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Original Article

Learning to read may help promote attention by increasing the volume of the left middle frontal gyrus and enhancing its connectivity to the ventral attention network

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Attention and reading are essential skills for successful schooling and in adult life. While previous studies have documented that attention development supports reading acquisition, whether and how learning to read may improve attention among school-age children and the brain structural and functional development that may be involved remain unknown. In this prospective longitudinal study, we examined bidirectional and longitudinal predictions between attention and reading development and the neural mediators of attention and reading development among school-age children using cross-lagged panel modeling. The results showed that better baseline reading performance significantly predicted better attention performance one year later after controlling for baseline attention performance. In contrast, after controlling for baseline reading performance, attention did not significantly predict reading performance one year later, while more attention problems also significantly predicted worse reading performance. Both the increasing gray matter volume of the left middle frontal gyrus and the increasing connectivity between the left middle frontal gyrus and the ventral attention network mediated the above significant longitudinal predictions. This study, directly revealed that reading skills may predict the development of important cognitive functions, such as attention, in school-age children. Therefore, learning to read is not only a challenge for school-age children but is also an important way to optimize attention and brain development.

Key words: reading; attention; left middle frontal gyrus; ventral attention network; school-age children.

Introduction

Both attention and reading are important for successful schooling. Attention and reading development in childhood are closely associated with adulthood education attainment (Duncan et al. 2007), mental health (Wrulich et al. 2014), socioeconomic status (Ritchie and Bates 2013), and longevity (Livingston et al. 2020). Attention and reading development closely correlate with each other (Hoffman and Subramaniam 1995; Clark 1999), even after controlling for children's other cognitive abilities and behavior problems (Rabiner and Coie 2000). However, it remains unclear how attention and reading are related to one another among school-age children at both behavioral and neural levels during development. The present study thus aimed to explore the longitudinal relationship between school-age children's reading and attention development, as well as the mediating roles of structural and functional brain development.

Attention development involves multiple facets. Selective attention is one's ability to focus on a target (Tsal et al. 2016). It plays important roles in word recognition accuracy, fluency, and reading comprehension (Commodari 2017; Yildiz and Çetinkaya 2017). Selective attention was found to correlate with almost all dimensions of reading development in novice readers (Commodari 2017). In both China and the United States, selective attention was closely correlated with reading development in a cross-sectional study of preschoolers in Lan et al. (2011). Furthermore, a longitudinal study found that selective attention in preschoolers in grade 1 significantly predicted their reading performance (Franceschini et al. 2012). Preschoolers at risk of developing reading

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difficulties showed worse selective attention than their typically developing peers (Commodari 2012). The above previous studies have well documented that selective attention, particularly in preschool, plays important roles in reading development and reading difficulties.

Executive attention is one's ability to inhibit responses to irrelevant stimuli (Tsal et al. 2016). It contributes significantly to reading comprehension among elementary school children even when family socioeconomic status is controlled for (Locascio et al. 2010), particularly for children from low-income families (Kieffer et al. 2013). Poor readers experienced more difficulties in executive attention than their peers, partly due to their difficulties in inhibiting irrelevant information during reading (Borella et al. 2010). A meta-analysis of 14 studies demonstrated a positive and moderate association between executive attention and reading comprehension (Follmer 2018). A longitudinal study found that executive attention in preschoolers could predict reading comprehension in children in grade 1 but not in children in grade 3 (de Franchis et al. 2017). This suggests that the prediction of reading by executive attention may be unstable.

Among children with attention problems, ~20% may also experience reading difficulties (Carroll et al. 2005). A longitudinal study of 387 children found that attention problems in preschool significantly predicted reading difficulties in children in grade 5, and 34% of inattentive preschoolers developed reading impairment at grade 5 (Rabiner and Coie 2000). A longitudinal study of 2,014 elementary school children confirmed that a negative association between attention problems and reading performance are found throughout the time that children are in elementary school (Ehm et al. 2016). Furthermore, another longitudinal study of children from 7 to 11 years of age found that the association between attention and reading problems may be genetically influenced (Greven et al. 2012).

The above studies consistently support that attention, especially attention in preschool-age children, may significantly predict children's reading development in school. Is it possible for children's success in learning to read to predict their attention development during their school years? Schooling means receiving systematic instruction that help one build academic skills, such as reading, which may also benefit a person's cognitive development (Ceci and Williams 1997; Jacob and Parkinson 2015; Ritchie and Tucker-Drob 2018). Thus, cognitive abilities and academic skill acquisition may mutually impact each other (van der Maas et al. 2006). For example, reading interventions over 3 years improved both reading and attention performance of struggling readers in middle school (Roberts et al. 2015). Compared with illiterate adults, formerly illiterate adults improved their attention significantly with a few reading instructions (mean = 0.8, standard deviation, SD = 1.6 years of instruction; Brucki and Nitrini 2008). However, whether learning to read may help promote attention development and mitigate attention problems has not been fully investigated in typically developing school-age children.

Despite a few studies on the connection between attention and reading, little is known about the structural and functional brain development underlying this connection. Previous research has found that learning to read alters the ventral occipitotemporal pathway in the visual system of illiterate individuals (Dehaene et al. 2015; Skeide et al. 2017) for native alphabetic readers. The left middle frontal gyrus was recognized as critical for Chinese reading and reading acquisition. The left middle frontal gyrus was weakly activated or remained in active in illiterate Chinese adults compared with the activity in this region noted in their literate peers when performing certain tasks (Li et al. 2006; Wu et al. 2012b). Also, dyslexic Chinese children not only showed less activation in the left middle frontal gyrus (Tan et al. 2005; Siok et al. 2009; Xu et al. 2015; Siok et al. 2020) but also had decreased gray matter volumes in the left middle frontal gyrus when performing pertinent tasks (Siok et al. 2004, 2008). A recent study found that Chinese readers activated the left middle frontal gyrus for reading as early as the beginning of reading acquisition at age 6 (Siok et al. 2020). The critical roles of the left middle frontal gyrus in Chinese reading have been confirmed by a meta-analysis of 26 studies on neural networks for Chinese character reading (Wu et al. 2012a). A few previous studies also found the left middle frontal gyrus to be an important area for reading in alphabetic languages, such as Spanish, English, and Hebrew (Rueckl et al. 2015).

