NeuroImage: Clinical 26 (2020) 102214

Contents lists available at ScienceDirect

NeuroImage: Clinical

journal homepage: www.elsevier.com/locate/ynicl

Greater functional connectivity within the cingulo-opercular and ventral attention networks is related to better fluent reading: A resting-state functional connectivity study

Lidan Freedman[a], Michal Zivan[a], Rola Farah[a], Tzipi Horowitz-Kraus[a,b,*]

[a] *Educational Neuroimaging Center, Faculty of Education in Science and Technology, Faculty of Biomedical Engineering, The Technion – Israel Institute of Technology, Haifa, Israel*

[b] *Reading and Literacy Discovery Center, Cincinnati Children's Hospital Medical Center, Cincinnati, OH, USA*

ARTICLE INFO

Keywords:
Cognitive control
Dyslexia
Fluency
Functional MRI
Functional connectivity

ABSTRACT

Executive functions are higher-order cognitive abilities that affect many of our daily actions, including reading. A two-system model for cognitive control comprises a bottom-up system composed of the dorsal and ventral attention networks and a more evolved top-down system involving the frontoparietal and cingulo-opercular networks. We examined both within- and between-network functional connectivity of these four networks in 26 8–12-year-old children with readong difficulties and 30 age-matched typical readers using resting-state functional MRI. Fluency and nonfluency behavioral reading measures were collected, and the scores were analyzed together with the functional data. Children with reading difficulties did not differ in functional connectivity for the four networks compared to typical readers. Grouping the entire cohort into low vs. high fluency-level reading groups, however, revealed significantly higher functional connectivity values within the cingulo-opercular and ventral attention cognitive-control networks for the high fluency group. Higher functional connectivity Trends between the cognitive-control networks were also observed in the high fluency group compared to the low fluency group. A similar analysis using a nonfluency word-reading task grouping did not uncover differences between the two groups. The results emphasize the complexity of the fluency task, as a test that relies on cognitive-control abilities, at both the bottom-up and top-down levels. Therefore, it may be posited that the fluency task may also be a challenge for typical readers despite their intact performance. The results reinforce the relationship between fluent reading and functional connectivity of the cognitive-control networks, emphasizing the various cognitive-control abilities that underlie this complex reading ability.

1. Introduction

1.1. Fluent reading and underlying mechanism

The definitions of fluent reading are numerous, yet most include the ability to read a text at a steady pace, accurately, and with proper expression (Berkman et al., 2007; Fairburn and Harrison, 2003). Reading is a complex action that is influenced by two independent paths, which comprise the aptly named 'dual-route' reading model (Simos et al., 2002). The first path is the phonological route that assembles (i.e., is sublexical) and maps specific letters into orthographic segments, which are then further assembled into relevant complete phonological representations (Simos et al., 2002). The second route is the orthographic one (i.e., lexical), which relates to the mediation of visual content conversion into a complete phonological word—also called the word recognition process—and is used when reading words aloud (Simos et al., 2002). Neurobiologically, it is thought that the phonological and orthographical routes are associated with the activation of the angular and the fusiform gyri, respectively (Pugh et al., 2000; Dehaene, 2009). These routes are the basis for reading acquisition. The reader starts using the phonological route and then gradually moves over to use the orthographic route. This dual route model describes accurate word reading (in a nonfluent manner), but does not, however, take into account the speed of word recognition (fluency), which is a crucial component in becoming a proficient reader (Breznitz, 2006) . Given that fluent reading relies on speeded, automatic word recognition (Breznitz, 2006), with attention geared towards the written material, without a working memory load to process the written information

---

[*] Corresponding author at: Educational Neuroimaging Center, Faculty of Education in Science and Technology, Faculty of Biomedical Engineering, The Technion - Israel Institute of Technology, Haifa, Israel.

E-mail address: Tzipi.Kraus@Technion.ac.il (T. Horowitz-Kraus).

https://doi.org/10.1016/j.nicl.2020.102214
Received 14 November 2019; Received in revised form 21 January 2020; Accepted 16 February 2020

