reading acquisition



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ABSTRACT

Numerous studies have consistently reported functional activation of the cerebellum during reading tasks, especially in the right cerebellar hemisphere. However, it remains unclear whether this region is also involved in reading during the earliest stages of reading acquisition. Here, we investigated whether and how the cerebellum contributes to reading acquisition. We tested 80 5-6-year-old kindergarteners, who performed a visual word matching task during which functional MRI (fMRI) data were collected. We found that bilateral cerebellar hemispheres were significantly activated during visual word processing. Moreover, activation of left cerebellar lobule VII extending to lobule VIII negatively and significantly correlated with current reading ability, whereas activation of right cerebellar lobule VII extending to lobule VIII significantly and positively correlated with future reading ability. Functional decoding via functional connectivity patterns further revealed that left and right cerebellar lobules connected with different cerebral cortex regions. Our results suggest a division of labor between the left and right cerebellar lobules in beginning readers.

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1. Introduction

Successful reading requires the integration of different neural systems, such as the attention, articulatory, phonological, and semantic networks (Achal, Hoeft, & Bray, 2015). Previous studies have mainly focused on how these systems work with each other during reading in the cerebrum (Cao, 2016; D'Mello & Gabrieli, 2018). Recently, extensive studies have also observed cerebellar activation during reading or reading-related tasks, especially in the right cerebellar hemisphere (Cattinelli, Borghese, Gallucci, & Paulesu, 2013; Martin, Schurz, Kronbichler, & Richlan, 2015; Meng et al., 2016; Peng et al., 2003; Tan, Laird, Li, & Fox, 2005). In addition, these regions are known to be functionally connected with regions within the reading network established in the cerebrum (Alvarez & Fiez, 2018; Booth, Cho, Burman, & Bitan, 2007). Functional or structural deficits in right cerebellar lobules VI and VII are also associated with reading impairment (Eckert et al., 2016; Feng et al., 2017; Hancock, Richlan, & Hoeft, 2017; Linkersdörfer, Lonnemann, Lindberg, Hasselhorn, & Fiebach, 2012). Overall, these results suggest that the right cerebellar hemisphere, in particular, lobules VI and VII, play important roles in reading. An intriguing issue concerns whether these regions are also involved in reading during the early stages of reading acquisition.

As to the cerebellar contributions to early reading, previous reviews provide some clues. For example, the Cerebellar Deficit Hypothesis proposed that the cerebellum supports pre-reading skills, such as motor skills or articulatory/phonological skills (Nicolson, Fawcett, & Dean, 2001). Moreover, this hypothesis also suggests that the cerebellum has a longitudinal influence on reading during reading acquisition. Deficits in the cerebellum in the early stage of reading may lead to reading impairments. This idea is consistent with a consensus paper on language and the cerebellum (Mariën et al., 2014). Recently there have been two studies by the same research group that reported the longitudinal effect of the cerebellum on reading, which showed that the left inferior cerebellar peduncle (white matter connection to the brain stem) at age six could predict an oral reading outcome that required reading comprehension at age eight (Borchers et al., 2019; Bruckert et al., 2019). However, the relation between microstructural properties of white matter or gray matter in the cerebellum and subsequent reading abilities (e.g., comprehension or single word reading) has not been found (or at least reported) by any other research groups (for gray or white matter volume that predicted reading outcomes in cerebral regions, see Linkersdörfer et al., 2014; Myers et al., 2014). On one hand, this divergence in whether the cerebellar structure may be associated with reading outcomes may be due to different brain indices (white matter integrity or gray/white matter volume), sample sizes, or reading measurements, used across these studies. On the other hand, this inconsistency also indicates that it is still an open question whether the development of the cerebellum in the early stages of reading contributes to future reading. In addition, these longitudinal studies were mainly focused on anatomical properties, which might not determine whether the cerebellum is an active participant during reading acquisition. Moreover, these studies mainly focused on relations between

the cerebellum and reading without quantitatively decoding the role of the cerebellum. Therefore, the role of the cerebellum in reading remains elusive.

In the current study, we focused on three issues: (1) whether cerebellar lobule VI and/or VII are already associated with reading at the beginning stages of reading acquisition; (2) whether the functional status of these reading-related regions in early reading influences future reading ability; and (3) what the functional contributions of the cerebellum to reading are. Reasons to focus on the cerebellar lobules VI and VII are twofold. First, activation in these regions are frequently reported in reading research (Ang et al., 2020; Hancock et al., 2017; Li et al., 2020, p. 107630; Norton et al., 2014; Peng et al., 2003). Second, a recent study parcellated the cerebellum into ten functional subareas with multiple functional MRI (fMRI) tasks. The cerebellar regions engaged in language were mainly located at the right lobules VI and VII (King, Hernandez-Castillo, Poldrack, Ivry, & Diedrichsen, 2019).

To address these issues, kindergarten children who were just beginning to learn to read (Time 1), were instructed to perform a reading-related task during fMRI. Additionally, participants completed a series of behavioral assessments outside of the scanner to measure their reading ability or reading related skills. One year later, after receiving formal reading instruction, reading ability was tested again (Time 2). Using data collected at Time 1, we conducted voxel-wise activation analysis and brain-behavior (i.e., the cerebellar activation & reading ability) correlation analysis to identify regions in the cerebellum associated with early reading. Then, a similar correlation analysis was further conducted between activation at Time 1 and reading ability at Time 2 (one year later) to examine whether the reading related regions identified at Time 1 would predict later reading ability at Time 2. We hypothesized that multiple regions in the cerebellum are related to early reading, especially right cerebellar lobule VI and/or VII, and functional activity in these regions might predict future reading ability. An emerging view suggests that the role of a brain region is best determined by its functional connectivity (FC) pattern with other regions (Achal et al., 2015; Alvarez & Fiez, 2018; Buckner, Krienen, Castellanos, Diaz, & Yeo, 2011; Johnson, 2000; Li et al., 2020). We then inferred the fine-grained role of reading related regions in the cerebellum by its connectivity patterns to the cerebral regions (Buckner et al., 2011) with the current imaging data and a bigger database integrated into Neurosynth, i.e., F1000 (De La Vega, Chang, Banich, Wager, & Yarkoni, 2016; Rubin et al., 2017; Yarkoni, Poldrack, Nichols, Van Essen, & Wager, 2011).

2. Materials and methods

2.1. Participants

Eighty beginning readers (mean age = 5.8 years old, range: 5.6–6.6 years old; boy/girl: 39/41) were included in the current study as part of a larger project (NIH/NICHHD R01HD078351). Two prior studies overlapped partially with the current sample (Haft, Kepinska, Caballero, Carreiras, & Hoeft, 2019; Marks et al., 2019). All participants were native English speakers, and attended kindergartens in Northern Californian public schools

in the United States. Among these children, eight participants were left-handed, three were ambidextrous, and the remaining sixty-nine participants were right-handed.

2.2. Behavioral measures obtained outside the scanner

2.2.1. Baseline behavioral measures (Time 1)

Kaufman Brief Intelligence Test (KBIT) was used to measure nonverbal intelligence (Kaufman & Kaufman, 2004). Children with typical intelligence were included in this study, quantified by a standard score above or equal to 85. Children's reading abilities were measured by the Woodcock-Johnson IV Letter Word Identification subtest (WJ LWID; Schrank, Mather, & McGrew, 2014). Initial items (from 1 to 13) of this subtest were designed to identify letters and words. From item 14, participants were required to read words arranged in the order of difficulty.

Eight tests tapping into language skills related to reading, were also administered at Time 1. The WJ Word Attack (Schrank et al., 2014) was used to measure decoding ability. The Test of Orthographic Competence Homophone Choice subtest (TOC Homophone Choice; Mather, Roberts, Hammill, & Allen, 2008) were used to measure orthographic processing. Three subtests from the Comprehensive Test of Phonological Processing (CTOPP-2): Elision, Blending Words, and Sound Matching, were used to assess phonological manipulation ability (Wagner, Torgesen, Rashotte, & Pearson, 2013). The Peabody Picture Vocabulary Test (PPVT-IV) was used to measure children's receptive vocabulary level (Dunn & Dunn, 2007). The WJ Picture Vocabulary and the WJ Oral Comprehension were used to assess their oral language ability (Schrank et al., 2014).

2.2.2. Behavioral measures at follow-up (Time 2)

One year later, 43 out of 80 participants returned for a follow-up behavioral assessment (mean age = 7.1 years old, range: 6.5–7.5 years old; boy/girl: 22/21). The mean duration between Time 1 and Time 2 testing was 1.3 years with a range of 1–1.5 years. Letter-word identification (LWID) was assessed again among the 43 participants.

2.3. MRI data acquisition and analyses

2.3.1. Visual word matching task during fMRI

Given that the participants were all beginning readers with limited reading skills, we used a relatively easy task, a visual word matching task, to ensure the task was accessible to them. Visual word matching has been widely used as an implicit reading task (Feng et al., 2017; Gao et al., 2015). During the task, 24 pairs of words were presented in sequence with each trial lasting for 6000 msec. The first word was presented above a fixation cross for 2000 msec, followed by the second word under the fixation cross for another 2000 msec. Immediately after, a question mark was presented for another 2000 msec replacing the fixation cross. Participants were required to indicate whether the two words were the same or not (“game” – “road” = no; “wolf” – “wolf” = yes). There were 6 24-sec task blocks (12 matching and 12 unmatching) that consisted of 4 trials as well as 6 12-sec resting blocks after each task block. The whole run lasted approximately 4 min (see also Marks et al., 2019).