On the other hand, the middle frontal gyrus may also be important for attention (Fan et al. 2005; Xuan et al. 2016). The middle frontal gyrus has been proposed to be a convergence of the dorsal and ventral attention networks; pertinently, the former is in charge of reorienting attention from endogenous stimuli and the latter is in charge of exogenous stimuli (Corbetta et al. 2008; Japee et al. 2015; Suo et al. 2021). Fox et al. identified the ventral attention network involving the ventral prefrontal cortex (inferior frontal gyrus) and temporal parietal junction (superior temporal gyrus and inferior parietal lobule; Fox et al. 2006). The ventral attention network may highly overlap with the language network and mirror the language network in the right brain hemisphere (Bernard et al. 2020). Also, higher functional connectivity within the ventral attention network was linked to better reading performance (Freedman et al. 2020). Moreover, the inferior frontal gyrus was activated in both executive attention and word recognition tasks (Eckert et al. 2009), and the inferior parietal lobe was involved in both selective attention (Mort et al. 2003; Sturm et al. 2011) and phonological processing of reading (Tan et al. 2005; Zhu et al. 2014). However, to our knowledge, it remains unknown whether the middle frontal gyrus and its regulation of the ventral attention network may be shared by both reading and attention development in children. We aimed to examine whether the structural development of the middle frontal gyrus and its functional connectivity to the ventral attention network may mediate the longitudinal prediction between reading and attention capabilities in school-age children.

In sum, this study aimed to examine the mutual predictions between attention and reading development and the neural mediators of these abilities among typically developing school-age children. More than 200 children aged 6–12 years completed assessments on selective attention, executive attention, attention problems, and reading achievement twice with a 1-year interevaluation interval. First, we examined whether attention and reading development may be used to unilaterally or mutually predict each other. We used a series of cross-lagged panel models (CLPMs) to control for baseline performance in attention or reading as well as the covariates including sex, family background, handedness, and scanner centers. We hypothesized that learning to reading could improve attention ability and reduce attention problems and that attention problems and low attention levels would restrict reading development. Second, we examined whether the gray matter volume of the left middle frontal gyrus and its modulation of the ventral attention network may mediate the longitudinal association between reading and attention development among school-age children. We hypothesized that learning to read would enhance one's ability to pay attention by shaping the role of the left middle frontal gyrus and its connection to the ventral attention network.

Methods

Participants

Neuroimaging and behavioral data were obtained from the Children School Functions and Brain Development Project (CBD, Beijing Cohort). Comprehensive assessments included yearly multimodel magnetic resonance imaging (MRI) scans of the brain, physical health, academic achievement, and cognitive and noncognitive functions. Children were recruited from dozens of primary schools in Beijing. Informed consent was obtained from the parents/guardians (written) and children (oral). The exclusion criteria included a history of neurological/psychiatric disorders, the use of psychoactive drugs, significant head injury, and physical illness not suitable for MRI scanning. All study procedures were reviewed and approved by the Institutional Review Boards at Beijing Normal University in accordance with the Declaration of Helsinki.

The initial data collection by May 2019 included 327 children at baseline and follow-up assessments. Among the sample, 290 children completed all MRI scans, attention tasks and reading tasks, and 233 met the requirements of T1 and resting-state functional magnetic resonance imaging (fMRI) data quality criteria at both baseline and follow-up assessments. All 233 children were 6–12 years old (mean age = 9.21 ± 1.33 years at baseline, 10.22 ± 1.36 years at follow-up). More detailed information about the participants are presented in Table 1. There were no significant differences in sex, age, parental education, family income, reading, and attention ability between passed and missed quality control children. The details of the 94 children removed during the quality control process are presented in Supplementary Table S1.

Assessments of reading achievement and attention

Reading achievement test

The reading achievement test was developed by the project team of the National Children's Study of China (NCSC). This test was based on the national curriculum standard and focused on the content domain and capability domain (Dong and Lin 2011). Reading achievement tests evaluated character and word recognition as well as sentence and short passage comprehension. The test established a data model system based on the data of 140,000 Chinese children and adolescents. After inputting children's grades and answers on each test item into the system, it gives a standard score with an average of 500 and a standard deviation of 100, which is the reading score. Based on a well-national representative sample from mainland China, the reading achievement test shows good psychometric properties of reliability and validity. The Cronbach's alpha coefficients were 0.72–0.94. The average difficulty coefficient was 0.69. Children completed the test in a group within 45 min.

Attention

Attention was assessed by the tasks of selective attention and executive attention, and parents reported inattention problems based on the Strengths and Difficulties Questionnaire (SDQ) on a 3-point Likert scale (Goodman 1997). The sums of the scores were computed by adding up the z scores of each task.

Selective attention task

The number cancellation task was used. It was developed by the project team of NCSC (Dong and Lin 2011). The test materials were numbers (0–9) with or without short lines (2, 3, and 4). The target stimulus was the number "9" with 2 short lines, which was not preceded by the number "5." There were 4 consecutive sections, each lasted for 60 s. The total number of hits minus the number of false responses was computed as the score. The Cronbach's alpha coefficient of this task was 0.94, and the test–retest reliability coefficient at a month interval was 0.90. Children completed the task within 10 min.

Executive attention task

The flanker task was adapted from the attention network test (ANT; Rueda et al. 2004). It was designed to be more engaging and child friendly. A stimulus was

Table 1. Characteristics of the study population at baseline and follow-up.

		Baseline ($n = 233$)	Follow-up ($n = 233$)	t Value
Age (mean ± SD)		9.21 ± 1.33	10.22 ± 1.36	
Sex, females, *n* (%)		107 (45.9%)		
Parental education (mean ± SD)		8.45 ± 2.63		
Family income (mean ± SD)		7.39 ± 1.81		
Reading achievements (mean ± SD)		531.40 ± 95.21	559.52 ± 105.98	3.32**
Selective attention (mean ± SD)		95.22 ± 10.01	101.15 ± 10.97	8.35***
Executive attention	RT (ms)	62.05 ± 28.48	56.88 ± 23.82	−2.64**
(mean ± SD)	Error (%)	4.31 ± 6.96	3.59 ± 5.19	−1.47
Attention problem (mean ± SD)		6.24 ± 2.18	5.83 ± 2.28	−3.31**

Note. The parent's education level refers to the highest level of education between children's parents. Parental education: 1 = Uneducated; 2 = Primary education; 3 = Junior school; 4 = High school; 5 = Secondary vocational school; 6 = Polytechnic school; 7 = Higher vocational education; 8 = Junior college (part-time); 9 = Junior college (full-time); 10 = Bachelor degree (part-time); 11 = Bachelor degree (full-time); and 12 = Graduate education or above. Family Income (RMB/year): 1 = Less than 3,000; 2 = 3,001–6,000; 3 = 6,001–10,000; 4 = 10,001–30,000; 5 = 30,001–50,000; 6 = 50,001–100,000; 7 = 100,001–150,000; 8 = 150,001–200,000; 9 = 200,001–400,000; 10 = 400,001–600,000; 11 = Over 600,000. * $P < 0.05$, ** $P < 0.01$, *** and $P < 0.001$.

presented in the center of a computer screen and participants were required to indicate the left–right orientation while inhibiting attention to the surrounding stimuli (the flankers). There were trials in which the orientation of the flankers was congruent with the orientation of the central stimulus and trials in which the flankers were in incongruent orientations. The task consisted of a total of 24 practice trials and 4 blocks of 192 trials. Each block included 16 neutral, 16 congruent, and 16 incongruent trials. The test trials were presented in pseudorandom order. The error and reaction time scores were computed by subtracting the error number and reaction time between the congruent and incongruent trials, respectively, with lower values indicating better performance (Rueda et al. 2004). That is, executive attention (error) = error for incongruent trials—error for congruent trials; executive attention (RT) = RT for incongruent trials—RT for congruent trials. Both the error and reaction time scores were *z*-transformed. The sums of the scores of the executive attention performance were calculated with factor analysis (Moore et al. 2015) by extracting the common factor scores on both accuracy and reaction time data.