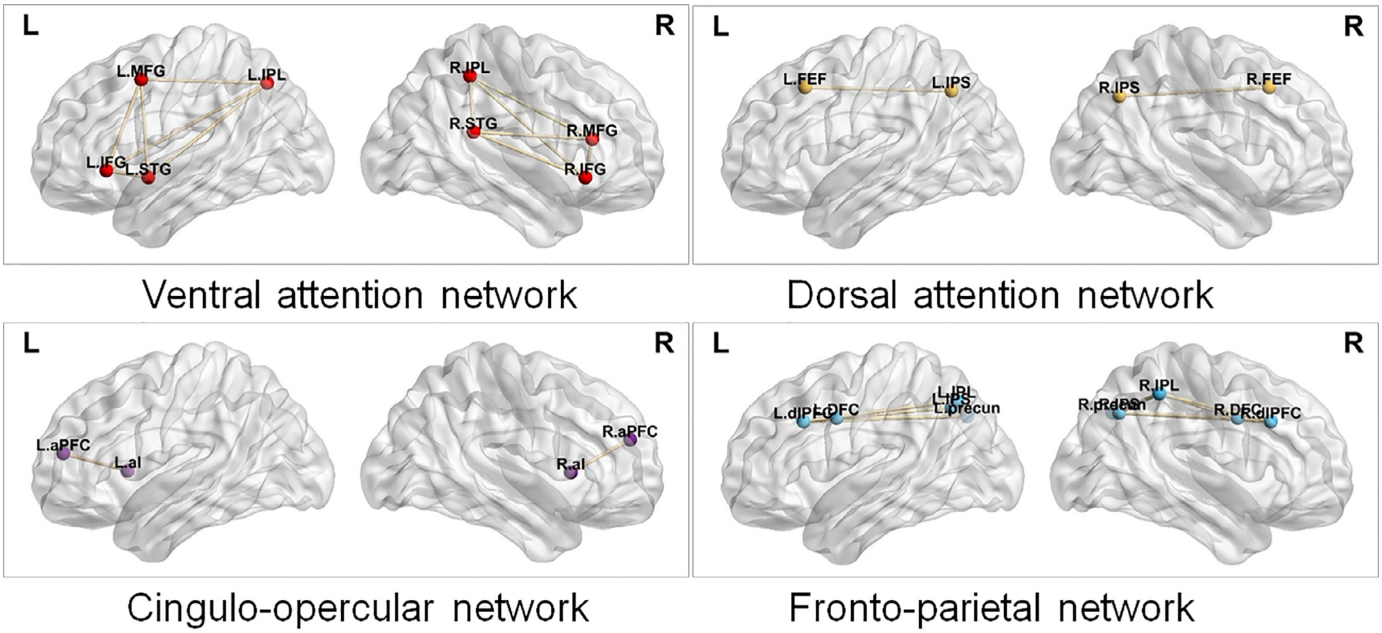

Fig. 1. Visualization of systems 1 (ventral and dorsal attention, upper row) and 2 (cingulo-opercular and frontoparietal, bottom row) on a glass brain.
The figure presents the center of mass for each region of interest listed in Table 1. DACC, dorsal anterior cingulate cortex; laPFC, left anterior prefrontal cortex; AI, anterior insula; raPFC, right anterior prefrontal cortex; SupF, superior frontal gyrus; LP, lateral prefrontal cortex; vmPFC, ventromedial prefrontal cortex; dmPFC, dorsomedial prefrontal cortex; PHG, parahippocampal gyrus; ITC, inferior temporal cortex; MFG, middle frontal gyrus; IPL, intraparietal lobule; IFG, inferior frontal gyrus; STG, superior temporal gyrus; FEF, frontal eye fields; IPS, intraparietal sulcus; dlPFC, dorsolateral prefrontal cortex; precun, precuneus.

(LaBerge and Samuels, 1974) and with error monitoring during reading (Horowitz-Kraus and Breznitz, 2008), we suggest that networks related to EF (Horowitz-Kraus, 2012) are involved in the process of automatic fluent reading.

1.2. Executive functions in children

The maturation of cognitive abilities, such as controlling thoughts and actions, fine-tuning attention, and obtaining and analyzing information that are referred to as EFs, occurs during childhood development (Anderson and Reidy, 2012; Anderson, 2002). EFs are thought to be included in the attentional network model (Petersen and Posner, 2012a). According to this model, cognitive control comprises two subsystems that differ in their information flow structure: a top-down subsystem (System 1) and a bottom-up subsystem (System 2, see Fig. 1). The top-down subsystem is involved in higher-level analysis and is divided into the cingulo-opercular (CO) and frontoparietal (FP) networks. The CO network has an important role in error monitoring, and initiating and adapting control, while the FP network enables goal-directed behavior and flexibility. It is also related to speeded processing (Dosenbach et al., 2008a), needed, as posited by Breznitz (2006), for automatic reading.

The bottom-up subsystem accepts stimuli from the environment and conveys the relevant information forward to other higher-level networks. This subsystem is divided into two further subsystems: the dorsal attention (DA) and ventral attention (VA) networks. The DA network is active when attention is oriented in space and helps maintain spatial maps, saccade planning, and visual working memory (Vossel et al., 2014a), which are important for fluent reading (Breznitz, 2006; LaBerge and Samuels, 1974). As in fluent reading, when attention should be focused on the written materials and not on external stimulation, the VA network may play a critical role in reading as it is responsible for orienting the attention to external stimuli and then reorienting it back to internal processes, such as teasing the meaning from the written words (see Fig. 1 for these two networks). Studies with children reported changes within the connectivity of these networks related to language and reading development: functional connectivity within the CO increased during narrative processing in children ages 1–9 years along development (Farah and Horowitz-Kraus, 2020) and increased reading ability was also related to increased functional connectivity within the CO in 8–12 years old children with reading difficulties (Horowitz-Kraus et al., 2015).

1.3. Reading difficulties, fluency and executive functions

The current definition of reading difficulties (RD), or dyslexia, is as a neurobiological learning disability (IDA 2011). Individuals with RD encounter difficulties with accurate and fluent word recognition, demonstrate poor spelling, and impaired decoding abilities (Lyon et al., 2003). A recent study by Reynolds and Besner (2006) found that some components of the sublexical and lexical contributions to phonology rely on the attentional networks. Indeed, extensive research examining EF impairments in individuals with RD have found that those with RD struggle with inhibition and working memory (Brosnan et al., 2002). Other EFs found to be impaired in children with RD include verbal fluency (Kinsbourne M et al., 1991), sequencing (Brosnan et al., 2002), and impaired set-shifting (Helland and Asbjornsen, 2000). Despite studies linking reading abilities to EFs and to specific regions or networks related to these abilities, there is still a gap in knowledge linking reading fluency to the exact networks related to either top-down or bottom-up abilities in the attention network including EFs. Accordingly, the goal of the current work is to fill in this lacunae.

We hypothesized that 1) overall fluent reading would be associated with greater functional connectivity of the cognitive-control networks (within and between networks) and 2) nonfluent reading tasks would not be associated with greater functional connectivity of cognitive-control networks, regardless of the existence of RD. We also anticipated that children with RD would demonstrate decreased fluency and nonfluency abilities and that functional connectivity within and between the networks would accompany changes in this group compared to typical readers.