Participants in the current study are from the same dataset as Marks et al. (2019). Because they were beginning readers, the stimuli used in the current study were all high-frequency nouns, taken from pictures of kindergarten classrooms with high-frequency words on the wall (e.g., pot, boat, dog, or green; Table S1) and from publicly available 1st and 2nd-grade spelling lists to ensure their familiarity. According to two age of acquisition indices, these words were typically acquired before age 5 (Gilhooly & Logie, 1980; Kuperman, Stadthagen-Gonzalez, & Brysbaert, 2012). All words had one or two syllables, with an average of 4.74 letters, 3.71 phonemes, and 1.24 syllables. For each pair, stimuli were matched for the number of phonemes and syllables. By and large, words were also matched for the number of letters, although three out of 24 word pairs had words that differed in length by one letter (e.g., bear – shark). There were no significant differences observed between the 12 matching (i.e., same words) and 12 non-matching (i.e., different words) pairs in terms of phoneme length, age of acquisition, familiarity, written frequency, or imageability.

A sensitivity index (d') was used to estimate children's performance on this task. This score was calculated by subtracting the z -transformed false alarm rate from the z -transformed hit rate. Hit rate was defined as the proportion of trials that participants correctly responded as “yes” relative to all “yes” trials. False alarm rate was defined as the proportion of trials where participants incorrectly responded as “yes” relative to all “no” trials. Children with d' larger than zero were included in the analyses, which means that they could differentiate between “same” and “different” trials. The larger the d' score, the better the participant's sensitivity. The mean d' score was 2.37, with a standard deviation of 1.12 ($n = 80$).

2.3.2. MRI data acquisition

Data was acquired using a 3-T Siemens Prisma MRI scanner equipped with a 64-channel head coil. Whole-brain functional images were acquired using a gradient-echo echo-planar pulse sequence [repetition time (TR) = 1250 msec, echo time (TE) = 33.40 msec, flip angle (FA) = 45°, field of view (FOV) = 220 mm, voxel size = 2.2 mm³, 64 contiguous 2.20-mm axial slices, 0-mm inter-slice gap]. Parameters for high resolution T1-weighted anatomical images were as follows: matrix size 256*256; 160 contiguous axial slices; voxel resolution 1 mm, TR = 2300 msec, TE = 2.98 msec, T1 = 900 msec; and FA = 9°.

2.3.3. Pre-processing of MRI data

Imaging data were processed using FSL software Version 6.0.0 (FMRIB's Software Library, FMRIB, Functional Magnetic Resonance Imaging of the Brain, www.fmrib.ox.ac.uk/fsl; Jenkinson et al., 2012). Pre-processing was carried out using FMRI Expert Analysis Tool (FEAT) Version 6.00. The pre-statistics processing steps included: removal of the first 11 volumes for signal equilibration (173 volumes retained); motion correction using MCFLIRT (Jenkinson, Bannister, Brady, & Smith, 2002); non-brain removal using BET (Smith, 2002); grand-mean intensity normalization of the entire 4D dataset by a single multiplicative factor; spatial smoothing using a Gaussian kernel of 5 mm full width at half maximum (FWHM); and B0 unwarping using BBR (Boundary-Based Registration; https://fsl.fmrib.ox.ac.uk/fsl/fslwiki/FLIRT_BBR; Jenkinson et al., 2002; Jenkinson & Smith, 2001), which also performs simultaneous registration

to the high resolution T1-image (rigid body, 6 degrees of freedom). After this, T1-images were registered to MNI-152 standard space using 12-parameter affine transformation and non-linear registration with a warp resolution of 10 mm in FNIRT (Andersson, Jenkinson, & Smith, 2007a, 2007b).

After conducting standard data pre-processing, we performed ICA-AROMA (Independent Component Analysis-based Automatic Removal of Motion Artifacts; <https://github.com/maartenmennes/ICA-AROMA>; Pruim et al., 2015) to identify and remove motion-related artifacts on data that passed motion quality control (i.e., data where the absolute mean displacement during the task was less than 5 mm). The denoised data were then high-pass filtered with a cutoff of 36 sec (.036 Hz) and the registration parameters were reapplied.

The design matrix for each participant included task blocks as events of interest, which was convolved with the Hemodynamic Response function (HRF). In addition, signals from white matter and cerebrospinal fluid were included as nuisance regressors. For the FC analysis, only the time series during the task were extracted. Given the effect of the hemodynamic response, we delayed the onset time of each task block to 4 TRs (each TR lasts 1.25s; 4 TRs equal to 5 sec in total).

2.3.4. MRI data analyses

2.3.4.1. THE VALIDITY OF THE CURRENT TASK IN ELICITING READING-RELATED ACTIVATION. In the first stage of data analyses, we aimed to examine the validity of the visual word matching fMRI task in eliciting reading-related activation. To this end, two analyses were performed:

- (1) First, we compared areas showing significant activation during this task with a reading-related network generated via Neurosynth. Areas showing significant activation were obtained by voxel-based whole brain activation analyses by contrasting task to fixation conditions. The threshold for significant activation of the statistical images was set non-parametrically using clusters determined by $Z > 2.3$ and a (corrected) cluster significance threshold of $p = .05$. A reading-related network was constructed via Neurosynth. Neurosynth is a platform for automated synthesis of large-scale fMRI data (<http://www.neurosynth.org/>; Yarkoni et al., 2011). The database consists of 507,891 activations reported in 14,371 studies and meta-maps for 1,335 keywords. When building the meta-map of reading, “reading” was used as a keyword and an association test map was automatically generated, which was corrected by false discovery rate (FDR of $\alpha = .05$), indicating regions more likely to activate in studies containing “reading” (i.e., the occurrence frequency of reading was more than 1/1,000 words) compared to studies that do not (i.e., occurrence was equal to or less than 1/1,000 words). We examined overlap in areas showing significant activation and the Neurosynth generated reading network by overlaying these two maps.
- (2) Second, we performed reverse inferencing to qualitatively identify potential cognitive states associated with brain activity pattern induced by the current task using

Neurosynth Image Decoder (<http://www.neurosynth.org/decode/>; Poldrack et al., 2011; Yarkoni et al., 2011), wherein Pearson’s correlation analyses were automatically performed between the unthresholded activation map from the current study and the unthresholded meta-maps of 1,335 keywords in the Neurosynth database. Correlation coefficients were then used to generate a ranking of the keywords associated with the current image of interest (whole-brain activation pattern).

2.3.4.2. CONCURRENT RELATIONSHIP BETWEEN CEREBELLAR ACTIVATION (AT TIME 1) AND READING ABILITY AT TIME 1. Voxel-based correlation analyses were further conducted with FSL, during which general linear models were built to examine whether and identify which regions in the cerebellum were associated with reading. Statistical images were thresholded using a non-parametric cluster threshold determined by $Z > 2.3$ at the voxel-level and a (corrected) cluster significance threshold of $\alpha = .05$. To control for the effect of variables of no-interest, age, sex, and handedness were used as covariates.

2.3.4.3. LONGITUDINAL INFLUENCE OF CEREBELLAR ACTIVATION (AT TIME 1) ON FUTURE READING (AT TIME 2). Further correlation analyses between reading ability at Time 2 or reading gain (differences between LWID raw scores at Time 2 and Time 1) and activation in the cerebellum at Time 1 were conducted to investigate whether activation in the cerebellum could predict future reading ability. Statistical images were thresholded the same as described above. Age, sex, and handedness were again used as covariates.

2.3.4.4. DECIPHERING THE FUNCTION OF THE CEREBELLUM BY EXAMINING THE FC PATTERN BETWEEN THE CEREBELLUM AND CEREBRAL REGIONS. An emerging view suggests that the role of a brain region is determined by its FC pattern with other regions (Johnson, 2000). Therefore, in the following analysis, we aimed to use FC to infer the role of the cerebellum.

- (1) We further examined the FC between cerebellar regions and regions within a “canonical reading network.” The cerebellar regions were defined as regions in the cerebellum that correlated with reading ability at Time 1 or Time 2. The coordinates of the “canonical reading network” that we used were those reported in a recent meta-analysis on single word reading (Murphy, Jogia, & Talcott, 2019). 11 spheres were created (regions of interest, ROIs) with a radius of 5 mm and coordinates in Table 1 as the center.

Then, FC between the cerebellar regions and these 11 cerebral ROIs within the “canonical reading network” were calculated. To determine functional connections between the cerebellum and those ROIs, the first eigenvariate of the time series of each region was extracted from the fMRI data (Thurston, Maki, Derby, Sejdić, & Aizenstein, 2015), which reflects the time course of the first component that contributes most to a region’s response (Hanson & Bunzl, 2010; Saxe, Brett, & Kanwisher, 2006). For each participant, we

Table 1 – Central coordinates of regions related to single word reading in the cerebral cortex (based on Murphy et al., 2019).

