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1 **A universal reading network and its modulation by writing system and reading**  
2 **ability in French and Chinese children**

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33

34 **Abstract**

35 Are the brain mechanisms of reading acquisition similar across writing systems? And do similar  
36 brain anomalies underlie reading disabilities in alphabetic and ideographic reading systems? In  
37 a cross-cultural paradigm, we measured the fMRI responses to words, faces and houses of 96  
38 Chinese and French 10-year-old children, half of whom struggle with reading. We observed a  
39 reading circuit which was strikingly similar across languages and consisting of the left fusiform  
40 gyrus, superior temporal gyrus/sulcus, precentral and middle frontal gyri. Activations in some  
41 of these areas were modulated either by language or by reading ability, but without interaction  
42 between those factors. In various regions previously associated with dyslexia, reading difficulty  
43 affected activation similarly in Chinese and French readers, including the middle frontal gyrus,  
44 a region previously described as specifically altered in Chinese. Our analyses reveal a large  
45 degree of cross-cultural invariance in the neural correlates of reading acquisition and reading  
46 disabilities.

47

48 **Keywords:** struggling readers, writing system, cross-cultural invariance, fMRI, visual  
49 categories

50

## 51 **Introduction**

52 A large proportion of published studies on reading concern English, even though this  
53 language may be considered as an outlier within alphabetic writing systems, compared to  
54 Finnish or Italian for example, due to its highly opaque grapheme-phoneme correspondences.  
55 Thus, international efforts should progressively extend the results obtained in English subjects,  
56 or more generally in Western languages, to other writing systems and languages, notably during  
57 childhood. Daniels and Share (2018) listed 10 dimensions that might affect reading acquisition  
58 and dyslexia phenotypes, and that fall into three main classes: the structure of the oral language,  
59 the complexity of the visual shapes, and the translation rules between those two domains. With  
60 regard to language, the number of phonemes, the syllabic structure and the complexity and  
61 regularity of morphological markers can modulate the ease with which children construct  
62 explicit representations of speech, which need to be converted in, or deduced from, writing  
63 (Goswami, 2008). The visual shapes of letters and characters also vary in number, uniformity,  
64 and complexity (Daniels and Share, 2018). Finally, the grapheme-to-phoneme correspondences  
65 vary on several dimensions across writing systems, including granularity, complexity,  
66 transparency, and consistency (Daniels and Share, 2018). All these factors may influence the  
67 speed and effectiveness with which children learn to read, and at least one of these dimensions,  
68 orthographic transparency, has been robustly reported to affect reading acquisition in Western  
69 languages (Seymour et al., 2003), with a reported impact on brain activation in the adult reading  
70 circuit (Paulesu et al., 2000).

71 Beyond these surface differences, the fundamental logic of reading remains the same from  
72 one writing system to another: all of them comprise a restricted number of visual symbols  
73 whose combinations allow to access the spoken language network through vision. Although  
74 accessing linguistic information from the visual system is a natural possibility for the brain, as  
75 demonstrated by the capacities for image naming, lip reading or sign language, writing  
76 introduces an additional step that involves converting an arbitrary visual form into speech.  
77 Grapheme-phoneme correspondences are arbitrary and have been shown to depend on a precise  
78 region of the visual system, the visual word form area (VWFA) and on the posterior superior  
79 temporal cortex, as shown by numerous brain imaging studies in adult readers (Baker et al.,  
80 2007; Dehaene et al., 2015; Stevens et al., 2017). However, most of those brain imaging studies

81 suffer from the bias noted above: they concern mainly Western alphabetic languages and mainly  
82 adults. Despite the existence of a few previous investigations (Chee et al., 1999; Nakamura et  
83 al., 2012; Rueckl et al., 2015; Szwed et al., 2014; Xu et al., 2017), controversy still surrounds  
84 the question of whether different cognitive and neural processes are involved in reading non-  
85 alphabetic material, or whether reading is based on a similar network regardless of the target  
86 language, with only minor variations in the degree of involvement of the different nodes of the  
87 network according to the graphic complexity and consistency (Paulesu et al., 2000) or to the  
88 linguistic grain size that predominates in a given writing system (Perfetti, 2003; Ziegler and  
89 Goswami, 2005). For instance, Chinese characters, like letters, eventually map onto phonology,  
90 but they do so at the syllable level and with a considerable degree of irregularity, with (in most  
91 cases) no parts in a character corresponding to phonological segments such as phonemes.

92 An additional source of bias in the literature is that most publications on brain imaging  
93 have focused on adults, i.e., reading experts. It is entirely conceivable that scanning children  
94 during the acquisition of reading would yield different results. The transient mechanisms of  
95 learning, in an immature and inexperienced brain, could be based on different mechanisms than  
96 those observed in the mature brain (Kersey et al., 2019). This is especially the case for a highly  
97 cultural, education-dependent activity such as reading (Dehaene and Cohen, 2007). Children  
98 may rely on different and possibly broader regions of the brain before converging onto the adult  
99 expert network for reading, for instance transiently recruiting parietal regions for effortful  
100 reading (Dehaene-Lambertz et al., 2018; Martin et al., 2015). Conversely, they may also enlarge  
101 their responses with skill acquisition, as described in the fusiform region (Olulade et al., 2013).  
102 Furthermore, given the differences between writing systems outlined above, initial reading  
103 might rest upon in different brain areas before converging to a common circuit. Therefore,  
104 functional neuroimaging studies in young children, comparing reading acquisition in different  
105 writing systems, although difficult, are highly desirable.