2. Methods

2.1. Participants

Fifty-six participants, 30 typical readers (*M* = 10.03, *SD* = 1.391, 46.67% males) and 26 children with RD (*M* = 10.04, *SD* = 1.267, 61.53% males), 8–12 years of age participated in the study. All participants were tested for nonverbal IQ using the Test of Nonverbal Intelligence (third edition) (TONI-3 Brown et al., 1997) and for verbal ability using a vocabulary subtest from the Wechsler Intelligence Scores for Children (WISC-III Wechsler, 2003). All participants were native English speakers with an average socioeconomic status and no history of emotional or neurological disorder. All participants displayed normal vision in both eyes and normal hearing.

Participants were recruited from posted ads and through commercial advertisements and were compensated for their inclusion in the study. Participants and their parents were asked to provide informed written consent prior to inclusion in the study. The study was approved by the Institutional Review Board.

2.2. Behavioral measures

Reading tasks: All participants performed nonfluent and fluent reading tasks. Nonfluent tasks included the “Letter–Word” and “Word Attack” subsets of the Woodcock and Johnson-III Diagnostic Reading Battery (WJ-III Woodcock et al., 2007). The “Letter–Word” subset is an oral reading test where the child is required to read words aloud from an increasingly difficult list of words. In the “Work Attack” task, the child reads a series of unfamiliar nonessential words with increasing complexity. To assess fluency, the Test of Word Reading Efficiency Sight Word Efficiency (TOWRE-SWE Torgesen et al., 1999) was used with non-time- and time-constrained tasks in reading.

Executive functions tasks: To determine the participants’ EF abilities, several tasks were administered to gauge EF subcomponents. For working memory, the digit span task from the Wechsler Intelligence Scale for Children (WISC-III Wechsler, 2003) was used. To assess switching, subtests of the Delis-Kaplan Executive Function System (D-KEFS) were used (Delis et al., 2001). Error monitoring was assessed using the preservative errors of the Wisconsin Card Sorting Task (Heaton, 1981). Visual attention was measured using the Sky Search measure from the Test of Everyday Attention for Children (TEA-Ch Manly et al., 2001). Inhibition and overall EF were assessed using the Behavior Rating Inventory of Executive Function (BRIEF Gioia et al., 2000).

2.3. Behavioral data analysis

To determine the differences between EF groups and reading, independent sample *t*-tests were performed. All data were corrected for multiple comparisons using a Bonferroni correction.

2.4. Neuroimaging data

2.4.1. MRI data acquisition

All fMRI scans were obtained using a 3T Philips Achieve MRI scanner (Philips Medical Systems, Best, The Netherlands). A T2*-weighted, gradient-echo, echo planar imaging (EPI) sequence was used with the following parameters: TR/TE = 2000/30 ms, matrix size = 80 × 80, slice thickness = 3 mm, resulting in a voxel size = 2.8 × 2.8 × 3 mm. During the resting-state scan, 300 whole-brain volumes were acquired for a total imaging time of 10 min. Participants were asked to look at a gray cross in the center of a projector screen and avoid sleeping or closing their eyes throughout the scan. In addition, a high-resolution T1-weighted 3D anatomical scan was acquired for 5 min using an inversion recovery (IR)-prepared turbo gradient-echo acquisition protocol with a spatial resolution of $1 \times 1 \times 1$ mm^3. Using a procedure described elsewhere (Byars et al., 2002; Vannest et al., 2014), participants were acclimated and made to feel comfortable with the scanning procedure. In short, children were allowed to explore the scanner environment, get on and off the bed, and practice lying still without moving their head or feet. Children also practiced the tasks outside and inside the scanner using a computer. Motion was controlled using head straps. Between tasks, participants communicated with the study team through a microphone and headphones.

2.5. Neuroimaging data analysis

2.5.1. Functional MRI data preprocessing

All fMRI data were first spatially preprocessed using CONN software (ver. 18.a, https://www.nitrc.org/projects/conn), including segmentation into grey matter/white matter/CSF, slice-timing correction, realignment, coregistration, normalization to MNI (Montreal Neurological Institute) standard reference space, and smoothing using 8-mm full width at half-maximum (FWHM) Gaussian kernels. The processing results in three translational and three rotational motion parameters. The six motion parameters were added as regressors and additional filtering of the resting-state data included using a band-pass filter of 0.008 to 0.2 Hz. Region of interest (ROIs) masks for the four cognitive-control networks (i.e., CO, FP, VA, DA) were created using the WFU pick atlas toolbox for SPM12 (http://www.nitrc.org/projects/wfu_pickatlas/). To decrease the bias of reference frame and scaling, best-fit transformation was used to transform the MNI coordinates into Talairach space (icbm_spm2tal; http://brainmap.org/icbm2tal/). Each brain region was referred to using Brodmann areas (BA) following (Hutton et al., 2017; Tomasi and Volkow, 2010; Zhang et al., 2018). The coordinates of the ROIs are listed in Table 1.

2.6. Parcellation method

Brodmann areas, as listed in Table 1, usually include several functional regions. Often, the shape or volumes of these regions are heterogeneous and may include several parts of the cortex that may not be part of the functional network of interest, Therefore, to further fine-tune the functional networks of interest, the four network maps were further parceled into 50 data-driven sub-parcels, functionally homogenous per network within the spatial ROIs defined in Table 1, using the Cradock parcellation method (Craddock et al., 2012). The radius of each parcel was defined as 8 mm (following Hutton et al., 2018). These parceled networks were fed back into CONN as masks for further analyses.

