Atypical relationships between neurofunctional features of print-sound integration and reading abilities in Chinese children with dyslexia

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Running Title: Print-sound integration in Chinese dyslexia

Abstract

Conquering grapheme-phoneme correspondence is necessary for developing fluent reading in alphabetic orthographies. In neuroimaging research, this ability is associated with brain activation differences between the audiovisual congruent against incongruent conditions, especially in the left superior temporal cortex. Studies have also shown such a neural audiovisual integration effect is reduced in individuals with dyslexia. However, existing evidence is almost restricted to alphabetic languages. Whether and how multisensory processing of print and sound is impaired in Chinese dyslexia remains underexplored. Of note, semantic information is deeply involved in Chinese character processing. In this study, we applied a functional magnetic resonance imaging audiovisual integration paradigm to investigate the possible dysfunctions in processing character-sound pairs and pinyin-sound pairs in Chinese dyslexic children compared with typically developing readers. Unexpectedly, no region displayed significant group difference in the audiovisual integration effect in either the character or pinyin experiment. However, the results revealed atypical correlations between neurofunctional features accompanying audiovisual integration with reading abilities in Chinese children with dyslexia. Specifically, while the audiovisual integration effect in the left inferior cortex in processing character-sound pairs correlated with silent reading comprehension proficiency in both dyslexia and control group, it was associated with morphological awareness in the control group but with rapid naming in dyslexics. As for pinyin-sound associations processing, while the stronger activation in the congruent than incongruent conditions in the left occipito-temporal cortex and bilateral superior temporal cortices was associated with better oral word reading in the control group, an opposite pattern was found in children with dyslexia. On the one hand, this pattern suggests Chinese dyslexic children have yet to develop an efficient grapho-semantic processing system as typically developing children do. On the other hand, it indicates dysfunctional recruitment of the regions that process pinyin-sound pairs in dyslexia, which may impede character learning.

Keywords

audiovisual integration, character, Chinese, dyslexia, individual differences, pinyin

Highlights

- Neural bases of print-sound integration in Chinese children with and without dyslexia are investigated.
- Dyslexia shows atypical relationships between neurofunctional features of audiovisual integration in the reading network and different aspects of reading.
- Chinese children with dyslexia are likely to use inefficient strategies to process characters and pinyin.

1 Introduction

Reading consists of multiple cognitive processes, and it takes years of formal instruction to achieve a high proficiency level. During this process, establishing a robust correspondence between orthographic code (e.g., grapheme) and phonologic representation (e.g., phoneme) is one initial and fundamental step (Perfetti & Harris, 2013). Behavioral and neuroimaging studies of alphabetic languages reveal that it is critical to conquer the grapheme-phoneme correspondence (GPC) rules to develop fluent reading skills. The failure will impede establishing efficient grapho-semantic mapping and eventually result in reading difficulties such as dyslexia (Blomert, 2011; Di Folco, Guez, Peyre, & Ramus, 2020; Richlan, 2019; Shaywitz, 1998). However, while the manifestation of dyslexia is associated with linguistic features in a given language (Richlan, 2020), whether and to what extent grapho-phonological processing is impaired in Chinese children with dyslexia remains underexplored, especially at the neurofunctional level.

Chinese has a morpheme-based logographic writing system (Perfetti, Cao, & Booth, 2013). Semantics is strongly involved in, even at the most fundamental processing level—character recognition, in addition to grapho-phonological mapping (Bi, Han, Weekes, & Shu, 2007; Guan, Fraundorf, & Perfetti, 2020; Liu et al., 2017; Yang, Shu, McCandliss, & Zevin, 2013; Zhao et al., 2014). At the behavioral level, longitudinal and meta-analytic studies have demonstrated the importance of both phonological-related (e.g., phonological awareness [PA], rapid naming [RAN]) and semantic-related (e.g., morphological awareness [MA]) skills in Chinese reading development and impairments (Pan et al., 2016; Lei et al., 2011; Liu et al., 2017; Ruan, Georgiou, Song, Li, & Shu, 2018). However, most tasks used in these studies require explicit processing of the written scripts. Hence, whether implicit and automatic processing is impaired in dyslexia remains largely unknown. A similar situation exists at the brain level. Previous functional magnetic resonance imaging (fMRI) studies revealed hypoactivation in the left inferior and middle frontal areas during visual rhythming and visual lexical decision in children with dyslexia, suggesting dysfunctions of the neural substrates underlying both print-to-sound and print-to-meaning mappings in tasks requiring explicit processing (Cao et al., 2016; Liu et al., 2012; Siok, Perfetti, Jin, & Tan, 2004). Paralleling the fMRI research, structural and diffusion imaging studies also provided evidence on alterations in these regions and white matter tracts connecting them (Siok, Niu, Jin, Perfetti, & Tan, 2008; Su et al., 2018; Xia, Hoeft, Zhang, & Shu, 2016). While these findings indicate deficits in grapho-semantic and grapho-phonological processing in Chinese children with dyslexia, evidence about the automaticity remains scarce.

In this study, we adopted the fMRI audiovisual paradigm, which is appropriate for investigating automaticity in reading-related processing. This paradigm has been used in shallow orthographies such as Dutch and demonstrated the impaired letter-sound automatized integration as a likely proximal cause of dyslexia that is independent of phonological processing deficits (Blau et al., 2010; Blau, van Atteveldt, Ekkebus, Goebel, & Blomert, 2009; Blau,

van Atteveldt, Formisano, Goebel, & Blomert, 2008). This paradigm's basic logic is that if a brain area integrates auditory and visual inputs, the neural responses should differ between congruent versus incongruent conditions. This effect is usually named “congruency effect” when the activation in the congruent condition was stronger than the incongruent condition and is named “incongruency effect” otherwise. Here we used the term “audiovisual integration effect” given that both directions indicate successful multimodal information integration. Since it has been repeatedly observed when no task or a passive task is used, researchers regard the condition differences to reflect implicit processing (Blau et al., 2010; van Atteveldt, Formisano, Goebel, & Blomert, 2007). To date, this audiovisual integration effect has been demonstrated in skilled adult readers and typically developing children (Blau et al., 2010; van Atteveldt & Ansari, 2014; van Atteveldt, Formisano, Goebel, & Blomert, 2004; van Atteveldt, Formisano, Blomert, & Goebel, 2007).

Of importance, the direction and strength of this effect can be affected by several factors, including characteristics of the participants and orthographic depth (Blau et al., 2010; Blau et al., 2009; Holloway, van Atteveldt, Blomert, & Ansari, 2015; Kronschnabel, Brem, Maurer, & Brandeis, 2014; Wang, Karipidis, Pleisch, Fraga-Gonzalez, & Brem, 2020). Researchers found that children with dyslexia showed atypical patterns in brain areas such as the superior temporal cortex (STC) (Blau et al., 2010; Blau et al., 2009). It was mainly driven by the hypoactivation in the congruent condition in dyslexia, indicating a reduced neural integration, along with higher activation in the incongruent condition, indicating a lack of suppression. In terms of orthography depth, recently, similar paradigms have been applied in studies with Chinese adults (Xu, Kolozsvari, Oostenveld, Leppanen, & Hamalainen, 2019) and typically developing children (Xia et al., 2020). In particular, Xia et al. (2020) used Chinese characters (deep orthography) and pinyin (a transparent alphabetic coding system that represents the pronunciation of characters, which is taught at the earliest stage of Chinese reading development and used as a scaffold in learning new characters) as experimental materials and observed a significant audiovisual integration effect (congruent < incongruent) in the left inferior frontal cortex (IFC) and bilateral STC for characters. Moreover, this effect in the left IFC in response to character-sound pairs and that in the left STC in response to pinyin-sound pairs were associated with children’s performance in silent reading comprehension that relies on grapho-semantic mapping and oral word reading that relies on grapho-phonological processing, respectively. In the current study, we aimed to examine the impaired audiovisual integrations of character-sounds and pinyin-sounds and their associations with different reading abilities in Chinese dyslexia with the same design.