106 Another approach to studying the universality and specificity of the neurocognitive bases  
107 of reading is to investigate whether children with reading disability from alphabetic and non-  
108 alphabetic languages exhibit similar brain anomalies. Neuroimaging studies of dyslexia have  
109 revealed common neural deficits in different alphabetic languages, with consistently decreased  
110 activation (Martin et al., 2016; Richlan et al., 2009) and reduced gray matter volumes

111 (Linkersdorfer et al., 2012; Richlan et al., 2013) in several left-hemispheric posterior regions,  
112 including the left temporoparietal and left ventral occipitotemporal regions. According to two  
113 recent meta-analyses, the left ventral posterior occipitotemporal cortex (including the Visual  
114 Word Form Area, VWFA) appears to be the most reproducible and consistent site exhibiting  
115 hypoactivation in dyslexic individuals across several alphabetic writing systems regardless of  
116 orthographic depth (Martin et al., 2016). Given its sensitivity to visual features (e.g. line  
117 junctions) and its efficient reciprocal projections to language areas (Bouhali et al., 2014;  
118 Hannagan et al., 2015; Saygin et al., 2016), this area has been proposed as one of the candidates  
119 for a universal effect of reading disability (Martin et al., 2016; Pugh, 2006).

120 By contrast, several neuroimaging studies of Chinese dyslexic children have emphasized  
121 the differences between Chinese and alphabetic languages, underscoring the role of the left  
122 middle frontal gyrus (LMFG) (Liu et al., 2013; Siok et al., 2004; Siok et al., 2009): Chinese  
123 dyslexic children showed a decreased activation in the LMFG compared with typical readers  
124 (with eight 11-year-old children in each group) during a homophone judgment task (Siok et al.,  
125 2004). This decreased activation in the LMFG was replicated by Siok et al (2008), with twelve  
126 11-year-old children in each group. It was associated with smaller gray-matter volume at the  
127 same location, and no other functional or structural differences was found in the regions singled  
128 out by other studies in alphabetic languages. These results were interpreted as showing a clear  
129 dissociation of the biological basis of reading disabilities between alphabetic and logographic  
130 writing systems. However, these findings contradict behavioral data that show similar profiles  
131 in Chinese and alphabetic-language dyslexics (Goswami et al., 2011; Ziegler and Goswami,  
132 2005) and similar predictors of reading abilities in both writing systems. For instance,  
133 phonological awareness and morphological awareness (lexical compounding) in 4-year-old  
134 Chinese children predict character recognition at 11 years of age, while naming speed (RAN)  
135 and vocabulary predict reading fluency (Su et al., 2017). These results are consistent with those  
136 obtained in alphabetic languages, which link phonological awareness to reading accuracy and  
137 RAN to reading fluency (Landerl et al., 2013; Moll et al., 2014). Moreover, another fMRI study  
138 revealed remarkably few differences in brain activity between 11 English and 11 Chinese  
139 dyslexic adolescents (13 to 16 years) once all confounding variables (e.g. stimuli and task in  
140 fMRI) were controlled for (Hu et al., 2010). It is worth noting that previous fMRI studies of

141 Chinese children with reading disability used a variety of tasks, e.g. picture and semantic  
142 matching (Hu et al., 2010), homophone judgement (Siok et al., 2004), font-size perceptual  
143 matching (Siok et al., 2009) and a morphological task (Liu et al., 2013), which may partially  
144 explain the inconsistency of the findings between studies.

145 Therefore, to clarify the question of the commonalities and specificities of reading  
146 acquisition across different writing systems, we used a similar experimental protocol in 96  
147 Chinese and French 10-year-old readers (48 in each language), with different reading  
148 proficiency. As in our previously published fMRI studies of reading (Dehaene-Lambertz et al.,  
149 2018; Monzalvo and Dehaene-Lambertz, 2013), all children performed the same passive  
150 viewing task with words, faces and houses, with the mere goal to detect an occasional target  
151 star. We studied the effect of reading proficiency in whole-brain analyses and in the specific  
152 ROIs highlighted in the literature, in both Chinese and French children. The two analyses are  
153 complementary: whole-brain analyses can reveal any regions with differences between Chinese  
154 and French children or between children with and without struggling reading, including at  
155 unexpected brain sites, while ROI analyses have a better sensitivity to detect small differences  
156 between groups by summing voxel activity in the cluster and decreasing the number of repeated  
157 measures and thus the severity of the correction for multiple comparisons.

158 Because group analyses leave open the possibility that the observed group differences  
159 might be due to spatially more variable activations in struggling readers than in typical readers,  
160 we also performed individual-based analyses and compared the location and activation values  
161 of the most responding voxels in each child. Finally, because classical analyses may mask the  
162 presence of fine-grained activity patterns that are specific to a given subject or a given category,  
163 we also quantified the stability of subject-specific activation patterns within reading-related  
164 ROIs using multivariate pattern analyses. The goal of these analyses is to circumvent the  
165 blurring effect of group analyses, which may hinder the discovery of genuine but more  
166 dispersed activations in struggling readers relative to typical readers.

167 In addition to activations to words, we were also interested in how reading acquisition, in  
168 French and Chinese, may differently reorganize the ventral visual areas. Fusiform regions have  
169 a distinct maturation profile than more medial regions (Gomez et al., 2017) and face-specific  
170 activations expand slowly with age (Golarai et al., 2007; Golarai et al., 2015). Several studies

171 in alphabetic languages suggest that, during reading acquisition in children, words and faces  
172 may compete for cortical territory within the left fusiform gyrus (Centanni et al., 2018;  
173 Dehaene-Lambertz et al., 2018; Hervais-Adelman et al., 2019; Li et al., 2013; Ventura et al.,  
174 2013). Given the complexity of Chinese characters and their frequently reported bilateral  
175 activation, we investigated how face activation might be differently modulated by different  
176 reading abilities in Chinese and French children. We thus performed the same analyses for faces  
177 than those described above for words and also considered more precisely the development of  
178 the anterior-posterior gradient of activations for these two categories.