Attention problems

The parent-reported version of the SDQ was used to assess symptoms of hyperactivity and inattention (Goodman 1997). The Chinese version was retrieved from the SDQ website (https://www.sdqinfo.org/py/sdqinfo/b3.py?language=Chinese). The SDQ is a reliable and valid measure of child emotional and behavioral symptoms (Goodman 2001). In this study, the Cronbach's α coefficient of this questionnaire was 0.77.

Working memory

Corsi blocks task was adopted to assess the working memory span. The Corsi board with the 9-gray circles was displayed on the screen. Participants have to denote the position of the previously highlighted circle in the order in which the circles were highlighted in turn (forward version) or in reverse order (reverse version). The highlighted sequences were from 2 to 9 circles. The test was terminated if the participant failed to reproduce the highlighted sequence of a certain length correctly after 2 attempts. Only repeated the highlighted sequence completely correctly was scored (Corsi 1972).

Image acquisition

All MRI scans were acquired on two 3T Siemens Prisma scanners with 64-channel head coil at Peking University and Beijing HuiLongGuan Hospital using the same imaging sequences. Blood oxygen level-dependent (BOLD) fMRI was acquired using a whole-brain, single-shot, multislice, echo-planar imaging (EPI) sequence of 240 volumes with the following parameters: repetition time/echo time (TR/TE) = 2,000/30 ms, flip angle = 90°, field of view (FOV) = 224 × 224 mm, matrix = 64 × 64, slice thickness = 3.5 mm, and slices = 33. The resulting nominal voxel size was 3.5 × 3.5 × 3.5 mm. A fixation cross was displayed as images were acquired. Subjects were instructed to stay awake, keep their eyes open, fixate on the displayed blank screen, and remain still. Prior to time-series acquisition, a 6-min magnetization-prepared, rapid acquisition gradient-echo T1-weighted (MPRAGE) image (TR = 2,530 ms, TE 2.98 ms, FOV 256 × 224 mm, matrix, effective voxel resolution of 1 × 1 × 1 mm, slice thickness = 1 mm, and slices = 192) was acquired to aid spatial normalization to standard atlas space. Prior to scanning, to acclimate subjects (children) to the MRI environment, a mock scanning session was conducted for each individual using a decommissioned MRI scanner and head coil. Mock scanning was accompanied by acoustic recordings of the noise produced by gradient coils for each scanning pulse sequence. To further minimize motion, subjects' heads were stabilized in the head coil using one foam pad over each ear.

MRI quality assurance

All MRI scan quality control procedures are described below. (i) Individual images were subjected to a careful visual examination by an experienced radiologist to exclude incidental abnormalities, such as arachnoid cysts, neuroepithelial cysts, and other intracranial space-occupying lesions. (ii) Careful visual inspections with a scan rating procedure were separately conducted by 5 experienced raters using a protocol similar to that used in the Human Connectome Project (Marcus et al. 2013). (iii) Images considered to have a better than fair quality by both raters were retained. We quantified the head motion of resting-state fMRI as framewise displacement (FD) (Power et al. 2012). The participants were also excluded if the mean FD exceeded 0.5 mm during resting-state scans (Xia et al. 2018).

Image analysis

Voxel-based morphometry (VBM) was conducted using the Computational Anatomy Toolbox (CAT12) (http://dbm.neuro.uni-jena.de/cat) and SPM12 (http://www.fil.ion.ucl.ac.uk/spm). T1 images were segmented into gray matter, white matter, and cerebrospinal fluid based on the default settings of CAT12. Next, images were normalized to Montreal Neurological Institute space using the DARTEL approach. The registered gray matter images were multiplied with the Jacobian determinants derived from the spatial normalization (voxel size 1.5 mm^3) process and then smoothed with an 8-mm full-width at half-maximum Gaussian kernel.

Resting fMRI preprocessing was performed using fMRIPrep 1.2.3 (Esteban et al. 2019), which is based on Nipype 1.1.6 (Gorgolewski et al. 2011). Preprocessing included the following steps: (i) head-motion correction; (ii) slice-timing correction; (iii) spatial normalization; (iv) whole-brain and white matter signals and 24 motion parameters being regressed out; (v) spatial smoothing with a 6-mm 3D full-width half-maximum kernel; and (vi) temporal bandpass filtering (0.01–0.1 Hz). For further details regarding image preprocessing and brain network construction, see Supplementary Information, SI Methods.

The mean value in the mask of the overlap between reading-related and attention-related gray matter volume (GMV) was used as a seed region for the connectivity analysis. The blood oxygen level dependent time course was extracted from the seed region, and the correlation coefficients between this time course and all other brain voxels were computed. The correlation maps were then z-normalized using Fisher's r-to-z transformation to approximate a normal distribution. In addition, automated anatomical labeling (AAL) atlas was used for anatomically labeling of the MRI peaks/clusters in this study.

Statistical analysis

Cross-lagged panel analyses were performed using AMOS 21.0 (IBM). All MRI statistical analyses were performed in DPABI software (http://rfmri.org; Yan et al. 2016). Pearson's correlation was used to evaluate gray matter volume and seed-based connectivity, with a significance threshold set at a voxel-size value of $P < 0.001$ and a family-wise error-corrected cluster probability of $P < 0.05$. Brain-behavior correlations were performed using SPSS 21 (IBM). As the directional association between attention and reading ability was determined by the CLPM, we assessed the mediation effect of overlapping clusters identified above. We used the overall attention and reading computed the reading-related and attention-related GMV and functional connectivity. The results are then refined on the 3 subdimensions of the attention. Age, sex, handedness, site, household income, parental education, head motion, and total intracranial volume were controlled as covariates.