ROIs	BA	MNI coordinates		
		X	Y	Z
left postcentral gyrus (L.PostG)	4	–50	–8	44
left middle frontal gyrus (L.MFG _a)	9	–40	28	24
left superior parietal lobule (L.SPL)	7	–22	–68	48
right inferior frontal gyrus (R.IFG)	9	48	12	24
left inferior occipital gyrus (L.IOG)	17	–24	–98	–4
left middle frontal gyrus (L.MFG _b)	6	–4	–2	56
right superior parietal lobule (R.SPL)	7	34	–56	50
left fusiform gyrus (L.FG _a)	37	–50	–48	–8
left fusiform gyrus (L.FG _b)	37	–42	–54	–18
left inferior frontal gyrus (L.IFG)	44	–44	6	26
left superior temporal gyrus (L.STG)	41	–54	–16	8

calculated the correlation coefficient between the first eigenvariate of each ROI and timeseries of each cerebellar region where activity correlated with reading ability. The values were then transformed to Z-scores via Fisher z transformation, indicating the strength of FC. We focused on FC of the time-series only during the task condition. Given the effect of the hemodynamic response, we delayed the onset time of each task block to 4 TR (each TR lasts 1.25 sec, 4 TRs are equal to 5 sec). For each FC value between the cerebellum and an ROI, we subtracted the mean FC of the cerebellum from the remaining ROIs to indicate the specific FC with that particular ROI. This index indicates a cerebellar cluster to be relatively more connected to a given cerebral reading ROI relative to the remaining reading ROIs. One sample t-tests were conducted to estimate the significance of each specific FC value, which were corrected for multiple comparisons at an FDR of $\alpha = .05$. The role of the cerebellum was inferred by the reading-related cerebral ROI that showed the most significant specific FC with cerebellar areas.

To supplement this result, we used the F1000 data in Neurosynth comprised of 1000 adults because of the availability of the large sample and the fact that the connectivity pattern would most likely reflect the mature brain network associated with reading and the cerebellum (Buckner et al., 2011). The peak of each reading-related region in the cerebellum described above was used as a seed region separately to pinpoint its resulting target cerebral regions (<https://www.neurosynth.org/locations/>). The threshold to identify these regions was set as voxel-level correlation coefficient larger than .2, cluster volume larger than 200 mm³.

(2) Finally, we used Neurosynth's "location based analysis" feature (<https://www.neurosynth.org/locations/>) to decode the cognitive terms associated with cerebral ROIs that connected with the cerebellar clusters. Based on the three-dimensional coordinates of the central voxel of a given ROI (Table 1), an association table with the keywords ranked by its relations with this location was generated using Neurosynth. The role of each region was inferred via the top 12 cognitive terms (Alvarez & Fiez, 2018).

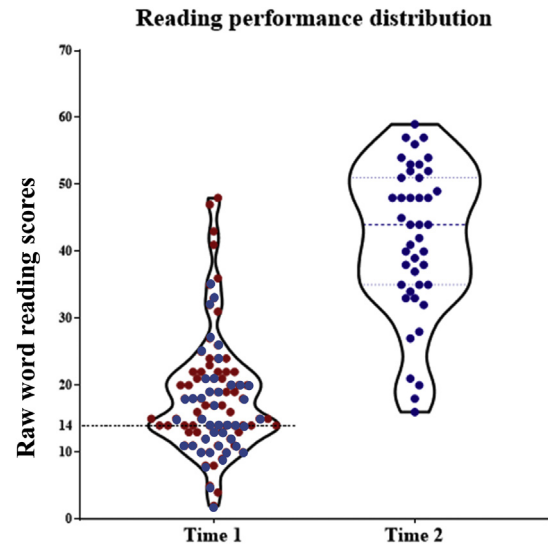


Fig. 1 – The distribution of reading performance at Time 1 and Time 2. The dotted line represents LWID scores equal to 14. Scores under 14 indicate that the children were still in the alphabetic phase of reading acquisition and could not identify words. Blue dots represent children who returned for Time 2, red dots represent children who did not return for Time 2.

3. Results

3.1. Demographic information

For behavioral performance on the LWID at Time 1, only 21 children scored under 14, indicating that they were still in the alphabetic phase of reading acquisition and could not identify words (Fig. 1). The remaining children could all identify at least one high frequency word. We compared the behavioral performance on all tests measured at Time 1 between children who returned ($n = 43$) and did not return one year later ($n = 37$). However, no significant group differences were observed except that children who did not return had a greater LWID score and behavioral performance (d' score) in the scanner in kindergarten than children who returned for Time 2 testing ($t_{(78)} = 2.8, p = .02$; Table 2).

All children who returned one year later ($n = 43$) scored 14 or more on LWID at Time 2 (Fig. 1). Moreover, LWID scores of these children significantly increased from Time 1 to Time 2 ($Mean_{Time1} = 16.4, SD_{Time1} = 7.2$; $Mean_{Time2} = 41.8, SD_{Time2} = 11.1$, $t_{(42)} = -17.6, p < .001$).

3.2. Activation pattern during the visual word matching task

Voxel-wise whole brain activation analysis showed that bilateral frontal gyri, bilateral superior parietal lobules extending to left inferior parietal lobule, and bilateral inferior occipital gyri were significantly activated during the visual word matching task (Table 3, Fig. 2A, regions with red/yellow

Table 2 – Demographic information of participants.

	Whole sample		Range	Return group		Non-return group		T (Return & Non-return)	p
	Mean	SD		Mean	SD	Mean	SD		
Sample size	80			43		37			
Sex (boy/girl)	39/41			22/21		17/20		$X^2 = .6$.70
Age	5.8	0.4	5.1–6.5	5.8	.4	5.7	.4	1.9	.06
Behavioral performance outside the scanner									
KBIT Non-verbal IQ ^s	105.2	14.1	85–141	104.0	11.8	106.5	16.4	.1	.92
WJ Word Attack subtest	7.9	4.0	0–18	7.3	3.7	8.7	4.2	–1.5	.13
TOC Homophone Choice	5.6	4.2	0–22	5.0	3.8	6.4	4.5	–1.5	.14
CTOPP Blending	14.4	4.8	5–24	14.0	4.6	15.0	5.0	–1.0	.32
CTOPP Elision	13.2	5.8	0–30	12.7	4.9	13.7	6.7	–.8	.41
CTOPP Sound Matching	15.3	6.5	1–25	14.8	6.3	15.9	6.9	–.8	.45
Peabody Picture Vocabulary Test	115.3	20.1	63–152	118.7	18.3	111.4	21.7	1.6	.11
WJ Picture Vocabulary	25.1	3.4	17–33	25.4	3.2	24.9	3.6	.7	.51
WJ Oral Comprehension	12.5	3.9	1–20	13.1	3.7	11.9	4.1	1.4	.18
WJ Letter Word Identification subtest	18.5	8.9	2–48	16.4	7.2	21.0	10.2	–2.4	.02
Behavioral performance inside the scanner									
d' score	2.4	1.1	.3–5.4	2.1	1.0	2.6	1.2	–1.9	.05

Note: ^s standard score. Others were raw scores. SD = standard deviation.

spectral color). In addition to these regions, bilateral cerebellar hemispheres were also significantly activated, even though no peak was reported in this region (Fig. 2A, regions with red/yellow spectral color). Notably, no significant difference in activation was observed for participants who did and did not return for Time 2 testing.

Further analyses were conducted to examine whether this activation pattern was related to reading. First, we used “reading” as a keyword and generated a reading-related network from the Neurosynth database (Yarkoni et al., 2011, Fig. 2A, lime color). The results showed that regions that showed significant activation in the visual word matching task largely overlapped with the reading-related network defined by Neurosynth (Fig. 2A). The overlap was observed both in the cerebrum and cerebellum.

The Neurosynth Image Decoder was further used to decode the function of the activated regions, where the correlation between all the term-based association test maps in the Neurosynth database and the unthresholded current activation map (β map) were calculated (Chang, Yarkoni, Khaw, & Sanfey, 2012; Rubin et al., 2017). Based on these correlations, we

observed that the whole brain activation pattern induced by the current task had a greater correlation with reading (Fig. 2B), task processing, goal, face, and visual processing compared to other Neurosynth terms.

Together, these results suggest that the visual word matching fMRI task that we used in the current study appropriately induced brain activation within the reading network including bilateral cerebellar hemispheres.

3.3. Correlations between the cerebellum and reading ability at Time 1

We next examined the correlation between the cerebellar activation at Time 1 and reading ability at Time 1 (performance on LWID). We limited our correlation analysis to the voxels within the cerebellum. The results showed that activation in left cerebellar Crus II extending to left cerebellar lobule VIII showed a significant negative correlation with reading ability at Time 1. From hereon we refer to this cluster with peak coordinates: $x = -6$, $y = -84$, $z = -30$, $p = .02$, cluster size = 250, $Z_{\max} = 3.91$ as Left T1CRBLM (Fig. 3A and B). This result suggests

Table 3 – Coordinates of peak activation during the visual word matching task.