Notably, while the group comparison approach has been widely used to identify neural deficits in dyslexia, approaches focusing on individual differences also provide valuable insights. In this case, brain-behavior correlation is a useful strategy (Jednorog et al., 2015; Pernet, Andersson, Paulesu, & Demonet, 2009). Two primary patterns can be identified with it. The first is a universal correlation between brain and behavioral performance regardless of group,

which indicates the neural system supports the cognitive processing in both groups. For example, children's PA was correlated with the microstructural feature of the left arcuate fasciculus, even after controlling reading status (dyslexic; typical) (Su et al., 2018; Vandermosten et al., 2012). Alternatively, there could be distinct ways in which reading abilities correlated with brain measures between children with and without dyslexia, indicating either dysfunction or compensation (Hoeft et al., 2011; Pernet et al., 2009; Rumsey et al., 1999; Tschentscher, Ruisinger, Blank, Diaz, & von Kriegstein, 2018). For example, while the typical readers relied more (higher regional cerebral blood flow) on the left inferior parietal lobule (IPL), higher activation in this area was associated with worse reading performance in dyslexia (Rumsey et al., 1999). However, in previous studies, correlation analyses were commonly conducted across the dyslexic and control groups. Since the subjects were selected on purpose, group differences could drive the results (Blau et al., 2010). As mentioned above, this issue can be addressed by controlling the effect of group in the statistic model or directly comparing correlations between dyslexia and typical readers.

To summarize, the main aim of the present study was to examine the impairment of print-sound integration and related processes in Chinese dyslexia. We asked two specific questions. First, whether the neurofunctional correlates of print-sound integration differ between Chinese children with and without dyslexia. Second, whether the relationships between such neural features and reading abilities differ between the two groups. For this, we adopted an fMRI audiovisual paradigm and used characters-sound pairs and pinyin-sound pairs as materials. Both group comparison and individual differences analytic approaches were performed. Based on the prior research in typically developing children (Xia et al., 2020), we predicted that Chinese children with dyslexia would show a reduced audiovisual integration effect. In addition, dyslexic children may also display atypical brain-behavior correlations or recruit other brain regions to integrate cross-modal information.

2 Methods

2.1 Participants and behavioral measures

Initially, one hundred children in grades 3-6 (45 dyslexia) from local elementary schools attended the experiment. According to inclusion criteria, 23 dyslexic children (10 girls; age 111-144 months, *M* [*SD*] = 122 [10]) were included in the final analysis. Twenty-one children were excluded due to uncompleted data collection (n = 9), head motion artifact (n = 9), and poor in-scanner performance (n = 3). One child with a history of dyslexia diagnosis but performed well in the character recognition task at the time of data collection was also excluded (this child had received an intensive behavior intervention program before). The control group consisted of 22 typically developing children (12 girls; age 118-140

months, *M* [*SD*] = 127 [6]) who were chosen to match the dyslexic group on grade, age, and sex.

In this study, dyslexia was operationalized by the criteria of having normal intelligence (⩾ 80 on the abbreviated version of the *Chinese Wechsler Intelligence Scale for Children* (Wechsler, 1974)) but manifesting reading difficulty (below -1 *SD* of the norm on a standardized reading screening task *Character Recognition* (Xue, Shu, Li, Li, & Tian, 2013)). All the children in the control group had normal intelligence (≥ 80) and scored above -0.5 *SD* of the norm on the reading screening task (the aim was to increase the gap in reading skills between the two groups). In addition, children in both groups were all right-handed (Oldfield, 1971) native speakers of Chinese, with normal hearing and normal or corrected-to-normal vision and were free from neurological or psychiatric disorders. Finally, only the children that completed 4 task fMRI runs, with an overall accuracy equal to or higher than 75% in the in-scanner passive task and less than 25% time-points labeled as outliers (i.e., "bad volume") in each run (data preprocessing section) were included.

Each child received a battery of behavioral tests on reading and cognitive-linguistic skills individually in a silent room on the same day of the MRI session. The reading measurements contained: (1) an untimed character naming task (*Character Recognition*) to estimate the number of characters children had conquered (Xue et al., 2013); (2) an oral word reading task (*Word List Reading*) to measure how fast the participant accurately retrieved phonological representation from visually presented high-frequency two-character words (Zhang et al., 2012); and (3) a timed comprehension task (*Silent Reading Comprehension*) to assess the proficiency of meaning access and semantic judgment (Lei et al., 2011). In addition, PA, RAN, and MA—the three most critical cognitive-linguistic skills in Chinese reading acquisition—were measured by *Phoneme Deletion* (Li, Shu, McBride-Chang, Liu, & Peng, 2012), *Digit RAN* (Liu et al., 2017), and *Morphological Production* (Shu, McBride-Chang, Wu, & Liu, 2006).

Written informed consents were obtained from all the children and their guardians after a detailed explanation of the objectives and procedure of the study. After the experiment, each child received one book and a set of stationery as compensation. This study was approved by the Institutional Review Board of the State Key Laboratory of Cognitive Neuroscience and Learning at Beijing Normal University, and data collection was conducted in 2018.

2.2 Experimental design

This study adopted the audiovisual paradigm that has been repeatedly used in the previous studies investigating letter-sound integration (**Figure 1**). The details about the stimuli and procedure can also be found in Xia et al. (2020). In brief, 56 high-frequency ($M \pm SD = 929 \pm 1486$ per million; Chinese Single-Character Word Database; https://blclab.org/pyscholinguistic-norms-database/) pictographic characters that are frequently used as radicals in phonograms were

selected. These characters are visually simple (number of strokes: $M = 4.34$, *Range* = 1-9) and learned early (age of acquire: $M = 3$ years, *Range* = 2-5 years). The pinyin spellings of these characters were used as the visual stimuli in the pinyin experiment. The auditory stimuli (duration: $M \pm SD = 476.3 \pm 87.5$ ms) were the characters' sounds (i.e., syllables). A native Chinese male recorded the audio files with a sampling rate of 44.1 kHz and 16-bit quantization, then normalized to 85 dB and bandpass (100-4000 Hz) filtered with Audacity (https://www.audacityteam.org/).

The study consisted of 4 task fMRI runs, with the first 2 for the pinyin experiment and the last 2 for the character experiment. Using such a fixed order was to prevent priming from characters on visually presented pinyin stimuli. Two unimodal (auditory [Aud]; visual [Vis]) and two cross-modal conditions (congruent [avC]; incongruent [avI]) were created for both the character and pinyin experiments (**Figure 1**). In this study, we focused on the audiovisual integration effect (i.e., the activation difference between the congruent condition against the incongruent condition). A block design was used to present stimuli. There were 8 task blocks (duration = 20.8 s; 2 for each condition) interleaved with 9 rest blocks (duration = 20.8 s) in a single run. A task block contained 4 mini-blocks. A 1.5 s period was used to collect a whole-brain volume within each mini-block, and a silent period of 3.7 s was used to present stimuli (see "image acquisition" part). The stimuli were presented in white at the center of a black background ("*KaiTi*" font, 96 pt for characters; "*Century Schoolbook*" font, 90 pt for pinyin). A crosshair was presented at the center of the screen whenever there was no stimulus. To help children keep their attention on the stimuli while avoiding explicit congruency judgment, we used a target detection task (Blau et al., 2010). Specifically, in each task block, two out of 16 experimental stimuli were randomly replaced with the auditory target (440 Hz pure tone), visual (an unpronounceable symbol) target or their combination. The participant was asked to press a button with the right index finger as accurately and quickly as possible whenever the target appeared.

Insert Figure 1 about here

2.3 Image acquisition

All brain images were collected at Beijing Normal University Imaging Center for Brain Research using a 3-Tesla Siemens MAGNETOM Trio Tim scanner with a 12-channel head coil. The children first attended a training session to get familiar with the experimental environment and the scanning noise. During the formal scan, foam pads were used to hold their heads secure during scanning to improve image quality. Between sequences, children were told to relax to reduce the fatigue effect. For each participant, 2 functional runs for the pinyin experiment, one run for anatomical images, and 2 functional runs for the character experiment were administered sequentially. The quality of the brain

images was evaluated immediately by a radiologist who was blinded to the details of this study.