179

180

## 181 **Results**

### 182 **Behavioral Results**

183 Within the scanner, Chinese children responded faster to the target star than French  
184 children (main effect of Language:  $F(1,92) = 60.94, p = 0.001$ ). There was no significant effect  
185 of Reading ability ( $F(1,92) < 1$ ) nor Language  $\times$  Reading ability interaction ( $F(1,92) < 1$ )  
186 (Chinese typical readers:  $534.95 \pm 71.47$  ms, Chinese struggling readers:  $536.13 \pm 72.84$  ms;  
187 French typical reader:  $661.15 \pm 102.29$  ms, French struggling readers:  $689.32 \pm 99.35$  ms).

188

### 189 **Whole brain analyses:**

190 **Category-specific activations:** We first examined the brain activations to each category  
191 (i.e. Words, Faces, and Houses) relative to the other two categories among all participants (see  
192 Figure 1A and Table 2). The [Words > Faces + Houses] analysis yielded the usual reading-  
193 related regions: fusiform gyrus, posterior superior temporal region, *planum temporale*, intra-  
194 parietal sulcus and inferior frontal regions in the left hemisphere and the posterior superior  
195 temporal gyrus in the right hemisphere. We also observed the classic mosaic of category-  
196 specific ventral visual areas, with category-specific activation to Houses occupying a medial  
197 parahippocampal location, Faces an intermediate fusiform location, and Words a lateral location  
198 in the left occipito-temporal sulcus (VWFA). Amygdala responses to Faces were also clearly  
199 seen. Those results were seen in each of the four groups of subjects, with the interesting  
200 exception that the left VWFA was not seen in both Chinese and French struggling readers,



201 contrary to the typical readers, at this classical threshold (voxel-level  $p < 0.001$ , cluster-level  
202 uncorrected) (Figure 1B and Supplementary file 3).

203 **Reading-related differences:** Reading scores across all 96 children were significantly  
204 correlated with fMRI activation in the [words > fixation] contrast, in the classical regions of the  
205 reading circuit in the left hemisphere (fusiform, superior temporal sulcus, middle frontal region  
206 and precentral) plus some of their right counterparts (Fig 2 and Table 3). When the French and  
207 Chinese groups were considered separately, similar regions (bilateral FFG, bilateral PCG,  
208 bilateral MFG, left STS,) were observed in each of the two languages (figure 2B and 2C).

209 We also observed a significant positive correlation, across all children, between reading  
210 scores and the face-evoked activation (vs. fixation) in the left fusiform gyrus (left [-33 -60  
211 -15], 74 voxels,  $Z = 4.31$ ,  $p_{FWE\_corr} = 0.001$ ). This region was close to coordinates of the classic  
212 left FFA (Scherf et al., 2007). A small cluster was also observed close to the classic right FFA,  
213 but did not survive the cluster-level correction ([45 -48 -15], 12 voxels,  $Z = 3.70$ ).

214

#### 215 **Group comparisons:**

216 No significant difference was found between typical and struggling readers in either direction  
217 when analyzing either the [Words > fixation] or the [Words > Faces+Houses] contrast across the  
218 whole brain. However, a few voxels reached the voxel-wise statistical threshold ( $p = 0.001$ ) in the  
219 left fusiform gyrus, left precentral and left superior temporal sulcus with greater activation in typical  
220 readers relative to struggling readers (see Figure 1—Figure supplement 1A). To improve our  
221 sensitivity to differences between groups and decrease the risk of false negatives, we restricted  
222 our analyses to reading sensitive regions defined by the mask comprising all voxels showing a  
223 preference for words relative to the two other categories across all participants. Typical readers  
224 showed larger activations relative to struggling readers in a left precentral cluster (79 voxels,  
225  $p_{FWE\_corr} = 0.027$ ,  $Z = 3.69$  at [-51 15 33]) and Chinese relative to French in the left intra-parietal  
226 sulcus (55 voxels,  $p_{FWE\_corr} = 0.004$ ,  $Z = 4.29$  at [-30 -60 39]) in the words vs fixation contrast  
227 (Figure 1—Figure supplement 1). No region showed more activation in French children relative  
228 to Chinese nor a significant language  $\times$  reading ability interaction, even when a very lenient  
229 voxel-wise threshold of  $p < 0.05$  was considered.

230 To summarize the results so far, our analyses recovered, in a large group of 10-year-old

231 children, the classical activations for words, faces and houses described in adults. Reading  
232 proficiency modulated the response to words in the classical reading circuit and contralateral  
233 regions, but also to faces in the fusiform region, in both languages. However, a binary  
234 classification of the participants in typical and struggling readers was less powerful, recovering  
235 a few voxels with significant hypo-activations at expected locations in struggling relative to  
236 typical readers, which did not survive corrections for repeated measures. To circumvent this  
237 reduced power, we next focused on brain regions which have been reproducibly shown to be  
238 under-activated in dyslexics or modulated by Chinese writing, and studied whether and how  
239 reading ability and writing system affected their response to words.

240

#### 241 **Literature driven analyses**

242 Figure 3A presents all foci reported in four published meta-analyses of dyslexia in  
243 alphabetic languages (Linkersdorfer et al., 2012; Maisog et al., 2008; Richlan et al., 2009;  
244 Richlan et al., 2011) and in four meta-analysis of Chinese typical reading (Bolger et al., 2005;  
245 Tan et al., 2005a; Wu et al., 2012; Zhu et al., 2014). As seen in figure 3A, dyslexia in alphabetic  
246 languages is consistently characterized by dysfunctions in the left occipito-temporal,  
247 temporoparietal and frontal regions. All ROIs (except two ROIs in the right-hemisphere) fell  
248 within the reading circuit identified in our participants (Words > other categories; see Figure 4  
249 and Figure 4 — Figure supplement 1). Figure 3B presents the correlation (FDR corrected)  
250 between reading score and activation to words in these ROIS. This correlation reached FDR-  
251 corrected significance in PCG, STS, MTG and FFG, as well as the MFG and RIOG previously  
252 reported in Chinese readers (Fig 3B).