Cluster	Cluster Size	Z	x	y	z	
Left inferior occipital gyrus	56,680	8.91	–42	–82	–10	Inferior occipital gyrus
		8.89	–38	–86	–10	
		8.84	–6	16	46	Supplementary motor area
		8.55	–32	–90	–4	Middle temporal gyrus
		8.53	–8	8	54	Supplementary motor area
Left superior parietal lobule	2150	6.79	–24	–62	44	Superior parietal lobule
		6.27	–28	–56	46	
		5.97	–26	–54	40	
		5.21	–28	–70	24	
		4.92	–48	–40	42	Inferior parietal lobule
		4.17	–48	–44	52	
Right middle frontal gyrus	365	4.64	24	44	–16	Middle frontal gyrus
		3.15	16	52	–22	Superior frontal gyrus
		2.67	32	64	–6	

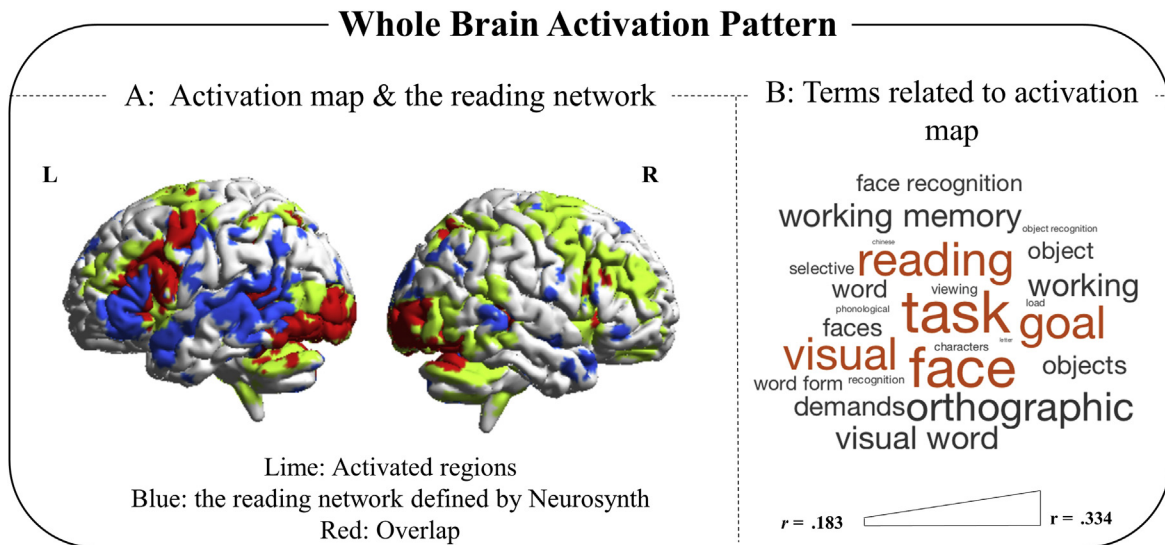


Fig. 2 – Whole brain activation pattern and its relations with reading. (A) The topographic relations between activation regions in the current study (lime), the reading network established by Neurosynth (blue), and the overlapping areas between the two (red). (B) The first 25 cognitive terms showing the greatest correlation with the whole brain activation map. The size of the font represents the strength of the correlation between the current activation map and term-based meta-maps generated by Neurosynth. The first five terms were colored orange and the remaining terms were colored black.

that greater reading skill was associated with less left cerebellar activity. In addition, the *Left T1CRBLM* largely overlapped with the regions that showed significant activation during the visual word matching task but was more focal (Fig. 3C).

Notably, we used a visual word matching task, which required participants to judge whether the words were identical or not. It might be argued that the performance on this task could also reflect visual perceptual abilities. In other words, the variation of activation in the *Left T1CRBLM* might be accounted for by visual perceptual ability, which in turn correlates with reading ability (d' score in the scanner significantly and positively correlated with LWID at Time 1, $r = .31$, $p = .006$). To address this concern, participants' d' score on the visual word matching task were used as a covariate in a follow-up brain-behavior correlation analysis. The result showed that left cerebellar lobule VII was still significantly and negatively correlated with children's performance on LWID at Time 1 (peak coordinates: $x = -6$, $y = -84$, $z = -30$, $p = .02$, cluster size = 240, $Z_{\max} = 4.25$), thus pointing to the discrimination ability between the items in the scanner task not being the only driving force behind the significant negative relationship between the activation in the *Left T1CRBLM* cluster and reading ability.

On the other hand, if variation in the *Left T1CRBLM* activation was due to visual perceptual ability, then a similar effect should be observed in cerebral regions responsible for visual processing (e.g., bilateral occipital gyrus). However, the results showed that reading ability at Time 1 negatively and significantly correlated with activation in left middle temporal gyrus, right supramarginal gyrus, and right inferior frontal gyrus. Activation in these regions together shows a pattern that is consistent with semantic processing, phonological processing, or social cognitive processes (Hartwigsen et al., 2010; Hartwigsen, Neef, Camilleri, Margulies, & Eickhoff, 2019; Weiss, Cweigenberg, & Booth, 2018), none of which are

typically associated with low-level visual processing. These two complementary analyses suggest that signal change in the *Left T1CRBLM* might be associated with the difference in reading abilities rather than visual perceptual abilities.

We also examined the negative brain-behavior relationship in the smaller sample of 43 participants that returned for Time 2 testing. The results showed that activation in the left cerebellum was also negatively and significantly correlated with reading ability at Time 1, even when only this smaller sample was examined (peak coordinates: $x = -14$, $y = -72$, $z = -36$, $p < .001$, cluster size = 553, $Z_{\max} = 3.69$). This region overlapped with *Left T1CRBLM* (Fig. 4A).

3.4. Longitudinal influence of the cerebellum on future reading ability

To examine whether cerebellar activation during the early stages of reading acquisition predicts future reading, using the 43 data-sets of participants who returned for the follow-up behavioral testing one year later, we conducted a similar voxel-based brain and behavior correlation analysis. Interestingly, we did not observe any significant correlation between activation in the left cerebellum at Time 1 and reading ability at Time 2. Instead, we observed that activation in right cerebellar lobule VII extending to right cerebellar VIII significantly and positively correlated with reading ability at Time 2. From hereon we call this cluster with peak coordinates: $x = 14$, $y = -76$, $z = -42$, $p = .04$, cluster size = 221, $Z_{\max} = 3.95$, *Right T2CRBLM* (Fig. 3A, D). Even after we excluded an extreme outlier (4 standard deviations from the group mean; $x = 14$, $y = -76$, $z = -42$, $p = .005$, cluster size = 221, $Z_{\max} = 4.16$, Fig. 3E) or regressed out reading ability at Time 1 ($x = 14$, $y = -76$, $z = -40$, $p = .046$, cluster size = 217, $Z_{\max} = 3.78$), this result remained significant.

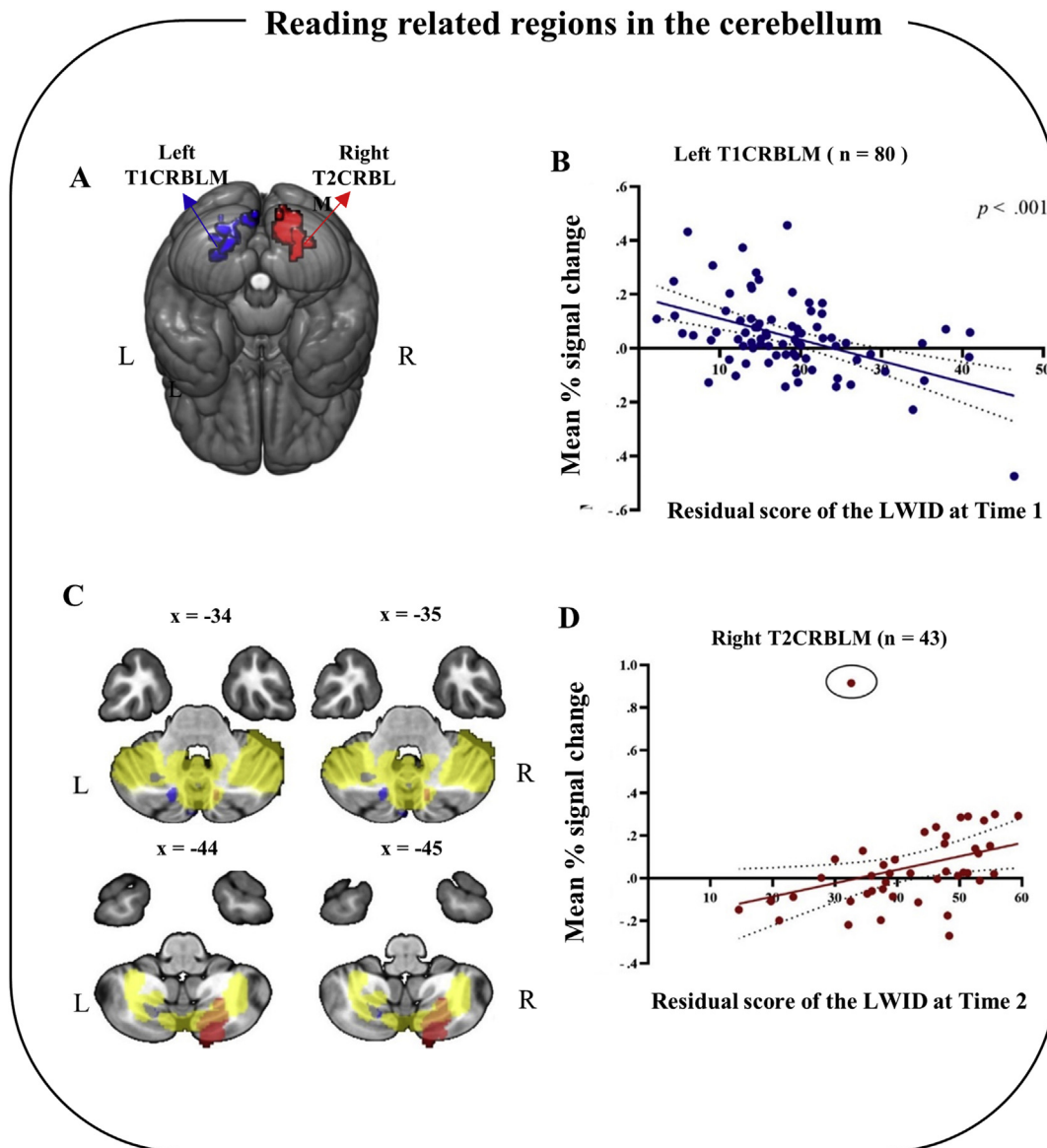


Fig. 3 – Brain (Mean % signal change) and behavior (LWID) relationship. LWID = Woodcock-Johnson letter word identification subtest. Left T1CRBLM = regions in the left cerebellum that negatively and significantly correlated with reading ability at Time 1; Right T2CRBLM = regions in the right cerebellum that positively correlated with reading ability at Time 2. (A) Locations of Left T1CRBLM and Right T2CRBLM. (B) Scatter plot to visualize the significant negative relationship between the mean % signal change of Left T1CRBLM and LWID score at Time 1 ($n = 80$, corresponding to statistical analysis in section 3.3). (C) Topographic relationship between the regions that were significantly activated during the reading fMRI task (yellow), Left T1CRBLM (blue; overlap with activation shown in light blue), and Right T2CRBLM (red; overlap with activation shown in light red). (D) Scatter plot to visualize the significant positive relationship between the mean % signal change of Right T2CRBLM and LWID score at Time 2 ($n = 43$, corresponding to statistical analysis in section 3.4). Dot in the black circle was an extreme value nearly 4 standard deviations from the group mean.