The parameters of the functional images (Gradient Echo Planar Imaging [EPI]) were: repetition time, 5.2 s; echo time, 32 ms; acquisition time, 1.5 s; flip angle, 90 degrees; slice thickness, 4.5 mm; interscan gap, 0.675 mm, voxel size, $3.0 \times 3.0 \times 4.5$ mm^3; 24 slices; 68 volumes). Since this study contained auditory stimuli, to avoid artifacts induced by the noise during scanning, a sparse sampling with 1.5 s for image collection and 3.7 s delay for stimuli presentation was used (Shah et al., 2000). The parameters of the structural images (Magnetization-Prepared Rapid Acquisition with Gradient Echo [MPRAGE]) were: repetition time, 5.2 s; echo time, 3.39 ms; inversion time, 1.1 s; flip angle, 7 degrees; slice thickness, 1.33 mm; interscan gap, 0 mm; voxel size, $1.3 \times 1.0 \times 1.3$ mm^3; 144 axial slices).

2.4 Data preprocessing

Functional data were analyzed with SPM12 (http://www.fil.ion.ucl). Since dummy scans were added at the beginning of each run to avoid the T1 equilibration effect, no additional volumes were discarded during the preprocessing. The sequence was then corrected for head motion. The "bad volumes" were identified with ART-based outlier detection (https://www.nitrc.org/projects/artifact_detect). Considering the age range of participants, a liberal threshold (intensity > 9 *SD*; frame-to-frame head motion > 2 mm) was used. T1 images were segmented and used for transferring the fMRI data from native space to the standard Montreal Neurological Institute (MNI) space. The normalized images were smoothed with an 8-mm Full-Width Half-Maximum Gaussian kernel, and the resulting data were used in the subsequent model estimation. In the 1st level analysis, 4 experimental conditions, 7 parameters for head motion (3 for translations, 3 for rotations, and 1 for framewise displacement), and the time point of each "bad volume" were included in the model. The contrast map referring to the difference between avC against avI conditions (positive value stands for higher activation in avC than avI; negative value stands for lower activation in avC than avI) was calculated for each child and used in the subsequent analyses.

2.5 Statistics

Reading and reading-related cognitive impairments in children with dyslexia were examined at the behavioral level. We first performed descriptive statistics and then compared children's performance in multiple behavioral tasks between groups. Next, we calculated correlations between reading and cognitive-linguistic skills within each group and compared between groups. For the variable that was not normally distributed, the Spearman method was used.

As for in-scanner performance, a correct response was defined as the button press to the target between 200 and 2000 ms. Only the correct trials were used to calculate the average reaction time (RT). Finally, the effects of group and

run and their interaction were examined on accuracy (ACC) and RT with analysis of variance (ANOVA).

We conducted brain analyses focusing on the differences between the two cross-modal conditions (i.e., audiovisual integration effect) for character and pinyin experiments, respectively, with the same analytic approaches. The nuisance variables of age, sex, and performance IQ were controlled in all the analyses. First, a voxel-wise whole-brain 2 (group: control vs. dyslexic) × 2 (condition: avC vs. avI) ANOVA (i.e., the group comparison approach) was conducted to examine whether the brain regions showing the audiovisual integration effect in children with dyslexia were the same as the control group. Significant clusters were identified with the FWE-corrected threshold of p-cluster < 0.05 (p-voxel < 0.001 for height). These clusters were then used as regions-of-interest (ROIs), and post hoc t-tests were conducted to interrogate the effects. Complementary ROI analyses were performed to examine correlations between the magnitude of the neural integration effect with reading and reading-related cognitive-linguistic skills in each group, to identify the reading-related processes most involved in audiovisual integration of character/pinyin for typical and dyslexic children, respectively. Once a significant correlation was revealed, we further conducted a correlation coefficients comparison between groups.

Next, we used two individual differences approaches to examine the shared and differential brain-behavior correlations in children with and without dyslexia in the character and pinyin experiments at the whole-brain level. First, to identify the shared neural basis associated with behavioral performance between groups, we conducted voxel-wise whole-brain regression analyses on the contrast maps of avC against avI across all the participants while controlling for reading status (i.e., dyslexic; control), age, sex, and performance IQ. Children's performance in *Word List Reading* and *Silent Reading Comprehension* tasks were used as regressors in separate models to examine the relationships between neural processing features during print-sound integration with reading abilities that rely more on grapho-phonological mapping and grapho-semantic mapping, respectively. Second, we examined whether the relationships between the neurofunctional features of multisensory processing and reading abilities differ between the two groups. Same as the previous analysis, we used *Word List Reading* and *Silent Reading Comprehension* scores as variates of interest in separate models, along with the factor of group and the interaction. In each analysis, an F-test was administered with the FWE-corrected threshold of p-cluster < 0.05 (p-voxel < 0.001 for height), followed by ROI analysis to interrogate the significant effects.

To visualize results, significant clusters were presented on a FreeSurfer surface template with BrainNet Viewer (Xia, Wang, & He, 2013). Anatomical labeling was performed by using the AAL atlas with DPABI (http://rfmri.org/dpabi).

All the behavioral and ROI analyses were administered with SPSS (v24; SPSS Inc., Chicago, IL, USA). Effects were considered significant at $p < 0.05$, and $0.05 < p < 0.1$ was considered indicative of a trend.

3 Results

3.1 Behavior

3.1.1 Description of reading measures and group comparisons

Statistical metrics including *M*, *SD*, *Range*, and result of the Shapiro-Wilk test of each behavioral measurement were presented in Table 1 (see Supplementary Figure 1 for plots). The dyslexic group performed worse in all the reading and reading-related cognitive-linguistic tasks than typically developing children (all *p*'s < 0.007). No significant differences were found between the two groups on age or sex (both *p*'s > 0.05). In addition, the IQs of all the children were within the normal range, while typical readers had higher scores on both verbal and performance sub-scores.

Insert Table 1 about here

3.1.2 Correlations between reading and reading-related cognitive skills

Same and differential correlations between reading and cognitive-linguistic skills were revealed between children with and without dyslexia. In typical readers, character recognition was significantly correlated with MA ($r = 0.589$, $p = 0.004$) but not PA ($r = 0.117$, $p = 0.606$) or RAN ($r = -0.301$, $p = 0.174$). In dyslexics, however, this ability was associated with PA ($r = 0.489$, $p = 0.018$), but not RAN ($r = -0.269$, $p = 0.214$) or MA (r = 0.008, p = 0.970). The group difference on the correlation coefficients between character recognition and MA was significant ($Z = 2.09$, $p = 0.037$). A similar pattern was found in reading comprehension proficiency, where the scores were correlated with MA ($r = 0.456$, $p = 0.033$) in controls but not dyslexia ($r = -0.012$, $p = 0.957$). On the contrast, oral reading fluency was significantly correlated with RAN in both groups (controls: $r = -0.531$, $p = 0.012$; dyslexics: $r = -0.578$, $p = 0.004$).

3.1.3 In-scanner performance

The aim of using a passive target detection task was to ensure the participant focused their attention on the stimuli delivered via auditory and visual modalities. The results revealed that children in both groups performed the task with high ACC (controls: *M* [SD] = 96.7% [2.9]; dyslexics: *M* [*SD*] = 92.4% [5.0]). In the ANOVA, the main effects of group were significant on both ACC ($p = 0.001$) and RT ($p = 0.012$). The post-hoc analyses showed that the children with

dyslexia had lower accuracy and used more time to complete the tasks than the normal controls. The main effect of run was significant on RT (p = 0.012; faster as the experiment proceeds) but not ACC (p = 0.645). No significant group × run interaction was observed on either ACC or RT (both p's > 0.05).

Insert Table 2 about here

3.2 fMRI

We used group comparison (ANOVA), and individual differences (brain-behavior correlation) approaches to investigate impaired neurofunctional features accompanying print-sound integration in Chinese children with dyslexia. In this section, we first present the character experiment results, followed by the pinyin experiment.