Results

Sample characteristics

All sample characteristics are presented in Supplementary Tables S1–S4. Both reading and attention performance increased at the follow-up compared with that at baseline (Table 1). Reading and attention performance differed by sex (Supplementary Table S2), parental education level (Supplementary Table S3), and family income (Supplementary Table S4). Female children (Supplementary Table S2), children from families with higher parental education (Supplementary Table S3), and children with higher income (Supplementary Table S4) showed better reading and attention performance. In the subsequent analysis, sex, parental education level, and family income were controlled as covariates.

The predictive role of reading in attention development

Children's attention and reading performance at baseline and follow-up were significantly correlated (Supplementary Table S5). With the CLPM, we found that higher reading performance at baseline was associated with better selective attention ($\beta = 0.355$, $P < 0.001$, Fig. 1A), better executive attention ($\beta = 0.166$, $P = 0.012$, Fig. 1B), and fewer attention problems ($\beta = -0.114$, $P = 0.027$, Fig. 1C) at the follow-up evaluation. In contrast, neither selective (Fig. 1A) nor executive attention (Fig. 1B) at baseline significantly predicted reading performance 1 year later. Also, more attention problems reported by parents at baseline significantly predicted worse reading performance in 1 year ($\beta = -0.156$, $P = 0.016$, Fig. 1C).

To further examine the robustness of the longitudinal prediction of reading performance to subsequent attention development and the mutual prediction between attention problems and reading development, we conducted a series of CLPM analyses by age group (Supplementary Fig. S1), sex (Supplementary Fig. S2), reading levels (Supplementary Fig. S3), reading experience (Supplementary Fig. S4), and attention development levels (Supplementary Fig. S5). First, neither age ($\chi^2 = 3.110$, $P = 0.078$) nor sex ($\chi^2 = 2.269$, $P = 0.132$) significantly moderated the cross-time prediction between attention and reading development (Supplementary Figs. S1 and S2). Second, reading levels significantly moderated the cross-time prediction between attention and reading development ($\chi^2 = 4.311$, $P = 0.038$, Supplementary Fig. S3), whereas reading experience did not ($\chi^2 = 1.340$, $P = 0.247$,

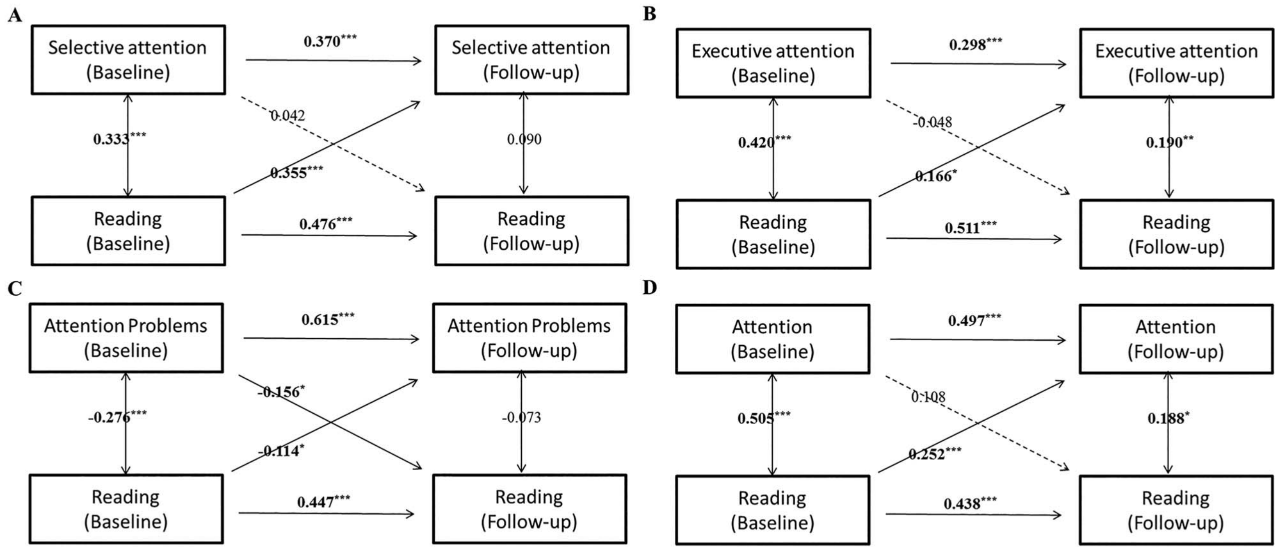

Fig. 1. The cross-time predictions between attention and reading development in school-age children. The CLPMs of A) selective attention, B) executive attention, C) and attention problems, and D) the sum scores of attention and reading development. Standardized estimates are presented. * $P < 0.05$, ** $P < 0.01$, and *** $P < 0.001$.

Supplementary Fig. S4). Among the subgroup with a lower reading level at baseline, reading performance at baseline significantly predicted attention development at the follow-up evaluation; however, such prediction was not significant in the subgroup with a higher reading level at baseline. Third, we used the combined z scores of the 3 indicators of attention to classify children into a lower attention group (z attention < 0) and a higher attention group (z attention > 0; Supplementary Fig. S5). We found that the baseline attention status significantly moderated the cross-time prediction of attention for reading development ($\chi^2 = 4.506$, $P = 0.034$) but not for the prediction of reading performance at baseline for attention problems at the follow-up evaluation ($\chi^2 = 0.26, P = 0.610$). Such findings were consistent with the above results regarding attention problems (Fig. 1C). When children's attention development was at the lower level or when they had attention problems, their reading development may have been delayed.

The shared neural correlates between attention and reading development

To examine whether attention and reading development may share common neural correlates, we conducted a VBM analysis at baseline. We found that better attention was associated with larger gray matter volumes in the frontal gyrus and anterior cingulate gyrus (Supplementary Table S6 and Fig. 2), and better reading was associated with larger gray matter volumes in the frontal gyrus, cingulate gyrus, parietal lobe, parahippocampal gyrus, fusiform gyrus, and cerebellum (Supplementary Table S7 and Fig. 2). Also, the left middle frontal gyrus (190 voxels, MNI coordinated: −21, 41, and 31) was among the brain areas shared by both attention and reading development (Fig. 2).

We further examined whether the spontaneous functional connectivity of the left middle frontal gyrus-related loop may be shared by both attention and reading development. First, based on the above findings that increased gray matter volume in the left middle frontal gyrus was associated with better performance in both reading and attention, we used the mean value of the left middle frontal gyrus mask as a seed region for the functional connectivity analysis. We found that attention performance was significantly correlated with increased connectivity between the left middle frontal gyrus and left ventral frontal cortex (anterior insula/inferior frontal gyrus), among the left and right inferior parietal lobule and right caudate (Supplementary Table S8 and Fig. 3). Also, reading performance was significantly correlated with increased connectivity between the left middle frontal gyrus and left anterior insula/inferior frontal gyrus and between the left inferior parietal lobule and cerebellum (Crus1/Crus2); moreover, reading performance was associated with decreased connectivity between the left middle frontal gyrus and right posterior cingulate (Supplementary Table S9 and Fig. 3). We found the overlapping areas included the inferior frontal gyrus (79 voxels) and inferior parietal lobule (32 voxels; Fig. 3).