Notably, as we presented before, the list of items is not homogeneous in LWID. The first 13 items require children to point to spoken letters (from item 1 to item 6), to name letters (from item 7 to item 10), and to point to spoken words (from item 10 to item 13), whereas the remaining items require word reading (from item 14). Accordingly, the participants who scored under 14 could only point to or name letters while those

scoring at or above 14 were able to read at least some frequent words. In the present study (Fig. 1), 21 out of 80 children could only identify letters at Time 1. In contrast, no child read fewer than 3 words at Time 2. Therefore, reading performance at Time 1 refers to either letter or word reading while reading performance at Time 2 refers exclusively to word reading. As a result, the positive relationship between activation in right

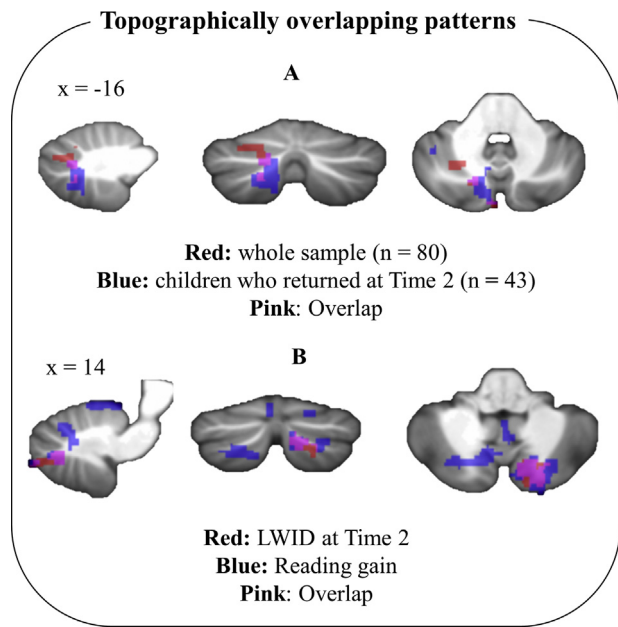


Fig. 4 – Topographic relationship between different analyses. (A) Regions in the cerebellum that show negative correlations with reading ability at Time 1 within the whole sample ($n = 80$) are shown in red, and within children who returned at Time 2 are shown in blue ($n = 43$). Overlapping regions are shown in pink. (B) Regions in the cerebellum that show positive correlations with reading ability at Time 2 are shown in red, and with reading gain across time are shown in blue. Overlapping regions are shown in pink.

cerebellar lobule VII and reading ability at Time 2 might be a reflection of the word reading effect rather than a longitudinal effect. To address this issue, the whole sample was split into two groups with a cut-off score of 14: the first one consisting of 21 children who mainly processed letters, and the second one including 59 children who were able to process words at Time 1. If the negative correlation between *Left T1CRBLM* and Time 1 reading represents a letter reading effect, and the positive correlation between *Right T2CRBLM* and Time 2 reading represents a word reading effect, then we should observe a negative relationship between Time 1 reading ability and left cerebellar activity among pre-readers, and a positive relationship between reading ability and right cerebellar activation among more advanced readers. However, this expected effect was absent, suggesting that the observed hemispheric dissociation in cerebellar activation was not due to differences in the process measured (the left cluster, *Left T1CRBLM*, primarily due to letter, and the right, *Right T2CRBLM*, primarily due to word processing), but rather due to developmental shifts.

As a complementary analysis, we also examined the relationship between activation in the cerebellum and reading gain over time (difference of raw scores between LWID at Time 2 and that at Time 1) with age, sex, and handedness as covariates. If the positive correlation between Time 2 reading and activation in the *Right T2CRBLM* represents a longitudinal

effect, we should observe a similar effect between activation in the right cerebellum and reading gain. The result showed that activation in the right cerebellum was indeed positively correlated with reading gain ($x = 14, y = -76, z = -40, p < .001$, cluster size = 625, $Z_{\max} = 3.91$; $x = -22, y = -80, z = -48, p < .005$, cluster size = 357, $Z_{\max} = 3.81$; $x = 16, y = -52, z = -12, p = .045$, cluster size = 211, $Z_{\max} = 4.39$), and these clusters partially overlapped with the *Right T2CRBLM* (Fig. 4B).

These results together support the idea that brain activity in the right cerebellum in the early stages of reading may be critical for future reading ability. More importantly, these results suggest that the left and right cerebellum differentially contribute to predicting children's concurrent as opposed to future reading ability. Specifically, activation in right cerebellar lobule VII at baseline was associated with future reading outcomes, approximately one-year after the start of formal reading acquisition.

3.5. Deciphering the function of the cerebellum using FC

3.5.1. FC between the cerebellum and cerebral regions based on task imaging data

Differential relationships with concurrent and future reading abilities suggest unique functional roles of cerebellar hemispheres in reading. Here, we further inferred the roles of *Left T1CRBLM* and *Right T2CRBLM* by estimating their FC patterns with the cerebral regions based on task imaging data. We focused on 11 cerebral ROIs within the reading network (see Table 1). The role of the cerebellum was presumed by the ROI with which the cerebellum showed relatively greater connectivity.

We found that *Left T1CRBLM* was significantly functionally connected with the *R.SPL* ($t_{(79)} = 7.8, p < .001$; FDR corrected), the *L.SPL* ($t_{(79)} = 5.1, p < .001$; FDR corrected), and the *L.FG* (*L.FG_b*, $t_{(79)} = 4.0, p = .001$; FDR corrected), see Fig. 5B. We also observed that *Right T2CRBLM* showed significant bias in FC with the *R.SPL* ($t_{(42)} = 2.6, p = .012$; FDR corrected), and the *L.SPL* ($t_{(42)} = 3.2, p = .002$; FDR corrected), see Fig. 5B.

When comparing the relative FCs indices seeded from *Left T1CRBLM* and *Right T2CRBLM*, we found that *R.SPL* ($t_{(42)} = -3.6, p < .001$; FDR corrected) and *L.IOG* ($t_{(42)} = -2.4, p = .019$; FDR corrected) showed greater connectivity with *Left T1CRBLM* compared to *Right T2CRBLM* (Fig. 5B). On the other hand, *L.STG* ($t_{(42)} = 2.4, p = .007$; FDR corrected), *L.IFG* ($t_{(42)} = 3.3, p = .002$; FDR corrected), and *L.MFG_a* ($t_{(42)} = 2.5, p = .018$; FDR corrected) had significantly higher connectivity with *Right T2CRBLM* than with *Left T1CRBLM* (Fig. 5B).

3.5.2. FC between the cerebellum and the cerebrum based on Neurosynth

To further estimate the role of the left and right cerebellum in reading, we used Neurosynth to decode the function of *Left T1CRBLM* (blue color cluster in Fig. 3A, Result Section 3.2) and *Right T2CRBLM* (red color cluster in Fig. 3A and Result Section 3.3), respectively. For each of the two clusters, we extracted the location of their first two peaks. The locations were for the *Left T1CRBLM*: cerebellar lobule VII (Table 4, Fig. 6, blue dot, L1), and cerebellar lobule VIII (Table 4, Fig. 6, blue dot, L2); and for the *Right T2CRBLM*: cerebellar lobule VII (Table 4, Fig. 6, red dot, R1), and cerebellar lobule VIII (Table 4, Fig. 6, red dot, R2).