3.2.1 Character: whole-brain ANOVA and ROI analysis

In the voxel-wise whole-brain 2 (group) × 2 (condition) ANOVA, we observed the left IFC and STC showed a significant main effect of condition that survived the FWE corrected p-cluster < 0.05 (p-voxel < 0.001 for height; **Table 2**; **Figure 2A**). The follow-up analysis revealed a similar pattern of lower activation in the congruent than incongruent conditions in both the control (LIFC: t = 4.361, p < 0.001; LSTC: t = 3.646, p = 0.002) and the dyslexic (LIFC: t = 2.346, p = 0.028; LSTC: t = 3.427, p = 0.002; **Figure 2B**). No main effect of group or group × condition interaction survived the whole-brain FWE correction.

In the complementary ROI analyses, we observed similar correlations in the two groups between the audiovisual integration effect and reading comprehension proficiency in the left IFC (controls: r = 0.571, p = 0.011; dyslexics: r = 0.391, p = 0.088, marginally significant; **Figure 2C**). Interestingly, distinct contributions of the cross-modal conditions within each group were observed. To be specific, the correlation was driven by the incongruent condition in typical readers (avC: r = 0.222, p = 0.360; avI: r = -0.526, p = 0.021) but was related to the congruent condition in dyslexia (avC: r = 0.400, p = 0.080, marginally significant; avI: r = -0.185, p = 0.436). Group difference on the correlation coefficients between reading comprehension proficient and brain activation in the incongruent condition was significant (Z = 2.41, p = 0.016). Correlations between the audiovisual integration effect and reading-related cognitive skills further support the idea that different mechanisms underlie the integration-comprehension relationships in the two groups (**Figure 2C**): the audiovisual integration effect in this region was correlated with MA in the controls (r = 0.551, p = 0.014) but not in the dyslexics (r = -0.025, p = 0.915). Group difference on the correlation coefficients was significant (Z = 2.01, p = 0.044). On the other hand, the effect was correlated with RAN in the dyslexics (r = -0.509, p = 0.022) but not in the controls (r = -0.338, p = 0.157).

3.2.2 Character: whole-brain group × reading interaction

Regarding the individual differences approach, no significant clusters survived the FWE-corrected threshold of *p*-cluster < 0.05 (*p*-voxel < 0.001 for height) in the analysis investigating relationships between the neural audiovisual integration effect and reading abilities across or that explored the difference between groups.

Insert Figure 2 about here

3.2.3 Pinyin: whole-brain group comparison

The same analytic approach was used in the pinyin experiment. In the voxel-wise whole-brain 2 (group) × 2 (condition) ANOVA, no regions showed significant main effect or interaction at the FWE corrected threshold of *p*-cluster < 0.05 (*p*-voxel < 0.001 for height).

3.2.4 Pinyin: whole-brain group × reading interaction and ROI analysis

Then, we investigated the neural deficits with the individual differences approaches in a whole-brain fashion. While no region displayed significant brain-behavior correlation similar across groups, clusters located in the left occipitotemporal cortex (OTC) and bilateral STC showed significant group differences in the correlation between the audiovisual integration effect and oral reading fluency (FWE corrected *p*-cluster < 0.05, *p*-voxel < 0.001 for height; **Table 2**; **Figure 3A**). The subsequent analyses revealed positive brain-reading correlations in typical readers and negative correlations in children with dyslexia (**Figure 3B, C and D; Table 3**). Furthermore, the correlations in the left OTC (avC: $r = 0.685$, $p = 0.001$; avI: $r = 0.118$, $p = 0.631$) and STC (avC: $r = 0.588$, $p = 0.008$; avI: $r = -0.014$, $p = 0.956$) were driven by the congruent condition in the control group, while fluent oral reading was not correlated with brain activation of the right STC in either congruent ($r = 0.240$, $p = 0.321$) or incongruent condition ($r = -0.259$, $p = 0.284$). In contrast, in dyslexia, the correlations were driven by the avI condition (left OTC: $r = 0.674$; $p = 0.001$; left STC: $r = 0.445$, $p = 0.049$; right STC: $r = 0.543$, $p = 0.013$) but not the avC condition (left OTC: $r = 0.026$, $p = 0.913$; left STC: $r = -0.050$, $p = 0.833$; right STC: $r = -0.181$, $p = 0.444$) in all three regions. Group differences on the correlations were significant between fluent oral reading and activation in the congruent condition in the left OTC ($Z = 2.54$, $p = 0.011$) and left STC ($Z = 2.26$, $p = 0.024$), and between fluent oral reading and activation in the in incongruent condition in the left OTC ($Z = -2.18$, $p = 0.029$) and right STC ($Z = -2.73$, $p = 0.006$).

Regarding correlations between neural audiovisual integration effect (avC-avI) with reading-related cognitive-linguistic skills, the left STC was

negatively associated with RAN in controls (r = -0.479, p = 0.038) and showed a trend positively correlated with RAN in dyslexics (r = 0.394, p = 0.085, marginally significant). Group difference was significant (Z = -2.93, p = 0.003).

Insert Figure 3 about here

Insert Table 3 about here

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4 Discussion

This study investigated the neurofunctional features of implicitly integrating print and sound and their relationships with reading abilities in Chinese children with and without dyslexia. We adopted an fMRI audiovisual paradigm with a passive target detection task. Character-sounds and pinyin-sounds, whose orthographic depths are dramatically different, were used as materials. Of importance, due to the morpho-syllabic nature of characters, semantic information can be automatically activated during character recognition, at least in typical readers. That is, this study enabled us to tap into the three-way relationship between orthography, phonology, and semantics in normal and impaired readers. Although no group differences on the audiovisual integration effect were found, the results revealed strikingly atypical correlations between neural integration of both character-sounds and pinyin-sounds with different aspects of reading ability in Chinese children with dyslexia. On the one hand, these findings indicate that children with dyslexia rely on articulatory phonological information during the implicit character processing, which indicates a less developed automatic grapho-semantic mapping and integration. On the other hand, it suggests a malfunctional grapho-phonological mapping in dyslexia and implies that these children may have difficulty in developing a typical pinyin processing strategy and transferring it to learning characters as their typically developing peers do.

4.1 **Left IFC: inefficient grapho-semantic mapping in Chinese dyslexia**

First, this study indicates insufficient semantic information access from visual input in Chinese children with dyslexia. At the behavioral level, we observed significantly less proficiency in the dyslexic group on silent reading comprehension. Moreover, while both character recognition accuracy and reading comprehension proficiency were associated with MA in typical readers, children with dyslexia showed significant correlations between reading abilities with

other cognitive-linguistic skills instead of MA. Specifically, character recognition was correlated with PA in dyslexia, in line with a previous study in an independent and larger sample (Song, Zhang, Shu, Su, & McBride, 2020). Regarding silent reading comprehension, although no correlation was significant, there was a trend with RAN, a phonological processing skill that consists of rapid and accurate phonological representation access, retrieval, and articulatory operations. This result is in line with recent studies in which phonological skill contributes to reading more at the early stages of reading acquisition, and the contribution of morphological processing skill increases as children grow (Liu et al., 2017). In addition to the direct effect, MA also mediates the effect of PA on reading (Pan et al., 2016).

Furthermore, we used the fMRI audiovisual paradigm to probe the neural bases of processing character-sound associations in Chinese children with and without dyslexia. In terms of brain activation in the left IFC and STC, dyslexic children seem to integrate information from auditory and visual modalities the same way as controls, reflected as a strong audiovisual integration effect (congruent < incongruent) in both groups. Moreover, the effect in the left IFC was associated with reading comprehension proficiency, regardless of reading status. Of note, group differences were uncovered in the subsequent ROI analysis. First, while the integration-comprehension association was driven more by the incongruent condition in typical readers, the correlation was driven more by the congruent condition in children with dyslexia, suggesting dyslexic and typical children may use different strategies in processing characters and corresponding sounds, and this difference enlarges with reading abilities increasing within each group. Second, while the audiovisual integration effect in the left IFC was associated with MA in the control group, it was correlated with RAN in dyslexia. These findings indicate that articulatory phonological processing is more likely involved in implicit processing of character-sound pairs in children with dyslexia. In previous studies investigating neural impairment in Chinese dyslexia, both hypo- and hyper-activation of the left frontal areas have been reported (Cao et al., 2016; Liu et al., 2012; Siok et al., 2004). In a meta-analysis, different parts of the left IFC were distinguished based on functionality, where individuals with dyslexia displayed reduced activation in the ventral part associated with semantic processing but increased activation in the dorsal part that was associated with articulatory processing, presumably compensating for their less efficient grapho-semantic route (Hancock, Richlan, & Hoeft, 2017; Richlan, Kronbichler, & Wimmer, 2011). Given that the frontal region is multifunctional (Fedorenko & Blank, 2020; Hagoort, 2014), dyslexia may recruit it in reading-related processing in a different way compared with typical readers.