253 We submitted the activation to words relative to fixation in each ROI to a 2×2 ANOVA  
254 with Language and Reading ability as between-subject factors. Below, we report only the *p*-  
255 values that survived an FDR correction over the 13 ROIs.

256 A significant main effect of Language was observed in the left middle frontal gyrus (F  
257 (1,92) = 15.23,  $p < 0.001$ ,  $p_{\text{FDR\_corr}} < 0.001$ ), superior parietal lobule (SPL, F (1,92) = 8.13,  $p =$   
258 0.005,  $p_{\text{FDR\_corr}} = 0.022$ ) and posterior superior temporal gyrus (pSTG, F (1,92) = 9.04,  $p < 0.003$ ,  
259  $p_{\text{FDR\_corr}} = 0.020$ ), always due to larger activation in Chinese readers than in French readers (see  
260 Figure 4).

261 Significant reduced activation was observed in struggling readers relative to typical readers  
262 in the left fusiform gyrus ( $F(1,92) = 21.08, p < 0.001, pFDR\_corr < 0.001$ ), middle frontal gyrus  
263 ( $F(1,92) = 10.17, p = 0.002, pFDR\_corr = 0.009$ ), superior temporal sulcus ( $F(1,92) = 11.88,$   
264  $p = 0.001, pFDR\_corr = 0.006$ ), and precentral gyrus ( $F(1,92) = 7.78, p = 0.006, pFDR\_corr =$   
265  $0.020$ ). Importantly, it was the case within each language group, except for the pSTG where a  
266 significant difference between typical and readers was only observed in French but not Chinese  
267 children (Figure 4). No ROI showed a significant language  $\times$  reading ability interaction (see  
268 Figure 4 and Figure 4—Figure supplement 1), even the pSTG ( $F(1,92) = 2.815, p = 0.097$   
269 before FDR correction).

270 We used Bayesian ANOVAs on the Word activation to assess the likelihood of the null  
271 hypothesis  $H_0$  over  $H_1$  in the case of the interaction language  $\times$  reading ability. As also  
272 explained in the methods, the Bayes factor ( $BF_{10}$ ) is the ratio of the amount of evidence for  $H_1$   
273 above  $H_0$  ( $BF_{01}$  for  $H_0$  above  $H_1$ ). Evidence for  $H_1$  against  $H_0$  is generally considered as  
274 moderate for  $BF_{10} \geq 3$ , and strong for  $BF_{10} \geq 10$ . Bayesian analyses provided similar  
275 conclusions to frequentist analyses for the main effect of Language and Reading ability (table  
276 4). The  $BF_{10}$  for an effect of language was 80.21 in the MFG, 7.05 in the SPL and 9.91 in the  
277 pSTG. The likelihood of an effect of reading ability in the FFG was  $BF_{10} = 1528.97$  higher than  
278 that of the null hypothesis; the same  $BF_{10}$  was 37.51 in the STS, 9.95 in the MFG and 5.63 in  
279 the PCG respectively. It was also the case in the post-hoc analyses within each language (table  
280 4). Notably, there was strong evidence of a reading ability effect in the fusiform gyrus (FFG)  
281 and moderate evidence in the STS and PCG in both languages. In the pSTG and also  
282 paradoxically in the MFG described as a dyslexic marker in Chinese, the evidence of a reading  
283 ability effect was strong in French ( $BF_{10} = 23.74$  and  $29.35$  for each site respectively) but absent  
284 or weak in Chinese children ( $BF_{10} < 1$  and  $1.62$ ). Sensitivity analysis revealed that the Bayes  
285 factor stayed about the same for a wide range of prior specifications (Cauchy prior width: 0-  
286 1.5) in the FFG, STS, PCG and MFG for the comparisons between typical and struggling  
287 readers in each language except for the pSTG in Chinese children.

288 Turning now to the effect of language in each reading group, differences between  
289 languages were mainly observed between the groups of struggling readers: Chinese children

290 showed larger activations than French in the MFG (BF10=309.65) and pSTG (BF10=74.01)  
291 although the same tendency was present in typical readers. The above Bayes factor stayed the  
292 same for a wide range of prior specifications (Cauchy prior width: 0-1.5) in the sensitivity  
293 analysis. However, there was no evidence for a significant interaction language  $\times$  reading ability  
294 in all these ROIs. On the contrary, the null effect was supported by moderate evidence in the  
295 FFG, MFG, STS, PCG, and SPL (respectively BF10 = 0.31, 0.31, 0.31, 0.27 and 0.32, i.e. the  
296 likelihood of the null hypothesis BF01= 3.23, 3.23, 3.23, 3.70 and 3.13); there was no evidence  
297 in either direction in pSTG (BF10= 1.05) (Table 4). Sensitivity analysis revealed that the Bayes  
298 factor stayed about the same for a wide range of prior specifications (Cauchy prior width: 0-  
299 1.5).

300 When these analyses were replicated for the activation to houses and to faces, no main  
301 effect nor interactions were found in any of these ROIs.