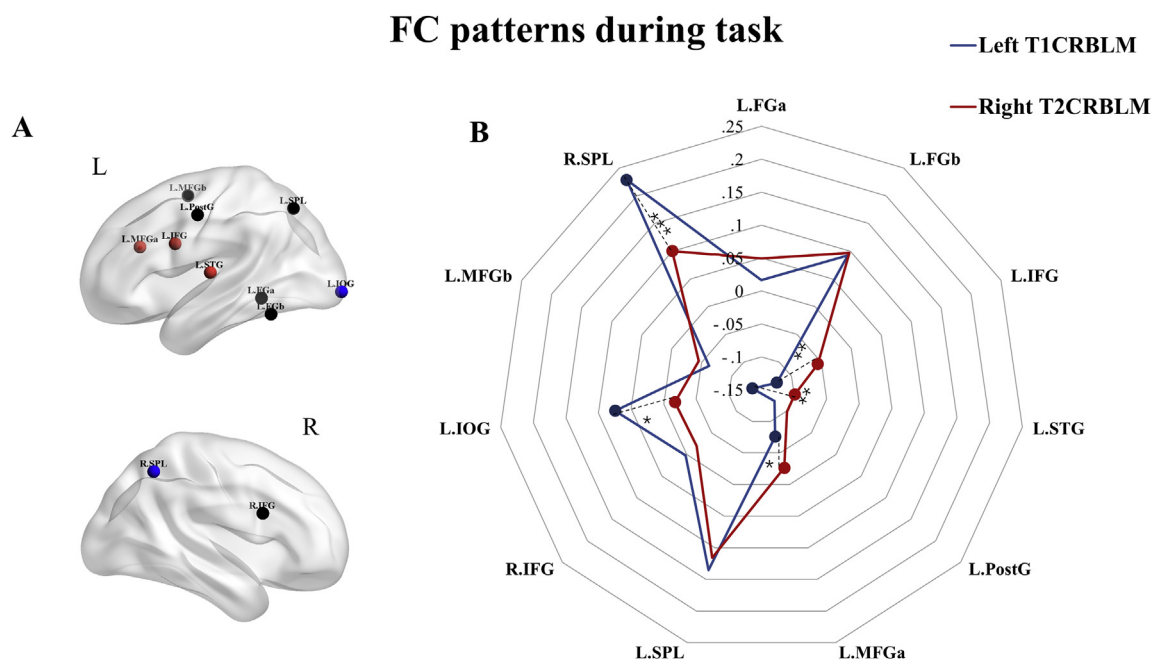


Fig. 5 – FC patterns during the task. FC = functional connectivity. L.MFG = left middle frontal gyrus, L.IFG = left inferior frontal gyrus, L.PostG = left postcentral gyrus; L.STG = left superior temporal gyrus; L.SPL = left superior parietal lobule; L.FG = left fusiform gyrus; L.IOG = left inferior occipital gyrus; R.SPL = right superior parietal lobule; R.IFG = right inferior frontal gyrus. (A) ROIs associated with reading based on [Murphy et al. \(2019\)](#). Blue dots represent regions that had greater FC with Left T1CRBLM. Red dots represent regions that have greater FC with Right T2CRBLM. (B) Visualization of the strength of FC between Left T1CRBLM and with Right T2 CRBLM and regions within the reading network. The value in each unit represents the difference between the FC from the cerebellum to a given ROI and the mean FC from the cerebellum to the remaining ROIs. This index indicates a cerebellar cluster to be relatively more connected to a given cerebral reading ROI relative to the remaining reading ROIs. Dots represent regions that showed significantly different FC with Left T1CRBLM and with Right T2CRBLM. *** $p < .001$, FDR corrected; ** $p < .01$, FDR corrected; * $p < .05$, FDR corrected.

The four peaks identified above in Left T1CRBLM and Right T2CRBLM were further used as seeds to identify cerebral regions that were functionally connected with these peaks using F1000 data in Neurosynth. Results showed that the first peak (L1) in the left cerebellum (that predicted Time 1 reading) positively correlated with right angular gyrus, right frontal regions, and right inferior temporal gyrus (Fig. 6). We did not observe significant FC between the second peak (L2) in the left cerebellum cluster and any cerebral regions.

In the right cerebellum (that predicted Time 2 reading), we found the second peak (R2) to correlate with phonological regions including left inferior frontal gyrus, left precentral gyrus/inferior frontal gyrus, and left supramarginal gyrus (Fig. 6).

Notably, FC patterns decoded by Neurosynth (Fig. 6) were consistent with FC patterns observed during tasks (Fig. 5). Specifically, based on Neurosynth, Left T1CRBLM connected significantly to the right angular gyrus, which overlapped with R.SPL where activation was observed during our fMRI task (Fig. 7). On the other hand, Right T2CRBLM connected significantly to the left precentral gyrus in Neurosynth, and largely corresponded to L.IFG observed during our fMRI task (Fig. 7).

3.5.3. Functional attributions of R.SPL and L.IFG via Neurosynth

Given that left and right cerebellar lobules VII showed a biased functional connection pattern with R.SPL and L.IFG, respectively, which were supported by results from Neurosynth, we then inferred the roles of left and right cerebellar lobule VII by decoding the role of R.SPL and L.IFG with the Neurosynth “location based analysis” feature. The central coordinates of R.SPL ($x = 34, y = -56, z = 50$, Table 1), as defined by the [Murphy et al. \(2019\)](#) meta-analysis, were first entered into Neurosynth. The closest available location ($x = 34, y = -56, z = 48$, Neurosynth coordinates) to these central coordinates offered the following top 12 cognitive terms: “task,” “working memory,” “symbolic,” “calculation,” “arithmetic,” “task difficulty,” “preparation,” “interference,” “memory,” “navigation,” “verbal,” and “maintenance”. A similar method was applied to L.IFG. The first 12 cognitive terms associated with the closest available location ($x = -44, y = 6, z = 24$) in Neurosynth to the central coordinates of L.IFG as defined by [Murphy et al. \(2019\)](#) ($x = -44, y = 6, z = 26$, Table 1), included “phonological,” “orthographic,” “lexical,” “reading,” “tasks,” “words,” “demands,” “word,” “task,” “fluency,” “semantic,” and “language”.

Table 4 – Cerebro-cerebellar connections decoded by Neurosynth.

Peaks	MNI coordinates			L/R	FCs with the cerebrum ($r > .2$)
	x	y	z		
Regions in the left cerebellum that negatively and significantly correlated with LWID at Time 1 (<i>Left T1CRBLM</i>):					
First peak (located in left cerebellar VII)	–6	–84	–30	R	Angular gyrus; inferior temporal gyrus; middle frontal gyrus; inferior frontal gyrus; inferior frontal sulcus; superior frontal gyrus.
Second peak (located in left cerebellar lobule VIII)	–20	–68	–42	–	–
Regions in the right cerebellum that positively and significantly correlated with LWID at Time 2 (<i>Right T2CRBLM</i>):					
First peak (located in right cerebellar lobule VII)	14	–76	–42	–	–
Second peak (located in right cerebellar lobule VIII)	22	–72	–46	L	Inferior frontal gyrus; prefrontal gyrus; superior temporal gyrus

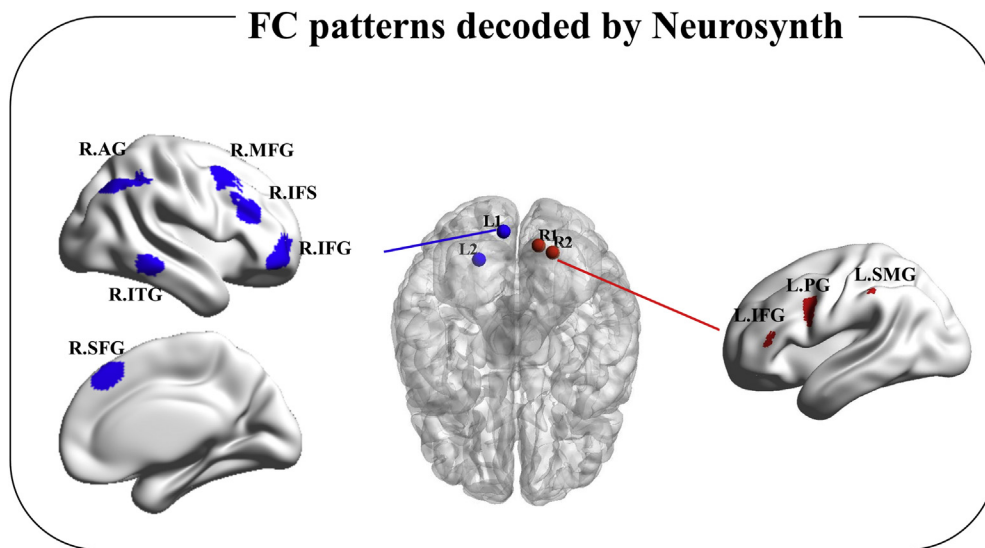


Fig. 6 – FC patterns decoded by Neurosynth. Regions in the cerebral cortex that functionally connected with the peaks in the left and right cerebellum clusters, which correlated with reading ability at Time 1 and Time 2, respectively. R.AG = right angular gyrus; R.ITG = right inferior temporal gyrus; R.MFG = right middle frontal gyrus; R.IFG = right inferior frontal gyrus; R.IFS = right inferior frontal sulcus; R.SFG = right superior frontal gyrus. L.IFG = left inferior frontal gyrus; L.PG = left precentral gyrus; L.SMG = left supramarginal gyrus; Threshold to identify these regions was set as voxel-level correlation coefficient larger than .2, cluster volume larger than 200 mm³.

Thus, the results suggest the left and right cerebellar regions connected with R.SPL and L.IFG may play differential roles during reading acquisition and influence reading via different neural circuits.

4. Discussion

In the current study, we examined how the cerebellum contributes to reading in the early stages of reading acquisition. To address this issue, we tested 80 kindergartners who participated in an fMRI experiment, during which the children performed a visual word matching task. One year after their first visit, the reading level of 43 out of the 80 children was tested again. First, we observed significant bilateral cerebellar activation during this task. Activation in left cerebellar lobule VII

significantly and negatively predicted reading ability at Time 1, whereas activation in right cerebellar lobule VII significantly and positively predicted reading ability at Time 2. These results suggest that bilateral cerebellar lobules VII play differential roles in early reading. In order to further examine how the left and right cerebellar lobules VII differentially contribute to reading, we investigated the FC pattern with the cerebral cortex using the current task data and resting state data implemented in Neurosynth. We found that left and right cerebellar lobules VII had greater FC with the R.SPL and L.IFG both in task and resting state. Brain-behavior correlation analysis and FC pattern with the cerebral cortex jointly suggest a division of labor of bilateral cerebellum in the earliest stage of reading acquisition. These results offer insights into how the cerebellum is engaged in the early stages of reading development. In the following sections, we elaborate on three critical findings.