Of note, our in-scanner task did not require any sound-semantic or print-semantic processing. However, Chinese has a morpheme-based logographic writing system, which involves semantic information in character recognition (Guan et al., 2020; Liu et al., 2017; Yang et al., 2013; Zhao et al., 2014). Therefore, phonological and semantic information could both be accessed effortlessly, at least in typically developing children after 4-5 years of formal

instruction. Thus, it is also reasonable to predict that semantic processing skill plays an equal or even more critical role in reading development than phonological processing skill, and its impairments will result in reading difficulties. In line with this hypothesis, previous studies of Chinese demonstrated morphological awareness uniquely predicted reading outcomes and dyslexia status (Pan et al., 2016; Ruan et al., 2018; Song et al., 2020). The current results also showed that while the left IFC was strongly involved in both groups, it was more associated with articulatory phonological processing in dyslexia and semantic processing in typical children. The region is close to the one found to underlie morphological processing and show hypo-activation in children with dyslexia during tasks requiring explicit semantic processing (Liu et al., 2013; Zou, Packard, Xia, Liu, & Shu, 2015).

These findings suggest that Chinese children with dyslexia have yet to develop a well-functioning brain system for automated semantic access and integration during implicit character/word recognition. In contrast, they are more likely to reply on an articulatory strategy by recruiting the multifunctional frontal area.

4.2 Bilateral TPC and left OTC: malfunctioning grapho-phonological mapping in Chinese dyslexia

In addition to inefficient grapho-semantic mapping, this study also indicates that children with dyslexia may neither develop a typical grapho-phonological mapping. At the behavior level, the dyslexic group performed worse in the tasks measuring oral reading fluency, PA, and RAN, in line with previous studies in larger samples of Chinese children (e.g., Lei et al., 2011). In the pinyin fMRI experiment, we observed differential brain-reading correlations in the classic reading-related areas. These regions have also been associated with oral reading fluency in terms of cortical thickness (Xia et al., 2018). In particular, the magnitude of the audiovisual integration effect in response to pinyin-sound pairs in the left OTC and STC was positively associated with oral word reading fluency in typical controls: the better the children performed in the oral reading task, the higher the activation was in the congruent condition than incongruent condition. In contrast, the direction of the brain-reading correlation was reversed in dyslexia: children with higher reading fluency showed higher activation in the incongruent condition than congruent condition. Additionally, the correlations in the control group were driven more by individual differences in brain responses to the congruent condition. In contrast, the correlations in the dyslexic group were driven more by the incongruent condition. These findings suggest that while the same regions were recruited for implicit audiovisual integration of pinyin, children with dyslexia may use different strategies.

The left OTC and STC have been regarded as critical nodes in the classic reading network. Deficits in these areas have also been reported in dyslexia (Richlan, Kronbichler, & Wimmer, 2009; Richlan et al., 2011). On the one hand, the left OTC has been considered the interface for initially integrating orthographic, phonological, and semantic information (Price & Devlin, 2011). The left OTC contains a specific portion in the fusiform gyrus named the visual

word form area that has been found to respond specifically to word and word-like stimuli. The left STC, on the other hand, is a central area that presents phonological information (Boets et al., 2013; Glezer et al., 2016), including lexical tone—the supramarginal phoneme in tonal languages such as Chinese (Si, Zhou, & Hong, 2017; L. Zhang et al., 2011). It is functionally and structurally connected to the left OTC, which can be shaped by learning grapho-phonological mappings (Stevens, Kravitz, Peng, Tessler, & Martin, 2017; Thiebaut de Schotten, Cohen, Amemiya, Braga, & Dehaene, 2014). In the current study, besides the left-hemispheric regions, the right STC also showed significant group differences in brain-behavior relationships. While this region has been less frequently reported in previous studies, it is a substrate for supporting lexical tone processing (Liang & Du, 2018; Si et al., 2017; Zhang et al., 2011). In addition, the cortical thickness of this area is also associated with oral reading in typically developing Chinese children (Xia et al., 2018).

The differential relationship between the audiovisual integration effect during pinyin-sound processing and oral word reading fluency in dyslexia can be interpreted in at least two ways. First, if pinyin processing skill is a continuum and dyslexia presents the lower end, the current finding then hints at the expansion and renormalization hypothesis of brain plasticity associated with skill learning (Wenger, Brozzoli, Lindenberger, & Lövdén, 2017). That is, the growth curve of print-sound integration is an inverse U-shape. When the child starts learning pinyin at the earliest stages, the brain response to incongruent audiovisual pairs is lower than congruent pairs. With learning, mismatching in information extracted from different modalities induces higher activation during integration. Children turn to focus on the overlearned visual scripts by efficiently suppressing attractive auditory information at the highly familiar stage. In this case, activation in the incongruent condition will be suppressed and lower than that in the congruent condition. This interpretation is in line with our findings that brain activation in the congruent condition was associated with oral reading in typical readers, whereas incongruent condition was related to oral reading in dyslexia. The alternative explanation is also associated with development but assumes that individuals with dyslexia process pinyin differently compared with typical controls. In general, typical readers shift from assembled to addressed phonology with reading experience increases (Mei et al., 2014). Pinyin is assembled in nature. But since there are only approximately 400 syllables, it can be expected that typical readers in upper elementary grades who are highly familiar with it could achieve the addressed phonology. Given that children learn Chinese characters as holistic syllable-level units, children who read pinyin with the same addressed phonology may benefit more. In this case, the differential brain-reading correlations probably reflect the inefficient assembled phonology adopted by dyslexic children in processing pinyin-sound pairs. However, although this explanation is appealing, conclusions cannot be made with the current evidence. To date, evidence on the developmental trajectory of pinyin reading is still lacking. More studies on preliterate and emerging readers with a longitudinal design are needed.

Nonetheless, these findings indicate impaired automatic grapho-phonological mapping in dyslexia from the perspective of individual differences. This anomaly could be underpinned by the altered recruitment of cortical areas such as the left OTC and bilateral STC. Such deficits may further impede the development of the ventral pathway for rapid character/word recognition and result in reading problems. Recruiting preliterate children and conducting longitudinal neuroimaging research is necessary to further answer this "cause vs. consequence" question (Nash et al., 2017).

4.3 Limitations and future directions

There are several limitations in this study, and caution should be taken when interpreting the results. First, we administered the pinyin experiment ahead of the character experiment to reduce the prime effect of characters on processing visually presented pinyin stimuli. This may influence brain activation to speech sounds in character runs because the same auditory stimuli were used. Second, to have sufficient statistical power, we used the liberal criteria to assess imaging data quality and exclude participants with poor quality data accordingly. Third, while the overall pattern indicates that children in both groups maintained their attention throughout the experiment, the dyslexia group performed worse. To deal with this issue, we controlled performance IQ in all the analyses. This could be why no group differences were detected but demonstrated that the main findings of brain-behavior relationships are robust. At last, we did not have enough cases for looking into different subtypes of dyslexia. Studies with larger sample sizes are needed, and a counterbalance design for estimating the order effect, much stricter criteria for controlling MRI data quality, well-matching on in-scanner performance between groups, and dividing dyslexia into subtypes can be applied.