2.7. MRI data analysis

Within- and between-functional connectivity values for each network were obtained using an in-house code for Conn written in MATLAB and compared between the groups. To examine differences in functional connectivity between high vs. low fluency reading performance, as well as between high vs. low nonfluency reading performance, separate *t*-tests were performed. The functional connectivity values were used as dependent measures, while the grouping variable was set according to the fluency/nonfluency score (with a threshold of 90) in two separate *t*-test analyses. To determine a lack of differences in motion between the groups of children with RD and typical readers, and between the low vs. high fluency groups, two separate two-way *t*-test analyses were conducted for the file displacement measure. Data were corrected for multiple comparisons using a Bonferroni correction.

Table 1
Networks and coordinates for the cognitive-control networks.

Network	Regions	Coordinates	Reference
Cingulo-opercular	Left anterior prefrontal cortex	−28, 51, 15	(Horowitz-Kraus et al., 2015)
	Right anterior prefrontal cortex	27, 50, 23	
	Left lateral anterior insula/frontal operculum	−51, 18, 13	
	Right lateral anterior insula/frontal operculum	45, 23, −4	
	Left medial anterior insula/frontal operculum	−33, 24, 1	
	Right medial anterior insula/frontal operculum	33, 25, −1	
	Left anterior insula/frontal operculum	−35, 14, 5	
	Right anterior insula/frontal operculum	36, 16, 4	
	Dorsal anterior cingulate/medial superior frontal cortex	−1, 10, 46	
Frontoparietal	Left dorso-lateral prefrontal cortex	−43, 22, 34	(Horowitz-Kraus et al., 2015)
	Right dorso-lateral prefrontal cortex	43, 22, 34	
	Left inferior parietal lobule	−51, −51, 36	
	Right inferior parietal lobule	51, 47, 42	
	Left intraparietal sulcus	−31, −59, 42	
	Right intraparietal sulcus	30, −61, 39	
	Left precuneus	−9, −72, 37	
	Right precuneus	10, −69, 39	
	Mid cingulate cortex	0, −29, 30	
Dorsal attention	Right FEF	28, −10, 53	(Fox et al., 2006b)
	Right posterior IPS	20, −67, 51	
	Right anterior IPS	35, −47, 45	
	Left FEF	−25, −12, 55	
	Left posterior IPS	−22, −68, 46	
	Left anterior IPS	−42, −41, 43	
	Left SMA/Pre-SMA	−4, −1, 53	
	Right inferior frontal gyrus	52, 6, 27	
	Right MT+	51, −63, −7	
	Right middle frontal gyrus	37, 38, 20	
	Right insula	30, 17, 9	
	Left MT+	−46, −68, −7	
Ventral attention	Right insula	28, 12, 2	(Fox et al., 2006b)
	Right supramarginal gyrus (TPJ)	57, −43, 34	
	Left insula	−41, 11, 1	
	Right superior frontal gyrus	29, 44, 29	
	Right inferior frontal gyrus	41, 41, 5	
	Right inferior/middle frontal gyrus	47, 14, 32	
	Right superior frontal gyrus	4, 20, 49	
	Right middle temporal gyrus	52, −32, −7	
	Left superior temporal gyrus	−60, −49, 19	
	Right precuneus	2, −53, 51	
	Right medial frontal gyrus	8, 3, 62	
	Right middle temporal gyrus	41, −13, −7	
	Right sulcus callosomarginalis	6, −28, 43	

3. Results

3.1. Behavioral results

Independent sample *t*-tests demonstrated that children with RD exhibited significantly lower EF scores in all domains. Moreover, significantly lower fluency and nonfluency reading scores on the timed reading tests [TOWRE ($t(54) = -7.45$, $p < 0.001$), and TOSREC ($t(44) = -7.74$, $p < 0.001$)] and on non-timed reading tests [Letter-Word ($t(54) = -5.92$, $p < 0.001$), Word Attack ($t(54) = -6.66$, $p < 0.001$)] were found in children with RD compared to typical readers. Results were corrected for multiple comparisons; see Table 2 for these results.

3.2. Neuroimaging results

An independent *t*-test for within- and between-network functional connectivity of the four cognitive-control networks did not reveal significant differences between children with RD and typical readers (see Table 3). Results were corrected for multiple comparisons.

3.3. Differences in functional connectivity between high vs. low fluency readers

The classification of subjects according to the fluency scores measured by the TOWRE SWE yielded two groups: high fluency ($n = 35$) and low fluency ($n = 21$). The high fluency group consisted of seven children with RD and 28 typical readers. The low fluency group consisted of 19 children with RD and two typical readers. The *t*-test performed on functional connectivity measures of FP, CO, DA, VA with the TOWRE grouping showed significant differences within the CO and VA functional connectivity measures between the high and the low fluency groups and trends in the between CO and FP and the between VA and DA connectivity measures (see Table 4 for these results). To find the specificity in the involvement of cognitive control networks in the fluency-based reading task, a similar classification of the nonfluency scores measured by the Letter–Word test was performed and showed no significant differences between the high ($n = 40$; 11 children with RD, 29 typical readers) and the low ($n = 16$; 15 children with RD, 1 typical reader) nonfluency groups (see Table 5). No significant differences in file displacement were found between children with RD ($M = 0.52$, $SD = 0.17$) and typical readers ($M = 0.401$, $SD = 0.09$) ($t(68) = 1.99$, $p = 01.60$) and between the high ($M = 0.405$, $SD = 0.1$) and low ($M = 0.56$, $SD = 0.21$) fluency groups ($t(68) = 2.04$, $p = 0.17$). Results were corrected for multiple comparisons.

Table 2

Comparison of behavioral measurements between children with reading difficulties and typical readers.