302 To summarize, when analyses were focused on specific ROIs outlined in the literature as  
303 sensitive to reading performance or to differences between writing systems, we replicated the  
304 reduced activation to words in struggling readers relative to typical readers in the FFG, MFG,  
305 STS and PCG. Crucially, this reduction was observed in both French and Chinese participants  
306 with no significant interaction language  $\times$  reading ability. Activation in SPL, pSTG and MFG  
307 was also modulated by language, with greater activation in Chinese than in French children.  
308 For the MFG, the language effect was mainly observed in struggling readers, due to a large  
309 reduction in activation in French struggling readers, but not in Chinese struggling readers.

310

### 311 **Individual analyses**

312 The above analyses were carried out in a standardized way at the group level. It is therefore  
313 possible that the observed group differences were due to a greater inter-individual variability in  
314 brain localization in the reading-struggling group than in the typical group. This possibility  
315 would lead to a completely different interpretation of the results: each child might have a well-  
316 organized brain activity for reading, with the only anomaly being a greater anatomical  
317 dispersion in the group of struggling readers compared to the group of typical readers. To test  
318 this possibility, we performed two individual-based analyses, one based on the comparison of  
319 the location and activation values of the most responding voxels and the other examining the

320 stability of the pattern of responses across runs through a multi-voxel pattern analysis (MVPA).  
321 We focused on the ROIs previously showing significant differences due to reading ability (i.e.  
322 left FFG, MFG, PCG and STS) and Language (i.e. left MFG, SPL and pSTG).

323 **Peak analyses:** Considering the locations of the individual centers of mass for word  
324 activations in the left FFG, MFG, STS, PCG, SPL, pSTG, their Euclidean distance to the group  
325 peaks did not differ between children with and without struggling reading (Supplementary file  
326 6), suggesting a similar dispersion among struggling readers and typical readers. These results  
327 of a null effect in peak location were further confirmed by Bayesian analyses (the BF10 for an  
328 effect of reading ability were 0.22, 0.25, 0.23, 0.36, 0.23 for left FFG, MFG, STS, PCG, SPL  
329 and pSTG, respectively, thus supporting the null hypothesis). Furthermore, even after having  
330 selected the best responding voxels in each child, the word activation remained weaker in  
331 struggling than typical readers in the left FFG, MFG, STS, PCG, and pSTG (all  $p_{\text{FDR\_corr}} < 0.05$ ).  
332 French also yielded weaker activations than Chinese children in the left MFG, pSTG and SPL  
333 (all  $p_{\text{FDR\_corr}} < 0.05$ ). There was no significant Language  $\times$  Reading ability interaction in any of  
334 these analyses, supported also by the following BF10 in Bayesian analyses (peak location:  
335 BF10 = 0.38, 0.30, 0.70, 0.35, 0.31, 0.35; peak activation: BF10 = 0.35, 0.377, 0.59, 0.35, 0.00,  
336 0.53 for left FFG, MFG, STS, PCG, SPL and pSTG). These results thus corroborated the  
337 standard analyses.

338 As concerns faces, we did not observe any effect of reading ability or Language on the  
339 peak locations and activations in bilateral fusiform face gyrus (FFA) in both frequentist (all  $p >$   
340 0.09) and Bayesian statistics (all BF10 < 1).

341

342 **MVPA of the activations to words:** The previous analysis asked whether, at the individual  
343 level, the peak activity is reduced in struggling readers. In the present section, we ask the same  
344 question about the stability of the response pattern across runs (i.e. the within-subject reliability  
345 of the activation patterns). Indeed, the reduced activation in the group analysis could be due to  
346 two distinct causes. Struggling readers could have a genuinely reduced and erratic activation,  
347 but alternatively, struggling readers could possess an identifiable and reproducible circuit  
348 similar to typical readers, only with a spatially more dispersed extent. In that case, the within-  
349 subject reproducibility of multivariate activation patterns may not differ between typical and

350 struggling readers.

351 To examine the within-subject reliability of activation across runs, we used a multi-voxel  
352 pattern analysis (MVPA) focused on the same regions than above. We computed the correlation  
353 between pattern of activations in run 1 and 2, separately for within-category patterns (words in  
354 run 1 and words in run 2) versus between-category patterns (average of words-faces, words-  
355 houses and faces-houses, each in run 1 versus run 2). A reproducible reading circuit should  
356 result in a significant effect of Condition (great within-category correlation than between-  
357 category correlation). Furthermore, if the activation pattern is less reproducible in struggling  
358 readers than in typical readers, there should be a significant interaction of this Condition effect  
359 with Reading ability.

360 In all these regions, when pooling over all subjects, there was an overall replicable pattern  
361 of activation evoked by words, as indicated by a significant main effect of condition, with a  
362 greater correlation coefficient within words than between words and other categories (all  
363  $p_{\text{FDR\_corr}} < 0.001$ ) (see Figure 5 and Figure 5—figure supplement 1A). Crucially, we also  
364 observed a significant interaction of condition  $\times$  reading ability (typical vs struggling readers)  
365 in the left FFG ( $F(1, 83) = 10.14, p = 0.002, p_{\text{FDR\_corr}} = 0.006$ ) and in the left pSTG ( $F(1, 83) =$   
366  $15.75, p < 0.001, p_{\text{FDR\_corr}} < 0.001$ ). Post-hoc analysis found that typical readers, but not  
367 struggling readers, exhibited a significantly similar pattern of activation from one run to the  
368 next. Those results show that the above differences between typical and struggling readers were  
369 not due to an artifact of group averaging, and that individual struggling with reading exhibited  
370 a genuinely more erratic activation pattern during reading in these regions (Figure 5).