4.4 Conclusion

The present study examined impaired audiovisual integration of character-sound associations and pinyin-sound associations in Chinese children with dyslexia at the neurofunctional level. The results revealed that dyslexia manifested deficits in grapho-semantic mapping, with the left IFC as the most relevant area, and the grapho-phonological mapping, with the left OTC and bilateral STC as central regions. Moreover, the current findings also imply that Chinese children with dyslexia may process pinyin—the alphabetic coding system representing the pronunciation of characters—in a lagged or deviated way, which impedes the development of the direct route for rapid character/word recognition and semantic access.

5 Author Contributions

Conceptualization: ZX, HS, XL; Investigation: ZX, TY, XC, HL, XZ; Formal Analysis: ZX; Data Curation: ZX; Writing – Original Draft Preparation: ZX;

Writing – Review & Editing: ZX, TY, XC, FH, HL, XZ, HS, XL; Funding Acquisition: ZX, HS, XL; Supervision: ZX, HS, XL

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8 Declaration of interest

The authors declare that there is no conflict of interest.

9 Data availability statement

The data that support the findings of this study are available from the corresponding authors upon reasonable request.

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Figure legends

Figure 1 Schematic description of the fMRI experimental procedure (A, B, C for a single run, a block, and a mini-block, respectively) and stimuli examples (D). Abbreviations: Aud = auditory, avC = audiovisual congruent, avI = audiovisual incongruent, Fix = fixation, Vis = visual.

Figure 2 (A) Results of the voxel-wise whole-brain ANOVA on the character conditions. Only clusters showing a significant main effect of condition were identified at the FWE corrected threshold of p-cluster < 0.05 (p-voxel < 0.001 for height). No region showed a significant main effect of group or group × condition interaction. (B) Bar plots present the brain activation level in the audiovisual congruent and incongruent conditions for the control group and dyslexic group. (C) Scatterplots display correlations between the neural audiovisual integration effect (avC-avI) in the left IFC with silent reading comprehension proficiency and related cognitive-linguistic skills (morphological awareness, rapid naming). Abbreviations: avC = audiovisual congruent, avI = audiovisual incongruent, IFC = inferior frontal cortex, STC = superior temporal cortex.

Figure 3 (A) Brain map of regions showing significant differences between dyslexic and control groups in correlation between the audiovisual integration effect and oral reading fluency (FWE corrected p-cluster < 0.05, p-voxel < 0.001 for height). Scatterplots presents correlations in each group (blue: control; red: dyslexic) in the left OTC (B), STC (C), and right STC (D). Abbreviations: avC = audiovisual congruent, avI = audiovisual incongruent, OTC = occipito-temporal cortex, STC = superior temporal cortex.

Supplementary Figure 1 The summary of demographic and behavioral measures is shown as boxplots, with the box indicating the interquartile range (IQR). The whiskers show the range of values within 1.5 × IQR and a horizontal line indicating the median. Individual data are shown as dots. The color coding is indicated in the legend below to the plot. Data visualization was done with PlotsOfData (https://huygens.science.uva.nl/PlotsOfData/).

Table 1 Demographic and behavioral profiles

	Typical Readers (n = 22)			Reading Disorder (n = 23)			Comparison	
Measures	Mean	SD	Range	Mean	SD	Range	t/χ^2	*p*-value
Age (month)	127	6	118 ~ 140	122 †	10	111 ~ 144	1.938	0.061
Sex (female/male)	12/10			10/13			0.552	0.556
Verbal IQ (standard score)	109	12	88 ~ 139	97	11	67 ~ 118	3.668	< 0.001
Performance IQ (standard score)	115	13	82 ~ 137	105	12	82 ~ 135	2.512	0.016
Full-Scale IQ (standard score)	113	11	93 ~ 130	101	9	84 ~ 116	3.986	< 0.001
Character Recognition (item)	122	8	107 ~ 140	86 †	11	53 ~ 99	11.830	< 0.001
Standard score	1.38	0.66	0.41 ~ 2.43	-2.18	0.83	-4.520 ~ -1.020	12.701	< 0.001
Word List Reading (word/minute)	94 ‡	16	72 ~ 140	63	11	40 ~ 83	7.612	< 0.001
Standard score	0.95 †	1.11	-0.38 ~ 4.06	-1.584	0.67	-2.930 ~ -0.130	7.278	< 0.001
Reading Fluency (character/minute)	361 ‡	104	220 ~ 565	163	56	70 ~ 304	7.890	< 0.001
Standard score	0.98 ‡	1.04	-0.38 ~ 3.12	-1.083	0.57	-2.250 ~ 0.430	7.998	< 0.001
Phoneme Deletion (item)	21 †	4	7 ~ 25	17 †	6	1 ~ 25	2.848	0.007
Rapid Naming (second)	17	2	11 ~ 20	22	4	15 ~ 30	-5.481	< 0.001
Morphological Production (item)	24 ‡	3	20 ~ 29	22	3	13 ~ 28	2.927	0.005

Note. † Shapiro-Wilk $p < 0.05$, ‡ $0.05 <$ Shapiro-Wilk $p < 0.01$

977

Table 2 Significant clusters in the voxel-wise whole-brain analyses

Material and contrast	Label	Brain area	$P_{\text{FWE-corrected}}$	Size	Peak *F*	X	Y	Z
Character								
Main effect of condition	LSTC	Left middle and superior temporal	0.007	391	26.86	-60	-32	6
	LIFC	Left inferior frontal gyrus,	0.024	281	23.90	-46	16	14
Pinyin								
Group difference in brain-reading	LOTC	Inferior and middle occipital gyri,	0.004	358	29.28	-44	-72	-2
(Reading: *Oral reading fluency*)	LSTC	Left middle and superior temporal	0.039	197	23.02	-52	-44	10
	RSTC	Right superior temporal gyrus,	0.047	185	38.68	62	-8	4

Note. The significant clusters were identified with the FWE-corrected threshold of p-cluster < 0.05 (p-voxel < 0.001 for height). Brain area labeling is based on the AAL atlas. Cluster size refers to the number of voxels.