Cognitive ability	Measure	RD Mean (SD)	TR Mean (SD)	T (*P* value)
Executive functions				
	Working memory (Digit Span, standard score)	8.44 (2.00)	9.72 (2.53)	−2.04 (0.05)
	Switching (D-KEFS, Condition 1, color naming, scaled score)	8.00 (2.92)	11.96 (2.94)	−4.58 (0.00)
	Switching (D-KEFS, Condition 2, color naming and inhibition, scaled score)	8.85 (2.96)	11.93 (2.43)	−3.91 (0.00)
	Error monitoring (preservative errors, T-score)	50.65 (11.13)	56.32 (9.05)	−2.01 (0.05)
	Visual attention (Sky Search, scaled)	7.42 (2.89)	9.27 (2.96)	−2.31 (0.03)
	Inhibition (BRIEF, T-score)	56.16 (11.03)	45.90 (9.28)	3.75 (0.00)
	General EF (BRIEF, T-Score)	58.72 (8.60)	44.53 (11.25)	5.17 (0.00)
Reading	Fluency (TOWRE efficiency index SWE and PDE, scaled score)	82.12 (14.95)	106.60 (9.37)	−7.45 (0.00)
	Nonfluency (Letter-Word, standard score)	87.23 (13.44)	109.40 (14.44)	−5.92 (0.00)
	Nonfluency (Word Attack, standard score)	91.69 (8.39)	108.10 (9.83)	−6.66 (0.00)
	Nonfluency (TOSREC, number correct)	15.80 (5.89)	34.48 (8.51)	−7.75 (0.00)

RD, reading difficulties; M, mean; TR, typical reader, SD, standard deviation; T, test statistic.

Table 3

Comparison of within- and between-network functional connectivity of cognitive-control networks between children with reading difficulties and typical readers.

Functional measure	RD Mean (SD)	TR Mean (SD)	T (*P* value)
Within- FP	0.1697 (0.06)	0.1708 (0.07)	−0.07 (0.95)
Within-CO	0.1522 (0.07)	0.1701 (0.06)	−0.98 (0.33)
Within-VA	0.1534 (0.05)	0.1541 (0.07)	−0.04 (0.97)
Within-DA	0.1733 (0.05)	0.1712 (0.07)	0.13 (0.90)
Between-FP and CO	0.1081 (0.05)	0.1149 (0.07)	−0.42 (0.67)
Between-DA and VA	0.1741 (0.05)	0.1705 (0.07)	0.23 (0.82)

RD, reading difficulties; M, mean; TR, typical reader, SD, standard deviation; T, test statistic; FP, frontoparietal; CO, cingulo-opercular; VA, ventral attention; DA, dorsal attention.

Table 4

Results of *t*-tests for functional connectivity measures with grouping according to fluency scores measured by the TOWRE SWE (Scaled Score) test.

	Low fluency score group Mean (SD)	High fluency score group Mean (SD)	T (*P* value)
Within-FP	0.153 (0.044)	0.181 (0.071)	−1.597 (0.116)
Within-CO	0.135 (0.042)	0.178 (0.076)	−2.322 (0.024)
Within-VA	0.132 (0.041)	0.167 (0.066)	−2.215 (0.031)
Within-DA	0.157 (0.039)	0.181 (0.068)	−1.525 (0.133)
Between-CO and FP	0.094 (0.039)	0.122 (0.066)	−1.762 (0.084)
Between-VA and DA	0.154 (0.041)	0.183 (0.066)	−1.8 (0.077)

Table 5

Results of *t*-tests for functional connectivity measures with grouping according to nonfluency scores measured by the Letter–Word (Scaled Score) test.

	Low nonfluency score group Mean (SD)	High nonfluency score group Mean (SD)	T (*P* value)
Within-FP	0.179 (0.084)	0.167 (0.054)	0.67 (0.505)
Within-CO	0.156 (0.079)	0.164 (0.064)	−0.428 (0.671)
Within-VA	0.154 (0.076)	0.154 (0.053)	0.029 (0.977)
Within-DA	0.181 (0.079)	0.169 (0.05)	0.73 (0.468)
Between-CO and FP	0.12 (0.081)	0.108 (0.048)	0.663 (0.51)
Between-VA and DA	0.179 (0.079)	0.17 (0.051)	0.512 (0.61)

4. Discussion

The aim of the current study was to determine the neurobiological correlates for cognitive control in fluent reading. To this end, we examined the traditional bottom-up and top-down networks (referred as System 1 and System 2, respectively) during rest in children with RD vs. typical readers in relation to their fluent vs. nonfluent reading. When classifying the entire sample as either low or high fluency readers, differences between the groups within the CO and the VA functional connectivity values, as well as trends in functional connectivity between VA-DA and the CO-FP, were found. Supporting our hypothesis, the high fluency group showed greater functional connectivity values, suggesting relations between higher connectivity in these networks and higher fluency compared to the low fluency group. Furthermore, classification according to the nonfluency behavioral measures (Letter–Word test) did not show any differences in connectivity measures as hypothesized, highlighting the specificity in utilization of these networks in fluent vs. nonfluent reading.

4.1. Reading difficulty as a multi-componential disorder

The definition for RD has changed along the years (Association, 2013). Nevertheless, the inclusion of several reading components such as word and non-word reading speed, accuracy, comprehension and fluency remain. Due to the broad range of characteristics subsumed under the phenomenon of RD and the different profiles children with RD demonstrate, several studies have followed Krafnick's definition that posits that children with RD can be defined based on a failure in two or more standardized reading tasks (Krafnick et al., 2011; Krafnick et al., 2014). Interestingly, our findings suggest that careful attention should be given to the timed vs. non-timed tasks chosen under this definition.