371 **MVPA of the activations to faces:** For the MVPA analysis in the bilateral fusiform face  
372 areas (bilateral FFA), only the main effect of condition reached significance ( $p_{\text{FDR\_corr}} < 0.001$ ),  
373 with a greater correlation coefficient for within-category patterns (faces-faces) than for  
374 between-category patterns (faces-words, faces-houses, words-houses). Neither the main effect  
375 of reading ability nor the interaction of condition  $\times$  reading ability reached significance. These  
376 results suggest an equally replicable pattern of activation to faces in typical and struggling  
377 readers bilaterally in the fusiform face area (see Figure 5—figure supplement 1B). This pattern  
378 resulted in a triple interaction of category (words versus faces)  $\times$  condition  $\times$  reading ability  
379 when the fusiform data from words and faces were analyzed together, indicating that the

380 reduced stability of activations in struggling readers was specific to words.

381 In summary, individual analyses substantiated a genuine reduction and instability of the  
382 activation to words in struggling readers relative to typical readers. Importantly, this instability  
383 was not universally present in all visual categories (as might be the case if, for instance, the  
384 struggling readers had greater noise or motion), because the activations to Faces in the fusiform  
385 regions did not differ between groups.

386

### 387 **Anterior-to-Posterior gradient in the visual cortex**

388 Finally, given the massive impact of reading on the organization of the ventral temporal  
389 areas, we focused on these regions and examined the anterior-posterior gradient of responses  
390 for the different visual categories vs fixation.

391 **Words:** Keeping constant  $x = \pm 48$  and  $z = -16$ , we studied the activation to Words vs  
392 fixation along the y-axis (ranging from -79 to -22). Firstly, we observed greater response to  
393 words in Chinese children compared to French children in the right hemisphere at several y  
394 coordinates, leading to a significant triple interaction of language  $\times$  hemisphere  $\times$  ROI.  
395 Secondly, we observed larger activation in the posterior relative to anterior sites as revealed by  
396 the main effect of ROIs. Crucially, the reading ability  $\times$  ROIs interaction was significant. In  
397 more detail, compared to typical readers, struggling readers had weaker activation to words at  
398 several consecutive sites (y axis at -64, -55, -46 and -37). However, when we considered  
399 separately Chinese and French children, only one site ( $y = -46$ ) survived correction for multiple  
400 comparison in both Chinese and French children. This site is only slightly anterior to the classic  
401 VWFA site (Cohen, et al., 2000) (see Figure 6B).

402 **Faces:** Keeping constant  $x = \pm 39$  and  $z = -16$ , we also studied the activation to Faces vs  
403 fixation along the y-axis (ranging from -79 to -22). We observed a significant Hemisphere  $\times$   
404 ROI interaction. This effect was due to greater right than left face activation at several y  
405 coordinates ( $y = -73, -64, -55, -46$ ). Besides, the main effect of reading ability reached  
406 significance, due to a lower activation to faces in struggling readers compared to typical readers  
407 bilaterally and in both languages (Figure 6C).

408 **Houses:** Along the medial house specific activation at  $x = \pm 30$  and  $z = -16$ , we similarly  
409 studied the activation to Houses vs fixation. We found a significant triple interaction of language



410 × hemisphere × ROI. French children had greater right than left activation at each of the six  
411 anterior-posterior y coordinates (all  $pFDR_{corr} < 0.005$ ) while Chinese children had the same  
412 pattern only at four sites ( $y = -73, -46, 37, 28$ ). We also observed a significant reading ability×  
413 ROI interaction, with decreased activation to Houses in struggling readers in several sites  
414 (Figure 6D).

415 In summary, we recovered the expected anterior-posterior and medial to lateral gradient of  
416 preferences for the different visual categories. Chinese had larger right-hemispheric activation  
417 to words than French; and struggling readers, in both languages, showed lower activation than  
418 typical readers at the VWFA site. Congruent with the whole brain analyses, we observed an  
419 effect of reading ability on Face activations in both hemispheres. The activation to Houses was  
420 also reduced in struggling readers at several sites.

421

## 422 Discussion

423 In the present study, we examined the universality and specificity of the neural bases of  
424 reading among novice readers by comparing two very different writing systems: French and  
425 Chinese. Our goal was to study whether the same neural circuit was involved in the success and  
426 failure of reading acquisition, regardless of the complexity of the written symbols and the size  
427 of the speech units that are mapped onto them. We investigated this question in 96 10-year-old  
428 children using a similar paradigm in both countries with a minimally demanding task (i.e.  
429 detecting a star) that did not directly tax reading or reading-related cognitive skills and thus was  
430 equally easy for everyone in four age-matched groups (French and Chinese × typical and  
431 struggling readers).

432 First, in a whole-brain analysis, we recovered the classical category-specific activations  
433 for words, faces and houses in extra-striate visual areas across all participants but also in each  
434 group (Figure 1). Second, reading scores were correlated with the word activations in common  
435 key-regions of the reading circuit (left VWFA, posterior superior temporal gyrus/sulcus, middle  
436 frontal gyrus and precentral gyrus) but also in the right hemisphere (middle occipital and  
437 fusiform gyri and precentral). Third, analyses based on ROIs from the literature confirmed these  
438 results, including an effect of reading ability in the left middle frontal gyrus which was true in  
439 both French and Chinese children, contrary to previous suggestions of a Chinese-specific effect



440 at this site. The main effect of reading ability across languages was replicated even when  
441 analyzing only the most responsive voxels in each individual.

442 We also observed a few differences in activations depending on the children's native  
443 language. Chinese reading tended to engage more symmetrical activations in the visual system,  
444 with stronger activations in the right hemisphere than French readers when we specifically  
445 tested the anterior-posterior organization of the fusiform region. Chinese children also had  
446 stronger activations than French children in the left parietal region, middle frontal region and  
447 posterior superior temporal gyrus.