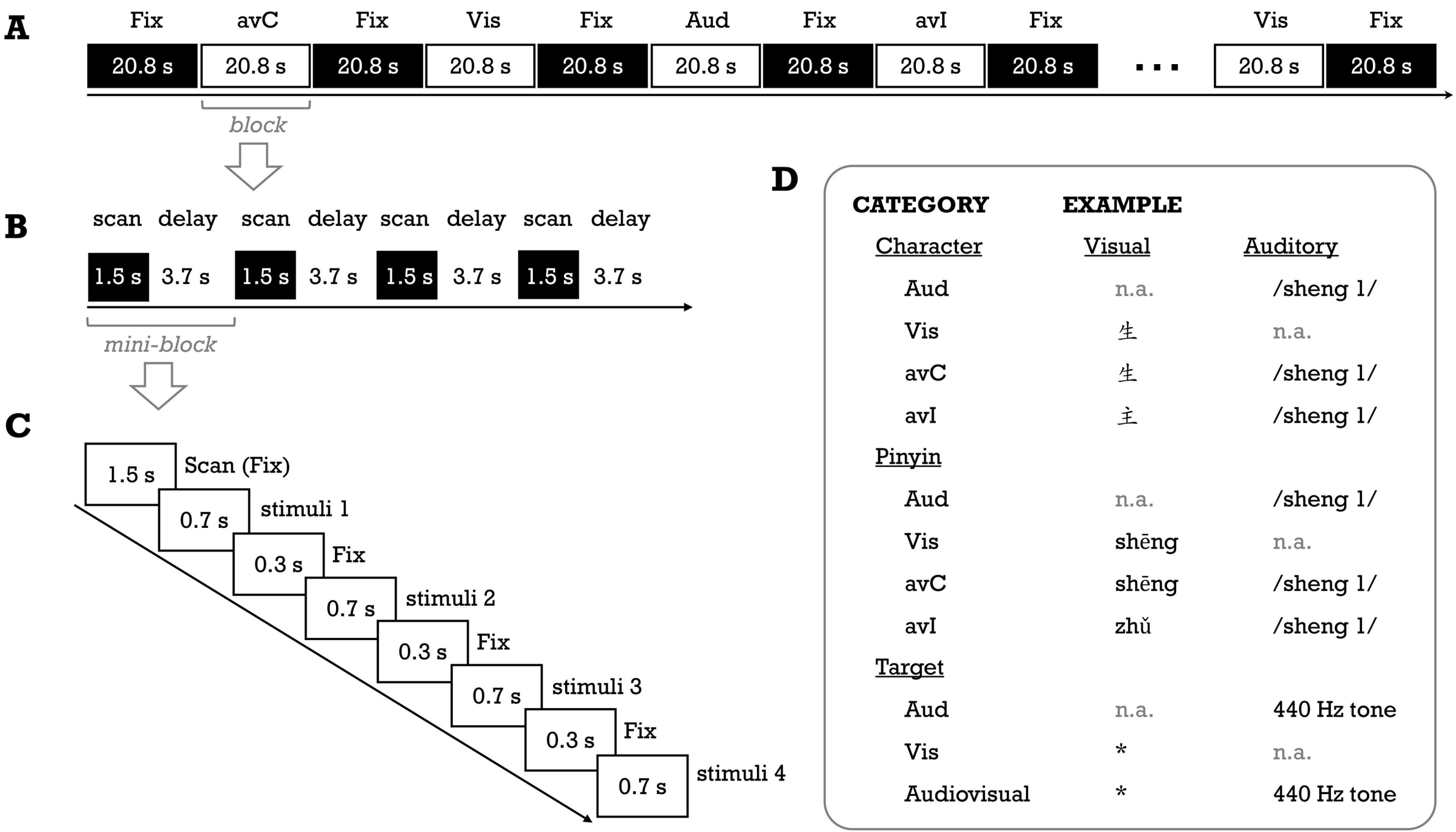
978

Table 3 Brain-behavior correlations in the significant clusters in the voxel-wise whole-brain regression analyses.

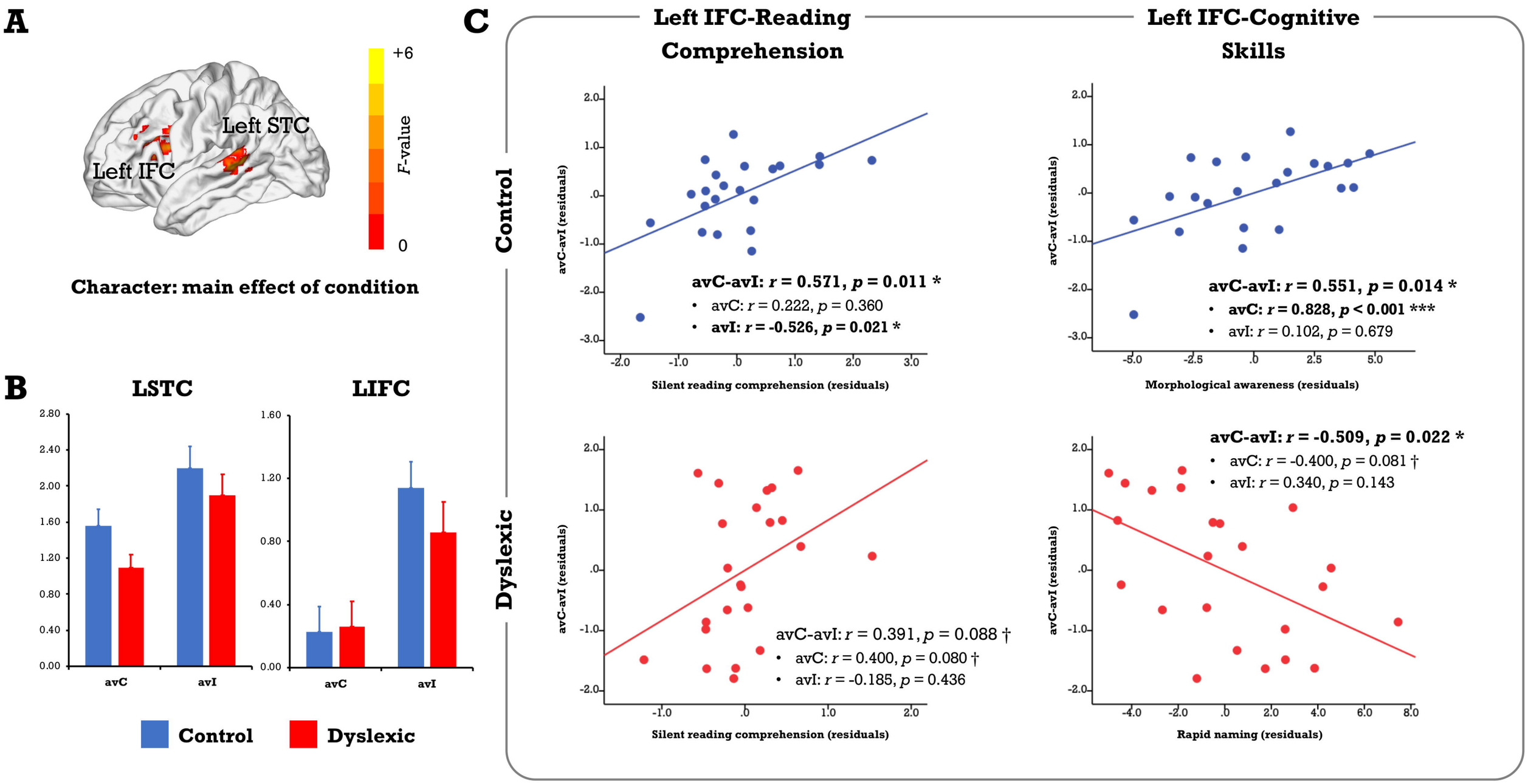
Behavior measure:	Group	Integration Effect (avC-avI)		avC		avI	
Oral reading fluency		*r*-value	*p*-value	*r*-value	*p*-value	*r*-value	*p*-value
L OTC	Control	0.525 *	0.021	0.685 **	0.001	0.118	0.631
	Dyslexic	-0.804 ***	< 0.001	0.026	0.913	0.674 **	0.001
L STC	Control	0.693 **	0.001	0.588 **	0.008	-0.014	0.956
	Dyslexic	-0.668 **	0.001	-0.050	0.833	0.445 *	0.049
R STC	Control	0.655 **	0.002	0.240	0.321	-0.259	0.284
	Dyslexic	-0.706 ***	< 0.001	-0.181	0.444	0.543 *	0.013