Fluent word reading, i.e., reading words fast and accurately, was previously related to cognitive control (or EF) abilities and networks (Horowitz-Kraus et al., 2015; Horowitz-Kraus and Holland, 2015; Levinson et al., 2020). It does not rely just on basic word recognition skills but also on timed, synchronized activation of neural networks related to word recognition and cognitive control (Horowitz-Kraus and Holland, 2015). We suggest that although fluency scores show differences between RD and typical readers on the behavioral level, there is no significant difference in the reliance on cognitive control networks in children with RD vs. typical readers, despite the significantly lower fluency ability in the RD group. We suggest that this ability may be a complex one and that to perform it proficiently, typical readers also engage neural circuits related to cognitive control. Support for this hypothesis was given by our previous findings showing that functional connectivity within the CO network was also related to better fluent reading in typical readers following a fluency-based intervention

(Horowitz-Kraus et al., 2015). To determine the specificity of our results as regards the low and high fluency groups, Pearson correlations between the networks of choice and reading measures in each group separately (children with RD and typical readers) were performed. These correlations did not reveal significant results (data not shown). Possibly, given greater reading exposure and more mature EFs, as in adults, changes in networks related to EFs associated with reading fluency between children with RD and typical readers will be found.

The results of the current study suggest that although children with RD and typical readers engage neural circuits related to cognitive control equally, children with RD do not manage to read within the average range of fluency and typical readers do. This situation may be related to a challenge in synchronization of additional neuronal circuits related to visual processing and language (see Dehaene, 2013).

4.2. Impaired functioning of Systems 1 and 2 in children with low fluency

Intriguingly, as fluent reading is considered a complex reading task, there are typical readers who demonstrate relatively lower fluency abilities, yet still score in the average range. On the other hand, there are children with RD who demonstrate relatively higher fluency abilities since their RD group assignment is based on other criteria than fluent reading (based on Krafnick et al., 2011; Krafnick et al., 2014). When splitting our cohorts into high and low fluent readers regardless of the diagnosis (RD or typical readers), results pointed at a significant difference between low and high fluent readers. Interestingly, not only were higher fluency abilities related to increased involvement of top-down abilities (i.e., CO network), but also to increased involvement of bottom-up abilities (i.e., VA network).

Reading ability was previously related to normal error monitoring (related to the anterior cingulate cortex Horowitz-Kraus and Breznitz, 2008; Horowitz-Kraus, 2012; Horowitz-Kraus, 2011; Horowitz-Kraus and Breznitz, 2011), part of the abilities referred to as the CO network. It was suggested that ongoing task maintenance and the ability to identify errors even during reading, differentiates typical vs. atypical reading (Horowitz-Kraus and Breznitz, 2008; Horowitz-Kraus, 2012; Horowitz-Kraus, 2011; Horowitz-Kraus and Breznitz, 2011). Additionally, the involvement of more basic attention abilities, such as the ability to reorient attention in response to salient stimuli (reflected in VA network functional connectivity Petersen and Posner, 2012b; Fox et al., 2006a) was also found to be associated with a higher fluency ability. The VA network, as opposed to the DA network, was found to be less engaged in "traditional" reading networks (15% vs. 22% involvement according to Bailey et al., 2018).

Some reports, however, demonstrate major functional differences in these two networks, specifically pointing to the role of the VA network in responding to changes in timing and characteristics of external stimuli (e.g., onset and offset of tasks) (Fox et al., 2006a). It may be that the intrinsic connectivity within the VA network is needed for fluent reading because of its role in maintaining the speed of reading and the efficient shift from one stimulus to the other. This capability, together with the importance of maintaining monitoring during reading, is not unique to children with RD, but is generally needed for this task. This might be the reason for its recruitment also by typical readers. We found, however, that those who fail to synchronize these networks to achieve these goals do not demonstrate fluent reading—results that were not replicated in nonfluent reading. The increased synchronization between the top-down EF networks (Dosenbach et al., 2008b) and bottom-up networks (Vossel et al., 2014b) for higher vs. lower fluent reading did not reach significance. Nevertheless, based on the trend found, we suggest that the direction of the results shown in the intrinsic connectivity part remains: greater synchronization within the bottom-up and top-down networks is related to better fluent reading. This may confirm the need for both maintaining attention and reorienting it to the task in a speeded manner as well as higher order monitoring and memory abilities related to EF. An additional study with a larger number of participants is required to confirm this point.

4.3. Studies limitations

The following limitations should be considered when reviewing the results of the current study. First, we only examined children with RD and typical readers. To verify the differences in reliance of fluent reading on attentional networks, a more extended population should be included (such as children with attention difficulties in the hyperactivity end as well as slower inattentive children). Second, an examination of the within- and between-network connectivity in the cognitive-control networks should be examined during a designated fluency functional MRI task vs. a nonfluency task.

5. Conclusions

The results of the study suggest that although behavioral scores for reading fluency may differ between children with RD and typical readers, underlying mechanistic factors determining reading ability that can be detected using neuroimaging tools show a similar reliance on components within the attention network. Comparison of higher fluent readers to lower fluent readers revealed the involvement of networks related to monitoring and reorienting attention in higher fluent readers. These findings may explain the variety of profiles among readers who demonstrate different abilities in the fluency, phonology and comprehension domains (Buly and Valencia, 2002). One traditional reading model, the "simple view" model, suggests that different routes including decoding and comprehension/language abilities together enable efficient reading (Gough and Tunmer, 1986). Our results echo the title of the paper published by Adolf and colleagues, asking "Should the simple view model include fluent reading as well?" (Adlof et al., 2006).

CRediT authorship contribution statement

Lidan Freedman: Formal analysis. **Michal Zivan:** Formal analysis, Writing - review & editing, Methodology. **Rola Farah:** Formal analysis, Writing - review & editing. **Tzipi Horowitz-Kraus:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing - original draft, Writing - review & editing.