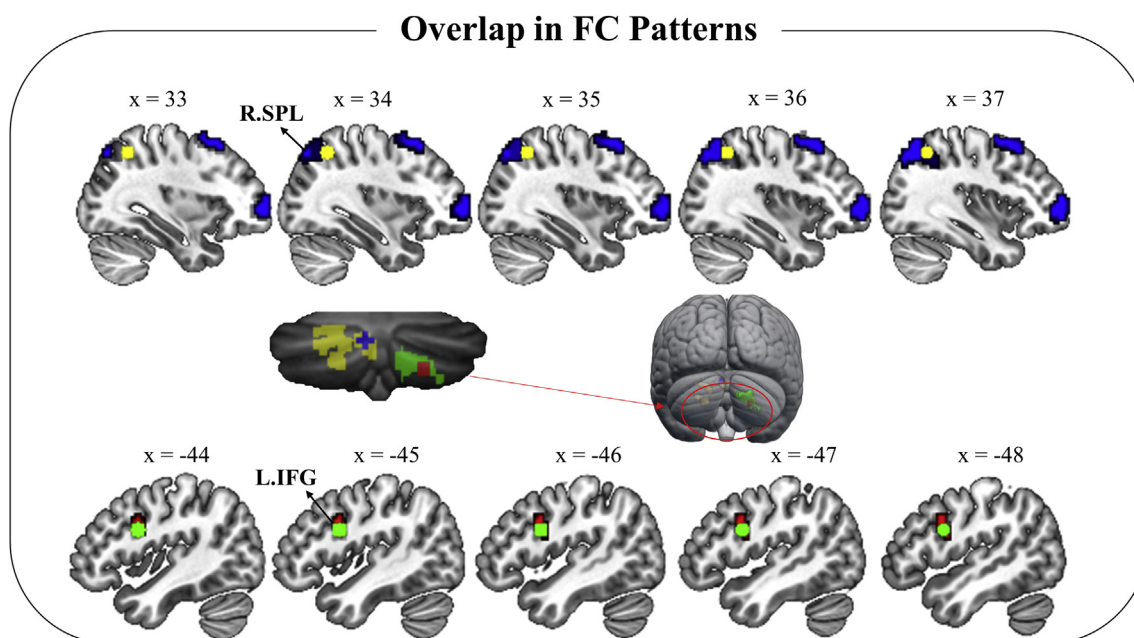


Fig. 7 – Overlap in FC patterns. FC = functional connectivity; Yellow regions in the cerebellum represent *Left T1CRBLM*, which positively correlated with the region represented by the yellow dot (R.SPL) in the cerebrum during the task. Green regions in the cerebellum represent *Right T2CRBLM*, which positively correlated with the region presented by the green dot (L.IFG) in the cerebrum during the task. The blue dot in the cerebellum represents the first peak of *Left T1CRBLM*, which demonstrated FC with blue regions in the cerebrum as decoded by Neurosynth. The red dot in the cerebellum represents the second peak of *Right T2CRBLM*, which demonstrated FC with the red region in the cerebrum as decoded by Neurosynth. R.SPL = right superior parietal lobule; L.IFG = left inferior frontal gyrus.

4.1. Functional dissociation of left and right cerebellar lobules VII in reading

Our study found that the left and right cerebellar hemispheres were involved in reading differently. We observed significant bilateral cerebellar lobules VI/VII activation in the visual word matching task during voxel-based activation analyses. This is consistent with previous findings that the cerebellar lobules VI/VII are responsive to reading tasks (Gao et al., 2015; Martin et al., 2015; Peng et al., 2003). However, we further observed that activation in left cerebellar lobule VII negatively and significantly correlated with current reading ability, measured at the beginning of kindergarten, whereas right cerebellar lobule VII positively and significantly predicted future reading ability, measured one year later. These results suggest that beginning readers in our study might have tended to reduce the reliance on the left cerebellum and might have depended more on the right cerebellum during reading acquisition.

Different brain and behavior relationships suggest that bilateral cerebellar lobules VII play differential roles in reading. To identify the role of the cerebellum, we investigated the cerebro-cerebellar connection patterns. To estimate these, for each cerebral reading ROI, FC from cerebellar clusters (mean percent signal change of all voxels) to all other cerebral reading ROIs (weighted by the number of ROIs) were subtracted from cerebellar FC to the given reading ROI, and examined for statistical significance. This index indicates a cerebellar cluster to be relatively more connected to a given cerebral reading ROI relative to the remaining reading ROIs.

The results showed that both left and right cerebellar clusters were significantly more connected with the R.SPL and L.IOG, relative to other cerebral areas. The L.IOG is a region known for lower-level visual processing, such as extracting elementary lines, curves, or surfaces from the input word (Dehaene, 2009). This likely explains why bilateral cerebellar hemispheres showed significantly greater connectivity with this region in the visual word matching task. Another brain region where we found significantly greater connectivity with bilateral cerebellar clusters was the R.SPL, also known to be important during visual matching tasks that require participants to judge whether two successive strings (e.g., F T S H G and S T F H G) are identical or not (Reilhac, Peyrin, Démonet, & Valdois, 2013). This region is considered part of the frontoparietal attentional network, which allocates attentional resources to the current task (Maidan, Jacob, Giladi, Hausdorff, & Mirelman, 2019; Moore, Porter, & Weissman, 2009). Studies have shown that dyslexics with deficits in visual attention span show reduced activity in this region (Lobier, Peyrin, Pichat, Le Bas, & Valdois, 2014). As a complementary analysis, we performed a data driven decoding via Neurosynth's "location based analysis" feature, which provides relative quantitative functional attributions of locations of interest based on a large database with a sample size of 1000 adults. The closest available Neurosynth coordinates to the central coordinates of R.SPL were associated with terms related to "mental effort," such as "working memory," "task difficulty," "preparation," "interference," and "maintenance," thus suggesting that functional attribution of R.SPL to reading may

largely be attributable to mental effort. This was consistent with a previous study, which showed that bilateral SPLs are more strongly activated when processing multiple characters (such as letters, digits, pseudo-letters, Hiragana, e.g., D F K M V) compared to single characters (which were surrounded by four pound signs to match in length, e.g., # # D # #) (Lobier, Peyrin, Le Bas, & Valdois, 2012). In the current study, since all participants were beginning readers, they may have required more mental effort during a word processing task. In line with this interpretation, a study reported SPL activation at the very beginning of literacy acquisition (Braga et al., 2017). Together, stronger connectivity with left occipital gyrus and R.SPL compared to other reading ROIs suggests the cerebellum to be functionally connected to cerebral cortical regions that are likely involved in lower-level visual processing of input words and mental effort required in early stages of reading acquisition.

We then compared the relative FC index associated with each cerebral reading ROI seeded from the left and right cerebellar lobules VII. Interestingly, we observed that compared to right cerebellar lobule VII, the left cerebellar lobule VII had significantly greater FC with R.SPL. This finding was further verified by the F1000 functional connectome analysis (Buckner et al., 2011), which is integrated into Neurosynth. This analysis showed that one peak in the left cerebellar cluster functionally connected with right angular gyrus within the R.SPL. These results further indicate that the left cerebellar cluster was more likely to be associated with mental effort during visual word processing. In contrast, compared to left cerebellar lobule VII, right cerebellar lobule VII showed significantly increased FC with L.IFG, which overlapped with the left precentral gyrus reported by Neurosynth. While the role of the inferior frontal gyrus in language processing is complex, it is known to be involved in phonological manipulation (Meng et al., 2016), articulation (Hancock et al., 2017), semantic and syntactic processing (Hagoort, 2016, pp. 339–347), and cognitive control (Fedorenko, Duncan, & Kanwisher, 2012). To quantitatively decode the role of the particular cluster, we also used the “location based analysis” feature in Neurosynth. The results showed that the top 12 cognitive terms associated with the available location in Neurosynth closest to the central coordinates of L.IFG were related broadly to reading (e.g., “phonological,” “orthographic,” “lexical,” “reading,” “words,” “fluency,” “semantic,” and “language”). This result indicates that the L.IFG observed in the current study may be more likely to be associated with reading. A stronger connection to this region suggests the FC from right cerebellar lobule VII to cerebral cortical regions reflect reading-related (e.g., phonological) processes.

Functional differentiation in the bilateral cerebellum observed in the current study was consistent with recent functional parcellation analyses of the cerebellum (Guell, Schmahmann, Gabrieli, & Ghosh, 2018, p. 254326; King et al., 2019). King et al. (2019) and Guell et al. (2018, p. 254326) used different tasks to delineate functional subregions in the cerebellum. The left cerebellar region whose activity negatively and significantly correlated with reading ability at Time 1 in our study overlapped with the functionally defined regions from Guell et al.’s parcellation involved in social, motor, and working memory tasks, and from King et al.’s parcellation that

implicated attention, emotion, and language processing. In contrast, the right Time 2 reading-related region in our study overlapped with the regions from Guell et al.’s functional subdivisions associated with language and social processing, and from King et al.’s parcellation that implicated word comprehension and verbal fluency.

In short, FC patterns suggest that left and right cerebellar lobules VII might be associated with mental effort and reading-related processes (e.g., phonological processing), respectively. The division of labor of bilateral cerebellar hemispheres during reading contributes to the interpretation of reversed brain and behavior relationships observed in the left and right cerebellum. As reading abilities increase, regions responsible for mental effort (i.e., left cerebellar lobule VII) might decrease their activity during reading. Whereas the functional properties of regions responsible for reading-related processes (i.e., right cerebellar lobule VII) in the early reading stages might positively contribute to future reading. Together, these results indicate that the left cerebellum may perform a scaffolding function in the early stages of reading acquisition, whereas the right cerebellum could be a contributor to future reading achievements.