448 We concluded our analyses by examining the reproducibility of the activation patterns  
449 between runs. The within-subject pattern of activity evoked by words was reproducible across  
450 runs in typical readers in all key reading regions, underscoring that the reading circuit is stable  
451 after 3 years of learning to read and can be reliably measured in a single fMRI run even in  
452 children. However, such was not the case for struggling readers, whose activity was  
453 significantly less reliable in left fusiform and posterior superior temporal gyrus in both Chinese  
454 and French struggling readers. We now discuss each of these results in turn.

455

#### 456 **The Reading network is largely universal, but modulated by reading skill**

457 A long-standing debate in reading research is whether the neurobiological circuitry for  
458 reading is universal across languages. Previous cross-cultural fMRI studies have compared  
459 brain activations in adult readers in different languages and suggested that the expert reading  
460 network may be universal across languages (Nakamura et al., 2012; Paulesu et al., 2000; Rueckl  
461 et al., 2015). The current study extends this finding to young children by showing common  
462 activation patterns to words in children in both alphabetic and non-alphabetic writing systems  
463 after only 3-4 years of primary school. Script invariance across English and Chinese was  
464 already reported after only one year of reading acquisition in the VWFA (Krafnick et al., 2016).  
465 This region is also the most strongly modulated by reading proficiency in both French and  
466 Chinese, with no difference (Bayes factor <1) between French and Chinese typical readers but  
467 also between French and Chinese struggling readers, thus confirming that VWFA activation is  
468 a universal marker of reading proficiency. The same observation can be made to a lesser extent  
469 for the STS and the PCG, the activation of which also depends on the reading proficiency in

470 both writing systems in a similar way.

471       These cultural invariance findings are in agreement with the neuronal recycling hypothesis,  
472 according to which recent cultural acquisitions (e.g. reading) rely on the preemption of  
473 universal pre-existing circuits of the human brain, with only small culture-dependent  
474 modulations (Dehaene and Cohen, 2007). In any language, reading recruits a pre-existing  
475 circuit that connects visual areas capable of learning to recognize orthographic symbols, and  
476 spoken language processing areas (Hannagan et al., 2015; Saygin et al., 2016). Successful  
477 literacy acquisition is thus the result of the convergence of visual and speech processing systems,  
478 both of which are likely to be largely universal and partially laid down under genetic control.  
479 Indeed, the spoken language network is already present at its usual left-hemispheric location in  
480 2-month-old babies (Dehaene-Lambertz et al., 2002; Dehaene-Lambertz et al., 2006; Dehaene-  
481 Lambertz and Spelke, 2015). The specific subpart of the ventral visual pathway which is used  
482 to recognize written characters seems to be, at least in part, determined by its pre-existing  
483 connections with this language network (Bartfeld et al., 2018; Bouhali et al., 2014; Hannagan  
484 et al., 2015; Saygin et al., 2016) and by its micro-structure (Weiner et al., 2016). Thus, according  
485 to the neuronal recycling hypothesis, in spite of variations in language and writing systems, a  
486 considerable amount of inter-cultural convergence should be expected.

487       In our study, although the main areas for reading were common to both groups, we also  
488 observed modulations of the amplitude of brain activity within culturally universal brain  
489 circuits. Chinese children had larger activations than French children in (1) left intraparietal  
490 sulcus; (2) left middle frontal gyrus (BA 9); (3) right hemisphere occipitotemporal regions; and  
491 (4) left posterior superior temporal sulcus.

492       Brain imaging research has well documented the role of the left intraparietal sulcus in  
493 visuo-spatial encoding and attention (Davranche et al., 2011; Offen et al., 2010), including the  
494 serial analysis of letters in a word or pseudoword (Cohen et al., 2008). We therefore speculate  
495 that the greater involvement of this region in Chinese reading is presumably due to the greater  
496 amount of spatial analysis required by Chinese character recognition. Indeed, activations in the  
497 inferior parietal region are observed in French children (Dehaene-Lambertz et al., 2018), but  
498 only transiently during initial reading instruction, when children must effortfully pay attention  
499 to the left-right succession of letters and disambiguate mirror-letters. Congruently,

500 improvement in reading skills over the first year of school correlates with microstructural  
501 changes in the connectivity between the VWFA and the inferior parietal region (Moulton et al.,  
502 2019). Activation in the intraparietal sulcus is also needed when adults read in an unusual  
503 format (vertical French words for example) (Cohen et al., 2008) or determine the position of a  
504 letter in a word (Ossmy et al., 2014), underscoring the role of this region in orienting attention  
505 and computing the spatial relationships of word elements. Our results indicate that this process  
506 is involved in alphabetic languages as well as in Chinese, but its activation may remain weak  
507 in alphabetic languages due to the simplicity of the spatial relationships.

508 The greater involvement of the left middle frontal gyrus (BA9) in Chinese than in French  
509 children is in line with existing research (Bolger et al., 2005; Tan et al., 2005a). This region has  
510 been proposed to support language-specific processing required by Chinese reading, such as  
511 whole-syllable retrieval (Tan et al., 2005a), the tonal nature of Chinese phonology (Gandour et  
512 al., 2002), memory-based lexical integration of orthography, phonology and semantics (Perfetti  
513 et al., 2005), visuospatial working memory (Wu et al., 2012) or writing gesture information  
514 (Cao and Perfetti, 2016; Nakamura et al., 2012). In the reading of English, its proposed  
515 functional role is also diverse: lexical semantics (Bolger et al., 2005), phonological processing  
516 (Pugh et al., 1996), lexical selection (Bolger et al., 2008), or grapheme–phonology conversion  
517 (Jobard et al., 2003).