Mediation analysis: the mediating roles of increasing volumes of the left middle frontal gyrus and enhancing connectivity to the ventral attention network in the prediction of attention development based on reading ability

We conducted a mediation analysis to understand how structural and functional brain development may mediate the contribution of reading development to subsequent attention development in school-age children. The results showed that the volume of the left middle frontal gyrus (Fig. 4A) and its connectivity to

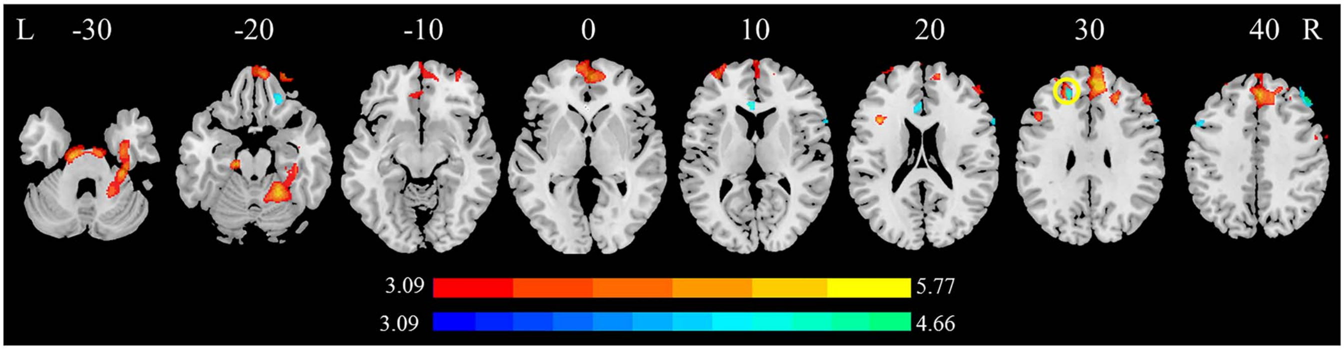

Fig. 2. Significant brain clusters of gray matter volume associated with attention and reading performances at baseline. Red areas indicate those associated with reading, blue areas denote those associated with attention, and yellow areas signify overlapping regions (overlapping in the left middle frontal gyrus). The color bar represents z value. L = left; R = right.

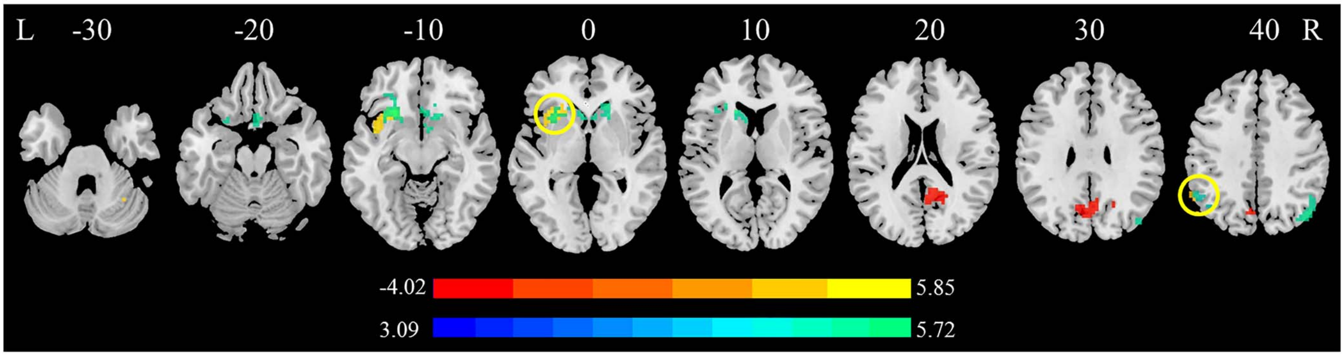

Fig. 3. Significant resting function connectivity with the left middle gyrus was associated with reading and attention performances at baseline. Red areas signify regions associated with reading, blue areas indicate those associated with attention, and yellow circles denote areas that have the overlapping regions (overlap in the left inferior frontal gyrus/insula and inferior parietal lobule). The color bar represents z value. L = left; R = right.

the inferior frontal cortex/insula (Fig. 5A) and inferior parietal lobule (Fig. 6A) significantly mediated the prediction of attention performance based on baseline reading performance at the follow-up. Further analysis showed that reading development may promote the development of executive attention (Fig. 4C) and reduce attention problems (Fig. 4D) by increasing the gray matter volume in the left middle frontal gyrus. Moreover, reading development may promote the development of executive attention by enhancing the connection between the left middle frontal gyrus and the inferior frontal gyrus (Fig. 5C) and promote the development of selective attention by enhancing the connection between the left middle frontal gyrus and the inferior parietal lobe (Fig. 6B).

To exclude the influence of other cognitive abilities, we performed mediation analysis and found that outcomes were not substantially affected after controlling for working memory as a covariate, with detailed results in Supplementary Figs. S6–S8. In addition, we found that attention (Supplementary Table S6) and reading (Supplementary Table S7) were associated with 2 regions of the right middle frontal gyrus, respectively. However, there was no overlap between the 2 regions. We sought the total gray matter volume of these 2 regions at follow-up as the right middle frontal gyrus for mediation analysis and found that the mediation effect was not significant (Supplementary Fig. S9), therefore, reconfirming that the right middle frontal gyrus may not be the brain basis for both reading and attention sharing.

Discussion

This longitudinal study of attention and reading development in school-age children provided novel evidence for understanding the developmental connections between attention and reading. Academic skills, such as reading, may predict the development of important cognitive functions, such as attention, in typically developing school-age children. Neither selective nor executive attention significantly predicted later reading development, whereas attention problems significantly hampered further reading development. In contrast, learning to read significantly improved attention development and mitigated attention problems 1 year later. Moreover, this study identified the middle frontal gyrus as an important mediator center for reading and attention development. The increasing gray matter volume in the left middle frontal gyrus and the increased connectivity to the ventral attention network may support such developmental connections between attention and reading development.