4.2. Lateralization pattern during reading in the cerebellum

Previous studies showed a right lateralization pattern of language processing in the cerebellum (Hubrich-Ungureanu, Kaemmerer, Henn, & Braus, 2002; Jansen et al., 2005; Sokolov Arseny, Miall R, & Ivry Richard, 2017). For example, the right cerebellum was engaged in language processing in verb generation (Frings et al., 2006). In addition, the right cerebellum showed consistent activation in phonological processing and connected with the phonological processing network (Alvarez & Fiez, 2018; Tan et al., 2005). More importantly, reading impairments were associated with functional and structural abnormalities in the right cerebellum (Hancock et al., 2017; Pernet, Poline, Demonet, & Rousselet, 2009).

In the current study, we observed bilateral cerebellar activation during visual word processing in beginning readers. However, with increase in reading ability, suppression of the left cerebellar activity (i.e., a significantly negative relationship between the left cerebellar lobule VII and reading ability), and increase in right cerebellar activity (i.e., a positive relationship between the right cerebellar lobule VII and future reading ability) may facilitate the reading network shifting from bilateral to right-lateralized (in the cerebellum).

This gradual establishment of hemispheric dominance for language processing has also been reported in the cerebrum. Different from the cerebellum, language processing is characterized by leftward asymmetry in the cerebrum (Cattinelli et al., 2013; Houdé, Rossi, Lubin, & Joliot, 2010; Knecht et al., 2000; Murphy et al., 2019). However, early in development, language processing has been shown to be bilateral (Holland et al., 2001). Everts et al. (2009) showed that functional lateralization strengthens over time and pointed to the dynamics of the process: emerging from an initially bilateral pattern, the cognitive functions in the language domain were shown to develop toward a specialized unilateral network. Similarly, increasing language lateralization during childhood was

reported by Szaflarski, Holland, Schmithorst, and Byars (2006), and Ressel, Wilke, Lidzba, Lutzenberger, and Krägeloh-Mann (2008). Activation patterns including the right-hemisphere have been shown to be beneficial for the early stages of language learning even among adults (Kepinska, de Rover, Caspers, & Schiller, 2017; Prat, Keller, & Just, 2007). Our data seem to be consistent with the findings from the cerebrum that language processing in the beginning stages is bilateral in both cerebellum and cerebrum, but will shift to the right cerebellum and left cerebrum with increasing proficiency.

4.3. Implications for reading impairment

There has been a long debate about whether abnormality in the cerebellum was a cause or a consequence of reading disorders (Bishop, 2002). Some studies suggest that deficit in the cerebellum is the cause of reading impairment (Nicolson et al., 2001). As proposed by the Cerebellar Deficit Hypothesis, deficits in the cerebellum before reading acquisition lead to future reading impairment via articulation and automatization (Nicolson et al., 2001). However, this hypothesis is inconsistent with Zeffiro and Eden (2001), who argued that if the cerebellar deficits result in reading impairment, reading disorders should show classical cerebellar clinical syndrome, such as disorders of the rate or regularity of voluntary movement. Additionally, why did patients with cerebellar damages not show disorders in reading or phonological processing? As an alternative, they proposed that deficits in the cerebellum could only be a bystander in developmental dyslexia (Zeffiro & Eden, 2001).

In recent years, a mounting number of studies comparing brain activation patterns between dyslexic and normal readers have been conducted aiming to investigate the role of the cerebellum in reading impairment, during which both hypo-activation (Cullum, Hodgetts, Milburn, & Cummine, 2019; Meng et al., 2016; Nicolson et al., 1999) and hyper-activation (Feng et al., 2017; Hancock et al., 2017; Patael et al., 2018; Yang, Bi, Long, & Tao, 2013) in the cerebellum were reported in dyslexics. However, these studies can hardly answer the question of causality (Li, Tao, Peng, & Ding, 2017; Xia, Hancock, & Hoeft, 2017).

One possible way to address this issue is to consider pre-readers. If a deficit in the cerebellum is observed in these children who have not received formal reading instruction, it might suggest that an abnormality in the cerebellum is the cause rather than the consequence of reading disorders (Ozernov-Palchik & Gaab, 2016a, 2016b; Raschle, Chang, & Gaab, 2011). Raschle, Zuk, and Gaab (2012) compared children with a family risk for dyslexia (FHD⁺) and without a family risk for dyslexia (FHD⁻), and found that FHD⁻ had greater activation in bilateral cerebellar regions compared to FHD⁺, suggesting that the cerebellar deficits could be the cause for future reading deficits. Another way is to conduct a longitudinal study. Longitudinal effects of the cerebellum on reading might also be evidence for causal relationships. Studies found that the integrity of the left inferior cerebellar peduncle at age 6 could predict reading ability at age 8 (Borchers et al., 2019; Bruckert et al., 2019). In addition, reading interventions also significantly increased the gray

matter volume of the right cerebellum (Krafnick, Flowers, Napoliello, & Eden, 2011).

In the current study, we also used a longitudinal design, but we focused on brain activity during reading task. We found that activation in the right cerebellum positively and significantly predicted reading performance after receiving one year of formal reading instruction. This result supports the causal account assuming that the functional properties of the cerebellum could contribute to future reading achievement. Our study offers direct evidence that functional deficits in the cerebellum might impair future reading ability.

4.4. Limitations

Although informative as to the role of the cerebellum in early reading, the present study has two limitations. This first limitation has to do with the reading ROIs, which were not based on pediatric studies. To define ROIs, meta-analytic studies have advantages in providing a consistent and reliable location for reading related regions. However, until now, few meta-analyses have ever focused on beginning readers, especially for children from 5 to 7 years old. Martin et al. (2015) investigated the reading network associated with children reading, but the age range, from 7 to 12 years old, was still inconsistent with the current study. As an alternative, we selected ROIs from a meta-analytic study conducted by Murphy et al. (2019). The reasons are twofold. First, it is a very recent study focusing on single word reading, which is similar to our task. Second, this study focused on native English speakers which were the same as the current study. However, this meta-analysis was not specific for beginning reading. Similar to this limitation, we used FC patterns generated by Neurosynth to supplement our results, which FC was based on 1000 adult readers, rather than children's imaging data. The use of pediatric meta-analyses of reading in future studies will therefore be an appropriate extension of the current results.

The second limitation was the visual word matching task that we used in the scanner, which served as an implicit reading task rather than an explicit reading task. We performed this task to ensure that it was accessible to beginning readers. In addition, implicit word reading tasks are frequently used to detect reading related brain activity in beginning readers. For example, Dehaene-Lambertz, Monzalvo, and Dehaene (2018) used a passive word view task to investigate the emergence of visual word form area in children of ages 5 to 6 years old, which was similar to Feng et al. (2020) in examining neural correlates of dyslexic children (8–12 years of age) across language. One recent study used a task to detect whether a given word has a tall feature (e.g., “eaten” has one letter that is tall, i.e., a tall feature, whereas “manor” has no such feature), which was also considered as an implicit reading task (Ashburn, Flowers, Napoliello, & Eden, 2020), and has been shown to elicit activation in phonological areas, such as left superior temporal cortex (Evans, Flowers, Luetje, Napoliello, & Eden, 2016; Turkeltaub, Gareau, Flowers, Zeffiro, & Eden, 2003). In the current study, we also observed activation in this region in the visual word matching task. However, for non-readers, they may perform these tasks simply using visual perception.

Future studies with explicit reading tasks are required to verify the current results.

5. Conclusion

In the current study, we investigated the roles of the cerebellum in the early stages of reading acquisition. We found that bilateral cerebellar hemispheres are involved in reading at the onset of schooling. Moreover, the cerebellum might have a longitudinal influence on reading development. Interestingly, we observed functional differentiation of left and right cerebellar lobules VII in reading. Specifically, brain activity in left cerebellar lobule VII negatively and significantly correlated with reading ability and had greater functional connectivity with the right parietal lobule possibly underlying mental effort. In contrast, brain activity in right cerebellar lobule VII predicted reading ability over time and had stronger connectivity with regions responsible for phonological processing, suggesting that right cerebellar lobule VII lays the foundation for reading development and is associated with reading-related processing. This study is the first to test whether and how the cerebellum contributes to early reading. More importantly, this study lays the foundation to advance future research that specifically investigates the functional differentiation of the cerebellum as one learns to read.

Declaration of competing interest

The authors have no conflicts of interest to declare.

Credit authorship statement

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Open practice

No part of the study procedures or the study analyses was pre-registered prior to the research being conducted. We report how we determined our sample size, all data exclusions (if any), all

inclusion/exclusion criteria, whether inclusion/exclusion criteria were established prior to data analysis, all manipulations, and all measures in the study. Public archiving of anonymised study data is not permitted by the ethics approval. Readers seeking access to the data should contact the corresponding author via email (fumiko.hoeft@uconn.edu). Data will be released to researchers on the following conditions: approval from the local research ethics committee and with appropriate safeguards to protect from the identification of individuals as well as completion of a request form (<https://drive.google.com/file/d/1kbYYfdomHHrPH6RbE4kV4WDVx1aAhNFn/view?usp=sharing>). Experiment presentation code could be found at OSF task materials for CORTEX-D-20-00596R1. No custom analysis code was used. Legal copyright restrictions prevent public archiving of the various assessment instruments used in the study (see section 2.2.1). These can be obtained from the copyright holders in the cited references accompanying each test.

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Supplementary data

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