Acknowledgments

This study was funded by a grant from The Eunice Kennedy Shriver National Institute of Child Health (grant number R01-HD 086011) and Human Development, National Institutes of Health (PI: Horowitz-Kraus).

References

Adlof, S.M., Catts, H.W., Little, T.D., 2006. Should the simple view of reading include a fluency component. Read. Writ. 19 (9), 933–958.
Anderson, P., 2002. Assessment and development of executive function (EF) during childhood. Child Neuropsychol. 8 (2), 71–82.
Anderson, P.J., Reidy, N, 2012. Assessing executive function in preschoolers. Neuropsychol. Rev. 22 (4), 345–360.
Association, A.P., 2013. Diagnostic and Statistical Manual of Mental Disorders, fifth ed. American Psychiatric Association, Washington, DC.
Bailey, S.K., Aboud, K.S., Nguyen, T.Q., Cutting, L.E, 2018. Applying a network framework to the neurobiology of reading and dyslexia. J. Neurodev. Disord. 10 (1), 37.
Berkman, N.D., Lohr, K.N., Bulik, C.M, 2007. Outcomes of eating disorders: a systematic review of the literature. Int. J. Eat. Disord. 40 (4), 293–309.
Breznitz, Z., 2006. Fluency in Reading: Synchronization of Processes. Lawrence Erlbaum Associates, Mahwah, New Jersey.
Brosnan, M., Demetre, J., Hamill, S., Robson, K., Shepherd, H., Cody, G, 2002. Executive functioning in adults and children with developmental dyslexia. Neuropsychologia 40 (12), 2144–2155.
Brown, L., Sherbenou, R., Johnsen, S., 1997. Test of Nonverbal Intelligence, third ed. Pro-

Ed, Austin.

Buly, M.R., Valencia, S.W., 2002. Below the bar: profiles of students who fail state reading assessments. Educ. Eval. Policy Anal. 24 (3), 219–223.

Byars, A.W., Holland, S.K., Strawsburg, R.H., et al., 2002. Practical aspects of conducting large-scale functional magnetic resonance imaging studies in children. J. Child Neurol. 17 (12), 885–890.

Craddock, R.C., James, G.A., Holtzheimer, P.E., Hu 3rd, X.P., Mayberg, H.S, 2012. A whole brain fMRI atlas generated via spatially constrained spectral clustering. Hum. Brain Mapp. 33, 1914–1928.

Dehaene, S., 2009. Reading in the Brain: The New Science of How We Read. Penguin, New York, NY.

Dehaene, S., 2013. Inside the letterbox: how literacy transforms the human brain. Cerebrum 2013, 7.

Delis, D.C., Kaplan, E., Kramer, J.H, 2001. Delis-Kaplan Executive Function System®(D-KEFS®): Examiner's Manual: Flexibility of Thinking, Concept Formation, Problem Solving, Planning, Creativity, Impluse Control, Inhibition. Pearson.

Dosenbach, N.U., Fair, D.A., Cohen, A.L., Schlaggar, B.L., Petersen, S.E, 2008b. A dual-networks architecture of top-down control. Trends Cogn. Sci. 12 (3), 99–105.

Dosenbach, N.U.F., Fair, D.A., Cohen, A.L., Schlaggar, B.L., Petersen, S.E, 2008a. A dual-networks architecture of top-down control. Trends Cogn. Sci. 12 (3), 99–105.

Fairburn, C.G., Harrison, P.J., 2003. Eating disorders. Lancet North Am. Ed. 361 (9355), 407–416.

Farah, R., Horowitz-Kraus, T., 2019. Increased functional connectivity within and between cognitive-control networks from early infancy to 9 years during stories listening: a developmental task-based functional MRI study. Brain Connect. 9 (3), 285–295. https://doi.org/10.1089/brain.2018.0625.

Fox, M.D., Corbetta, M., Snyder, A.Z., Vincent, J.L., Raichle, M.E, 2006b. Spontaneous neuronal activity distinguishes human dorsal and ventral attention systems. Proc. Natl. Acad. Sci. USA 103 (26), 10046–10051.

Fox, M.D., Corbetta, M., Snyder, A.Z., Vincent, J.L., Raichle, M.E, 2006a. Spontaneous neuronal activity distinguishes human dorsal and ventral attention systems. Proc. Natl Acad. Sci. 103 (26), 10046–10051.

Gioia, G.A., Isquith, P.K., Guy, S.C., Kenworthy, L., 2000. Behavior rating inventory of executive function. Child Neuropsychol. 6 (3).

Gough, P.B., Tunmer, W.E., 1986. Decoding, reading, and reading disability RASE. Remedial Special Educ. 7 (1), 6–10.

Heaton, R.K, 1981. Wisconsin card sorting test manual; revised and expanded. Psychol. Assess. Resour. 5–57.

Helland, T., Asbjornsen, A., 2000. Executive functions in dyslexia. Child Neuropsychol. 6 (1), 37–48.

Horowitz-Kraus, T., 2011. Does development affect the error-related negativity of impaired and skilled readers? An ERP study. Dev. Neuropsychol. 36 (7), 914–932.

Horowitz-Kraus, T., 2012. The error detection mechanism among dyslexic and skilled readers: characterization and plasticity. In: Breznitz, Z., Rubinsten, O., Molfese, V.J., Molfese, D.L. (Eds.), Reading, Writing, Mathematics and the Developing Brain: Listening to Many Voices 6. Springer, Dordrecht, pp. 113–130.