This study directly revealed the longitudinal predictions between attention and reading development in school-age children and found the unique contribution of reading development to attention development that

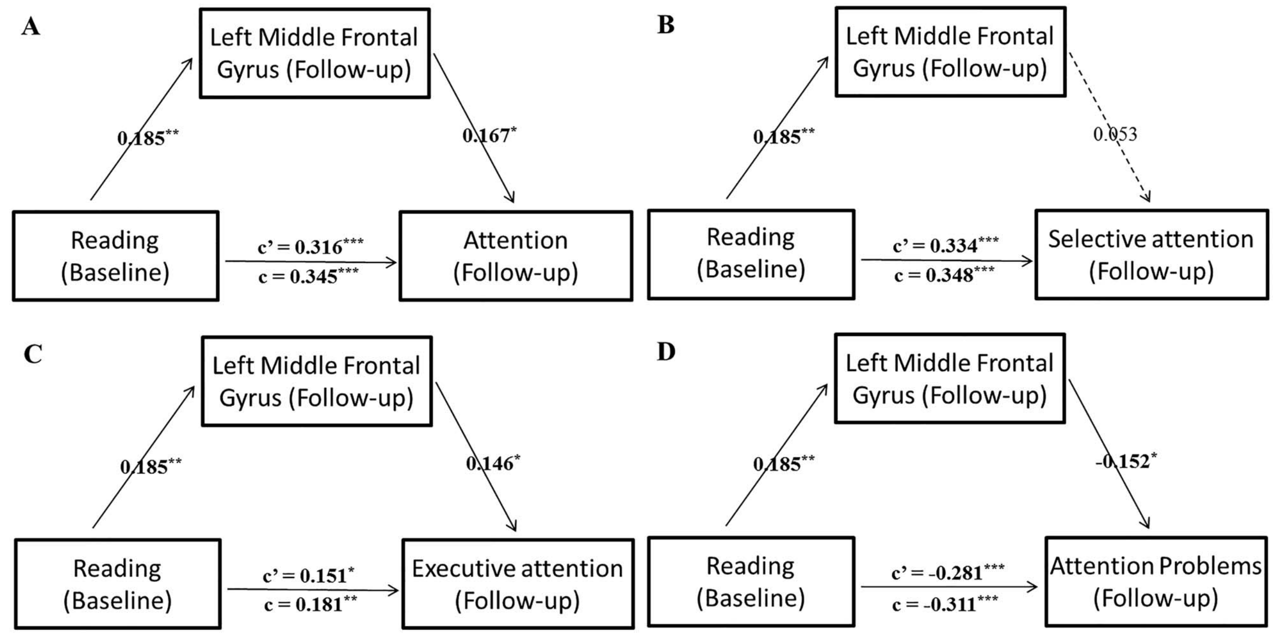

Fig. 4. Associations of average overlapping brain regions in the left middle frontal gyrus, reading achievements and attention ability. Mediation model using reading achievements at baseline as the predictor, gray matter volume of the middle frontal gyrus as the mediator, and attention at follow-up as the dependent variable. Mediation results are shown as unstandardized regression coefficients. The significance of the indirect effect was assessed using bootstrapped confidence intervals. Reading positively predicts the development of A) attention ability (indirect effect, 95% CI = [0.0002, 0.0007]) and C) executive attention (indirect effect, 95% CI = [0.0001, 0.009]) D) and negatively predicts attention problems (indirect effect, 95% CI = [0.0001, 0.008]) by increasing the volume of the left middle frontal gyrus but does not affect B) selective attention (indirect effect, 95% CI = [−0.0002, 0.0004]). Age, sex, handedness, site, household income, parental education, and total intracranial volume were used as covariates of no interest. * $P < 0.05$, ** $P < 0.01$, and *** $P < 0.001$.

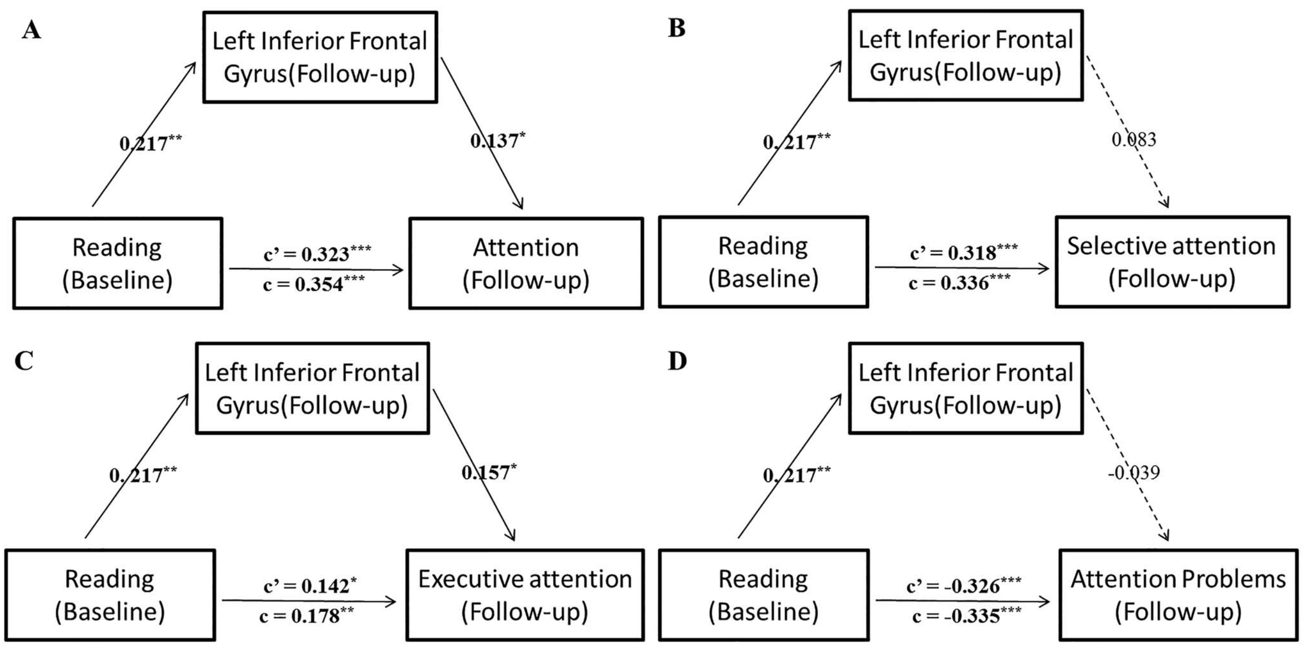

Fig. 5. Associations of the average overlapping connectivity among the left middle frontal gyrus and left inferior frontal gyrus/insula, reading achievements, and attention ability. Mediation model using reading achievements at baseline as the predictor, connectivity as the mediator, and attention at follow-up as the dependent variable. Mediation results are shown as unstandardized regression coefficients. The significance of the indirect effect was assessed using bootstrapped confidence intervals. Reading positively predicts the development of A) attention ability (indirect effect, 95% CI = [0.0001, 0.0006]) and C) executive attention (indirect effect, 95% CI = [0.0001, 0.0008]) by increasing the connectivity of the left middle frontal gyrus and the left inferior frontal gyrus/insula but does not affect B) selective attention (indirect effect, 95% CI = [−0.0001, 0.0006]) or D) attention problems (indirect effect, 95% CI = [−0.0001, 0.0006]). Age, sex, handedness, site, household income, parental education, and head motion were used as covariates of no interest. * $P < 0.05$, ** $P < 0.01$, and *** $P < 0.001$.