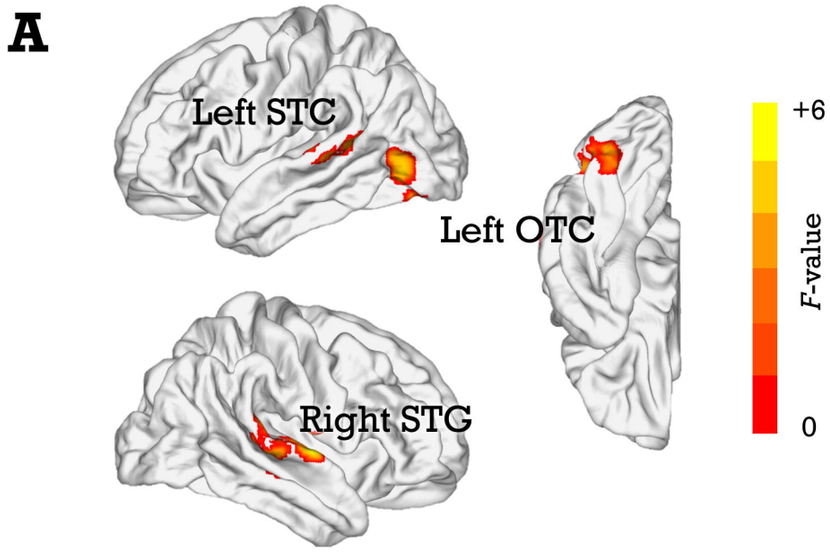
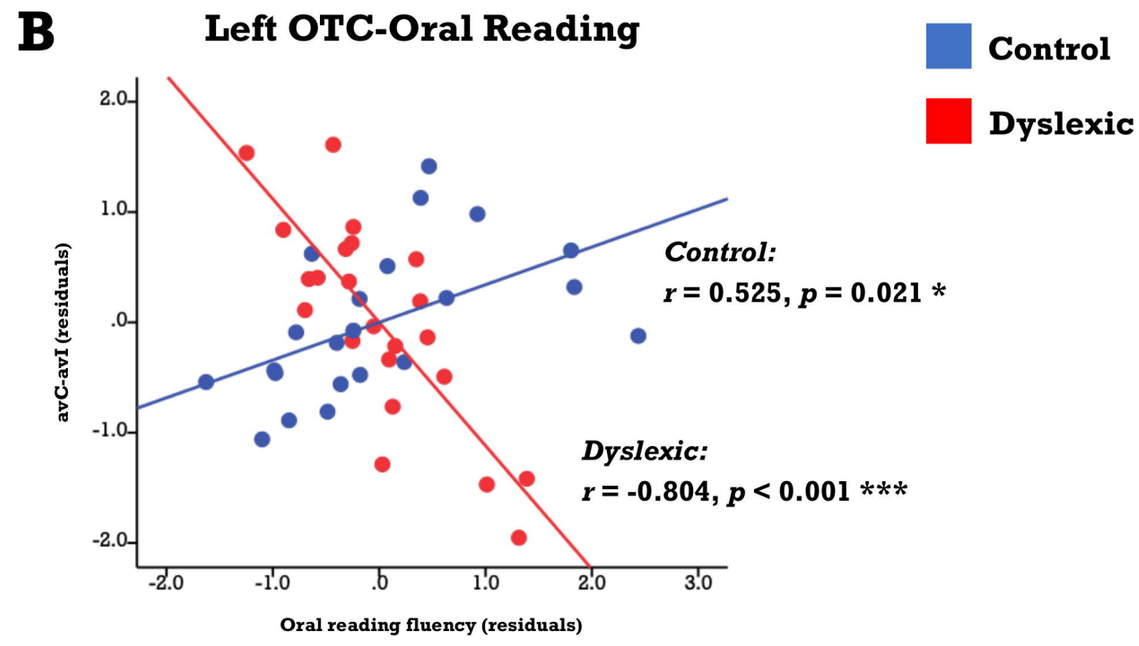
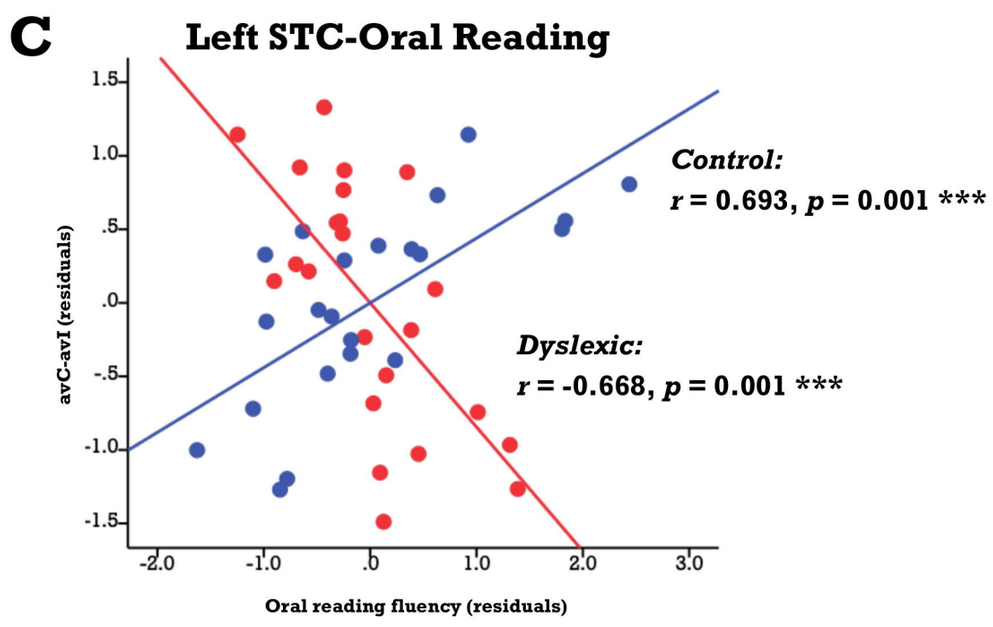
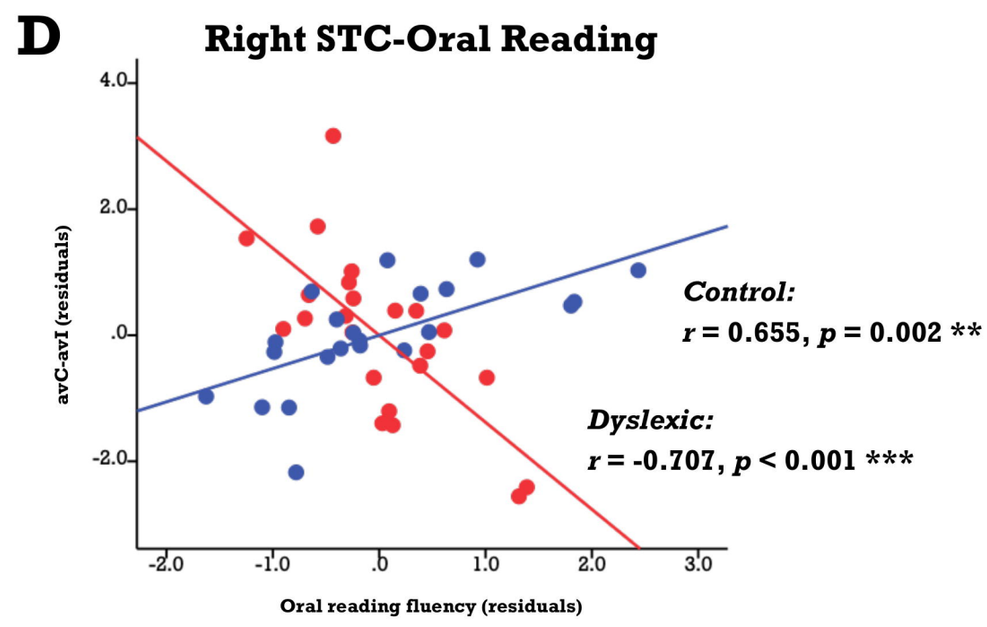
Note. Age, sex, and performance IQ were controlled statistically. Abbreviations: avC = audiovisual congruent, avI = audiovisual incongruent. *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$

979



CATEGORY	EXAMPLE	
Character	Visual	Auditory
Aud	n.a.	/sheng 1/
Vis	生	n.a.
avC	生	/sheng 1/
avI	主	/sheng 1/
Pinyin		
Aud	n.a.	/sheng 1/
Vis	shēng	n.a.
avC	shēng	/sheng 1/
avI	zhǔ	/sheng 1/
Target		
Aud	n.a.	440 Hz tone
Vis	*	n.a.
Audiovisual	*	440 Hz tone


A
Left STC
Left IFC
+6
F-value
0
Character: main effect of condition
B
LSTC
LIFC
avC
avI
Control
Dyslexic
C
Left IFC-Reading Comprehension
Left IFC-Cognitive Skills
Control
Dyslexic
avC-avI (residuals)
Silent reading comprehension (residuals)
avC-avI: r = 0.571, p = 0.011 *
avC: r = 0.222, p = 0.360
avI: r = -0.526, p = 0.021 *
Morphological awareness (residuals)
avC-avI: r = 0.551, p = 0.014 *
avC: r = 0.828, p < 0.001 ***
avI: r = 0.102, p = 0.679
avC-avI: r = 0.391, p = 0.088 †
avC: r = 0.400, p = 0.080 †
avI: r = -0.185, p = 0.436
Rapid naming (residuals)
avC-avI: r = -0.509, p = 0.022 *
avC: r = -0.400, p = 0.081 †
avI: r = 0.340, p = 0.143



Pinyin: group difference on brain-behavior correlation