Horowitz-Kraus, T., Breznitz, Z., 2008. An error-detection mechanism in reading among dyslexic and regular readers–an ERP study. Clin. Neurophysiol. 119 (10), 2238–2246.

Horowitz-Kraus, T., Breznitz, Z., 2011. Error detection mechanism for words and sentences: a comparison between readers with dyslexia and skilled readers. Int. J. Disabil. Dev. Educ. 58 (1), 33–45.

Horowitz-Kraus, T., Holland, S.K., 2015. Greater functional connectivity between reading and error-detection regions following training with the reading acceleration program in children with reading difficulties. Ann. Dyslexia. https://doi.org/10.1007/s11881-015-0096-9.

Horowitz-Kraus, T., Toro-Serey, C., DiFrancesco, M., 2015. Increased resting-state functional connectivity in the cingulo-opercular cognitive-control network after intervention in children with reading difficulties. PLoS One 10 (7), e0133762.

Hutton, J.S., Dudley, J., Horowitz-Kraus, T., DeWitt, T., Holland, S.K., 2018. Differences in functional brain network connectivity during stories presented in audio, illustrated, and animated format in preschool-age children. Brain Imaging Behav. 14, 1–12.

Hutton, J.S., Phelan, K., Horowitz-Kraus, T., et al., 2017. Story time turbocharger? Child engagement during shared reading and cerebellar activation and connectivity in preschool-age children listening to stories. PLoS One 12 (5), e0177398.

IDA, 2011. Definition of Dyslexia- Based in the Initial Definition of the Research Committee of the Orton Dyslexia Society, Former Name of the IDA, Done in 1994. International Dyslexia Association.

Kinsbourne M, R.D., Gamzu, E., Palmer, R.L., Berliner, A.K, 1991. . neuropsychological deficits in adults with dyslexia. Dev. Med. Child Neurol. 33 (9), 763–775.

Krafnick, A.J., Flowers, D.L., Luetje, M.M., Napoliello, E.M., Eden, G.F, 2014. An investigation into the origin of anatomical differences in dyslexia. J. Neurosci. 34 (3), 901–908.

Krafnick, A.J., Flowers, D.L., Napoliello, E.M., Eden, G.F, 2011. Gray matter volume changes following reading intervention in dyslexic children. Neuroimage 57 (3), 733–741.

LaBerge, D., Samuels, S.J., 1974. Toward a theory of automatic information processing in reading. Cogn. Psychol. 6 (2), 293–323.

Levinson, O., Hershey, A., Farah, R., Horowitz-Kraus, T., 2018. Altered functional connectivity of the executive-functions network during a Stroop task in children with reading difficulties. Brain Connect. 8 (8), 516–525. https://doi.org/10.1089/brain.2018.0595.

Lyon, G.R., Shaywitz, S.E., Shaywitz, B.A, 2003. A definition of dyslexia. Ann. Dyslexia 53, 1–14.

Manly, T., Anderson, V., Nimmo-Smith, I., Turner, A., Watson, P., Robertson, I.H, 2001. The differential assessment of children's attention: the test of everyday attention for children (TEA-Ch), normative sample and adhd performance. J. Child Psychol. Psychiatry Allied Discipl. 42 (8), 1065–1081.

Petersen, S.E., Posner, M.I., 2012b. The attention system of the human brain: 20 years after. Annu. Rev. Neurosci. 35, 73–89.

Petersen, S.E., Posner, M.I., 2012a. The attention system of the human brain: 20 years after. In: Hyman, S.E. (Ed.), Annual Review of Neuroscience 35. Palo Alto: Annual Reviews, pp. 73–89.

Pugh, K.R., Mencl, W.E., Jenner, A.R., et al., 2000. Functional neuroimaging studies of reading and reading disability (developmental dyslexia). Ment. Retard. Dev. Disabil. Res. Rev. 6 (3), 207–213.

Reynolds, M., Besner, D., 2006. Reading aloud is not automatic: processing capacity is required to generate a phonological code from print. J. Exp. Psychol. Hum. Percept. Perform. 32 (6), 1303–1323.

Simos, P.G., Breier, J.I., Fletcher, J.M., Foorman, B.R., Castillo, E.M., Papanicolaou, A.C, 2002. Brain mechanisms for reading words and pseudowords: an integrated approach. Cereb. Cortex 12 (3), 297–305.

Tomasi, D., Volkow, N.D, 2010. Functional connectivity density mapping. Proc. Natl. Acad. Sci. 107 (21), 9885–9890.

Torgesen, J.K., Wagner, R.K., Rashotte, C.A, 1999. Test of Word Reading Efficiency (TOWRE). Pro-Ed, Austin, TX.

Vannest, J., Rajagopal, A., Cicchino, N.D., et al., 2014. Factors determining success of awake and asleep magnetic resonance imaging scans in nonsedated children. Neuropediatrics 45 (6), 370–377.

Vossel, S., Geng, J.J., Fink, G.R, 2014b. Dorsal and ventral attention systems: distinct neural circuits but collaborative roles. Neuroscientist 20 (2), 150–159.

Vossel, S., Geng, J.J., Fink, G.R, 2014a. Dorsal and ventral attention systems: distinct neural circuits but collaborative roles. Neuroscientist 20 (2), 150–159.

Wechsler, D.W., 2003. Intelligence Scale for Children, fourth ed. The Psychological Corporation, San Antonio, TX.

Woodcock, R.W., McGrew, K.S., Mather, N., 2007. Woodcock–Johnson tests of achievement, three. Rolling Meadows. Riverside Publishing, IL.

Zhang, D., Zhou, Y., Yuan, J, 2018. Speech prosodies of different emotional categories activate different brain regions in adult cortex: an fNIRS study. Sci. Rep. 8 (1), 218.