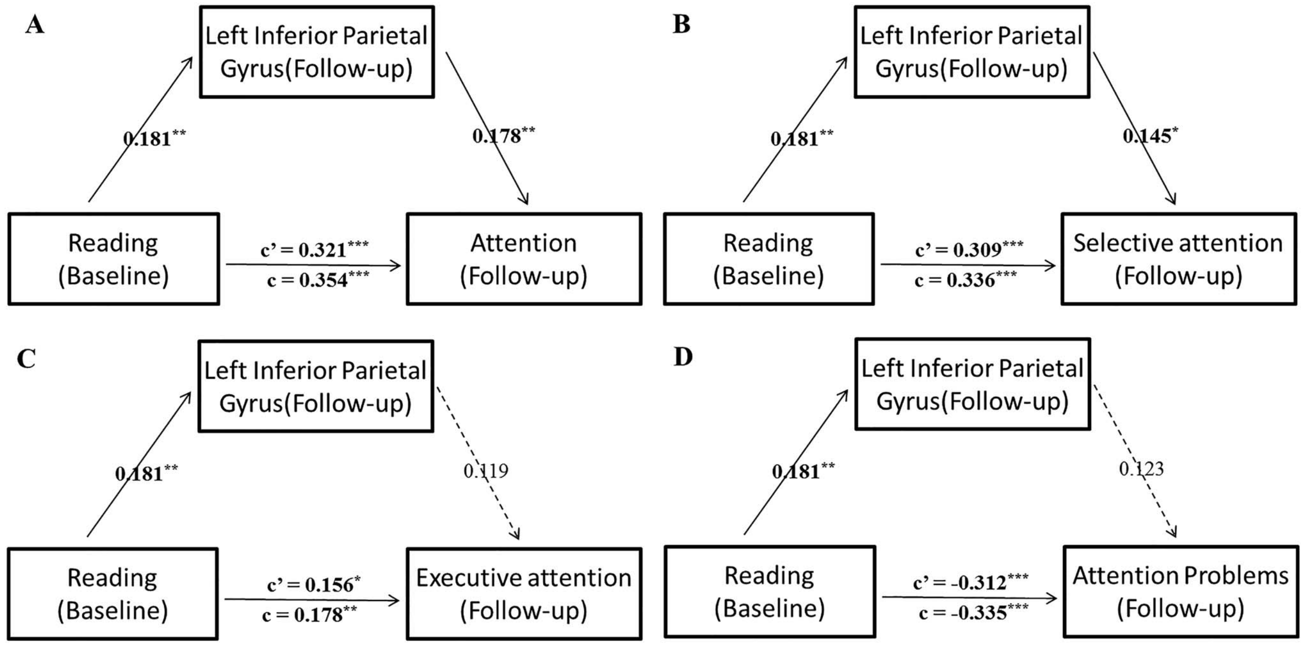

Fig. 6. Associations of average overlapping connectivity among the left middle frontal gyrus and left inferior parietal gyrus, reading achievements and attention ability. Mediation model using reading achievements at baseline as the predictor, connectivity as the mediator, and attention at follow-up as the dependent variable. Mediation results are shown as unstandardized regression coefficients. The significance of the indirect effect was assessed using bootstrapped confidence intervals. Reading positively predicts the development of A) attention ability (indirect effect, 95% CI = [0.0001, 0.0004]) and B) selective attention (indirect effect, 95% CI = [0.0001, 0.0006]) by increasing the connectivity of the left middle frontal gyrus and left inferior parietal gyrus but does not affect C) executive attention (indirect effect, 95% CI = [−0.0002, 0.0005]), or D) attention problems (indirect effect, 95% CI = [−0.0002, 0.0003]). Age, sex, handedness, site, household income, parental education, and head motion were used as covariates of no interest. * $P < 0.05$, ** $P < 0.01$, and *** $P < 0.001$.

persists beyond the preschool years. The longitudinal prediction attention development based on reading ability and the lasting constraints of attention problems on reading development were robust between the subgroups of age, sex, reading experience, and attention performance level. The significant moderating effects of reading levels further confirmed the important roles of reading achievement in attention development. The above consistent and robust findings suggest that learning to read can promote attention development. Previous studies often focused on how cognitive development may help individuals when they are learning to read (Cattell 1987; Deary et al. 2010; Evans and Stanovich 2013). A recent review proposed an examination of the bidirectional relationship between cognitive (i.e. working memory, reasoning, and executive function) and reading development (Peng and Kievit 2020). Since reading involves many cognitive processes, learning to read may offer long-term and highly demanding training for various cognitive abilities, including attention. Therefore, continued reading practice at school may be one great approach not only to reading acquisition but also to cognitive development (Ceci and Williams 1997). The faciliatory role of learning to read in cognitive development may be most obvious during elementary school years when reading is taught systematically and practiced intensively (Peng et al. 2019). In this study, we empirically demonstrated that various attention components indeed improved with better reading performance in elementary school.

On the other hand, attention problems may hinder one's progress in learning to read in elementary school. Attention develops rapidly before schooling (Petersen and Posner 2012), earlier than learning to read (Chall 1983; Foorman et al. 1998; Hill et al. 2008). Previous studies have found that attention at preschool significantly predicted reading performance at elementary school (Rabiner and Coie 2000; Franceschini et al. 2012). This study, on the one hand, found that neither selective nor executive attention significantly predicted reading performance 1 year later. This result suggests that attention may not contribute to variances in reading acquisition for most children with typically developing attention. This is consistent with previous findings that none of the attention tasks significantly accounted for variances in reading development, whereas working memory/cognitive flexibility did account for these variances (Engel de Abreu et al. 2014). In addition, poor attention restricts reading development, as demonstrated in previous research (Greven et al. 2012; Ehm et al. 2016). In this study, we further found that the relationship between attention problems and reading was influenced by the left middle frontal gyrus, a hub for both attention and reading development.

We found that learning to read may promote growth in the left middle frontal gyrus volume and strengthen the connectivity between the left middle frontal gyrus and the ventral attention network. To our knowledge, this is the first empirical evidence showing the mediating roles of the structural growth of the middle frontal gyrus and its functional regulation of the ventral attention network in reading and attention development in typically developing school-age children. The shared brain structural and functional development found in this study may help improve the present understanding of how learning to read may help promote attention development and mitigate attention problems.

The middle frontal gyrus is a common regulatory center for reading and attention. For attention, the middle frontal gyrus may be the convergence point of the dorsal and ventral attention networks; thus, it acts as a circuit breaker that interrupts the ongoing endogenous attentional processes in the dorsal network and redirects attention to exogenous stimuli (Corbetta et al. 2008; Japee et al. 2015; Suo et al. 2021). For reading, particularly for Chinese reading, the middle frontal gyrus is responsible for orthographic, phonological, and semantic processing (Wu et al. 2012a). Among the various brain regions involved in the ventral attention network, the inferior frontal gyrus is responsible for phonological and semantic processing and executive attention, and the inferior parietal lobule is responsible for phonological processing and selective attention (Smith and Jonides 1999; Mort et al. 2003; Ravizza et al. 2004; Sturm et al. 2011). Thus, the middle frontal gyrus regulates both attention and reading. Therefore, the functional connectivity between the middle frontal gyrus and the ventral attention network is an important shared brain basis for attention and reading.

Previous research revealed significant brain structural and functional differences between literate and illiterate adults (Li et al. 2006; Wu et al. 2012b, 2012c). We not only extended previous research to developing child populations but also to show the causal role that reading development may play in cognitive development. This study offers empirical evidence that the gray matter volume increase in the left middle frontal gyrus and its strengthened regulation of the ventral attention network may mediate the longitudinal prediction between reading and attention development. Moreover, this study highlights the relationship between the ventral attention network and reading network during childhood. Studies of illiterate and literate individuals found that learning to read Chinese promoted the development of the middle frontal gyrus (Li et al. 2006), inferior frontal gyrus (Li et al. 2006; Wu et al. 2012b), and inferior parietal lobule (Li et al. 2006; Wu et al. 2012c). Also, one study found that literate individuals exhibited activation in the inferior/middle frontal gyrus and inferior parietal lobule more strongly than illiterate individuals in word recognition and silent picture-naming tasks (Li et al. 2006), suggesting that learning to read may enhance one's cognitive processing efficiency. Another study found that the inferior frontal gyrus of literate individuals not only had stronger activation in orthographic processing but was also associated with better visual–spatial attentional performance compared with that of illiterate individuals (Wu et al. 2012b). The inferior parietal lobule also participates in the processing of phonology and visuospatial processing (Tan et al. 2003). Therefore, the left middle frontal gyrus and ventral attention network are not only important brain regions for attention but are also important for reading and further advance attention development as individuals learn to read.

Could the middle frontal gyrus and its connectivity to the ventral attention network also be shared by other cognitive and academic skills in addition to the connection between attention and reading development? The findings indicate that the answer is no. First, although the middle frontal gyrus is involved in both reading and mathematical operation (Tang et al. 2006), the left middle frontal gyrus is involved in reading and the right is involved in mathematics (Koyama et al. 2017). Second, although the middle frontal gyrus can be involved in other cognitive processes, its regulation of the ventral attention network is unique to attention (Corbetta et al. 2008; Japee et al. 2015; Suo et al. 2021). Third, as the core of the ventral attention network, the inferior frontal gyrus/insula is involved in both executive attention and word recognition (Eckert et al. 2009). The inferior parietal lobule is another core of the ventral attention network. Although working memory and mathematics may also involve the parietal lobe, working memory mainly involves the superior parietal lobule (Olesen et al. 2004; Koenigs et al. 2009), and mathematics involves the intraparietal sulcus (Wilkey et al. 2018). The inferior parietal lobule supports both selective attention (Mort et al. 2003; Sturm et al. 2011) and phonological processing during reading (Smith and Jonides 1999; Ravizza et al. 2004). Finally, after controlling for working memory span scores as a covariate, and we found that working memory did not affect the link between reading, left middle frontal gyrus structure/connectivity, and attention. Therefore, the mediating roles of the left middle frontal gyrus and ventral attention network may be specific to the developmental connection between reading and attention.

Limitations

Several limitations of this study should be noted and need further research. First, in this study, we used a CLPM to examine the longitudinal relationship between attention and reading development after 1 year, which offered important empirical evidence for our understanding of the connection between attention and reading development. Future studies may further address this important question over a longer period. Second, we used VBM and resting-state fMRI to examine the brain correlates for the connection between attention and reading development and found an important pathway between the middle frontal gyrus and ventral attention network. Task-fMRI data of attention and reading tasks performed by children throughout school years may help clarify how this pathway functions and changes due to age, attention, and reading development. Third, we used the sums of the z scores of each attention task as overall attention. Recently, some studies have found this practice may lead to Berkson's bias (McNeish and Wolf 2020; Haslbeck et al. 2021). Future studies can directly verify the results of this study by using the comprehensive attention test. Fourth, we found that better reading skills at the baseline were associated with both better executive attention and fewer attention problems at the follow-up, but these correlations were relatively weak. Therefore, future studies may be referred to with caution. Finally, although we confirmed that the mediating roles of the left middle frontal gyrus and ventral attention network in the developmental connection between reading and attention by reviewing previous literature and controlling for covariates (such as working memory). However, in addition to working memory, there are many other cognitive abilities, such as cognitive flexibility, requiring further verification to illustrate the specificity of the conclusions of this study for attention.

Conclusion

Learning to read help may help promote selective and executive attention and reduce attention problems. And attention problems restrict further reading development. The increasing gray matter volume of left middle frontal gyrus and its enhancing connectivity to the ventral attention network may serve as the neural mediators for the connection between reading and attention development. Altogether, learning to read may help promote children's attention development, by facilitating brain structural and functional development.

Authors' contributions

Sha Tao, Yanpei Wang, Shaozheng Qin, Yong He, and Qi Dong conceived and designed the study; Yanpei Wang, Mingming Hu, Jie Luo, Gai Zhao, Haoran Guan, and Leilei Ma collected the data under the supervision of Sha Tao, Shuping Tan, Weiwei Men, and Jia-Hong Gao; Yanpei Wang, and Jie Luo performed data analysis under the supervision of Congying Chu and Sha Tao; Yanpei Wang and Sha Tao wrote the manuscript; Yanpei Wang, Sha Tao, Leilei Ma, and Haoran Guan amend and proofread the draft of the paper. All authors reviewed and commented on the study and manuscript.

Supplementary material

Supplementary material can be found at *Cerebral Cortex* online.

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