518 Perhaps the most likely explanation is that the LMFG, as well as the more medial and  
519 dorsal Exner area, are systematically involved in writing (Planton et al., 2013; Purcell et al.,  
520 2011). fMRI studies in typical adult readers, comparing French and Chinese reading, have  
521 shown that the left MFG is not specific to Chinese writing, but includes a representation of  
522 handwriting gestures that is engaged in both alphabetical and non-alphabetical languages  
523 (Nakamura et al., 2012). As proposed by Nakamura et al (2012), the activation in the MFG and  
524 PCG, as seen here, might correspond to the “reading by hand” circuit (gesture recognition  
525 system) as opposed to the “reading by eye” circuit (shape recognition system in the VWFA).  
526 Furthermore, writing is not only learned in parallel with reading, but facilitates reading  
527 acquisition in children (Bara et al., 2004). Thus, the involvement of the left MFG in French  
528 children, although less important than in Chinese children, might be due to a heavier  
529 dependence on handwriting during reading acquisition than during adulthood. This

530 interpretation is supported by a recent study showing that, in second-language learners of  
531 Chinese, viewing characters that were learned through character writing induced greater  
532 activation in LMFG compared with those learned without character writing (Cao and Perfetti,  
533 2016).

534 The greater activation in the right ventral visual system in Chinese reading has been  
535 reported in previous literature and this region has been found to show a children-to-adult  
536 developmental increase for Chinese, suggesting that this region is especially important in  
537 Chinese reading acquisition, presumably because of its involvement of holistic visuo-  
538 orthographic processes (Bolger et al., 2005; Cao et al., 2014; Tan et al., 2005a).

539 We also found that Chinese children showed slightly larger activation than French children  
540 in the posterior superior temporal gyrus/sulcus. This region is associated with phonological  
541 processing and grapheme-phoneme conversion (Turkeltaub et al., 2003). Previous findings in  
542 adults suggested that it is more engaged in alphabetic than in logographic languages (Bolger et  
543 al., 2005; Tan et al., 2005a), but our study showed an opposite pattern. In Chinese reading, a  
544 large number of written characters correspond to the same syllable, thus phonological  
545 information is insufficient to access semantics of a printed character. As a result, Chinese  
546 readers must rely more heavily on the direct route from orthography to the lexicon (Cao et  
547 al., 2009; Shu et al., 2003). However, phoneme-level representation still plays an essential  
548 role in learning to read Chinese. This may be especially true in beginners, who rely on  
549 Pinyin, an alphabetic notation which allows children to manipulate different phonological  
550 units such as decomposing a syllable into onset, rime, tone and phonemes. Besides, there  
551 are also several other possibilities that may explain the greater activation of pSTG in Chinese  
552 than in French reading, including the possibility of more complex syllable decoding because of  
553 Chinese tones and connections to spoken language functions, or a need to suppress the  
554 activation of the syllable associated with the character as it leads to competition for character  
555 identification. Besides, contrary to previous studies which used explicit reading tasks, the  
556 current study used an implicit reading task and this area may do something else related to the  
557 target detection during incidental reading. Furthermore, when carefully comparing the  
558 activation of the posterior temporal gyrus with other regions, we found that the greater  
559 activation in Chinese was mainly due to a weak activation in French struggling readers (see

560 Figure 4). Interpretation must be very cautious, given that the language  $\times$  reading ability  
561 interaction was not significant, and that the Bayesian analysis provided no evidence favoring  
562 H0 or H1. Further research will be needed to probe whether a reduction in pSTG activation,  
563 presumably due to a phonological impairment, is a more frequent cause of reading disability in  
564 alphabetical scripts than in Chinese, as suggested by numerous prior studies of dyslexia (Hulme  
565 et al., 2002; Ramus and Szenkovits, 2008; Wydell and Butterworth, 1999).

566 Overall, our findings indicate that learning to read largely involves the same key regions  
567 across cultures and ages, but with quantitative modulations depending on the specific demands  
568 of the task, the learning stage, and culture-dependent characteristics. Our novice readers, who  
569 probably needed to deploy all their resources in order to succeed in reading, may be more  
570 informative than expert adults in objectifying the entire reading circuit (unless the latter are  
571 pushed to their limits by unusual, thus less automatized, format of words presentation, as was  
572 done for instance by Cohen et al., (2008).

573

#### 574 **A universal neural phenotype for reading disability**

575 Some authors have also proposed that the cortical regions mediating reading disability are  
576 different in Chinese and alphabetic languages (left middle frontal gyrus in Chinese versus left  
577 temporo-parietal regions in alphabetic languages) (Siok et al., 2008; Siok et al., 2004). On the  
578 contrary, our results are strikingly similar in Chinese and French struggling readers tested with  
579 the same paradigm, thus suggesting a universal neural phenotype for reading disability. Those  
580 children were less activated in all classical reading-related regions, most notably the VWFA in  
581 the left FFG and the left posterior STG, regions that have been consistently reported to show  
582 lower activations in dyslexics relative to controls in alphabetic languages (Blau et al., 2009;  
583 Martin et al., 2016; Van der Mark et al., 2009). The present study confirms that these reductions  
584 in activation can be observed since childhood in all writing systems, whether alphabetic systems  
585 with deep or shallow orthographies, or in Chinese characters. Hu et al. (2010) reached a similar  
586 conclusion at a later age by comparing a smaller group of 11 Chinese and 11 English dyslexics.

587 Thanks to individual peak location and intensity analyses, as well as multivariate pattern  
588 analyses, we could reject an alternative interpretation which, to the best of our knowledge, was  
589 not explicitly tested in previous studies: the possibility that the reduced activations are an

590 artifact of group averaging, solely due to greater inter-individual variability in the localization  
591 of reading-related circuits in the dyslexic brain. Using individual peak, we observed that the  
592 brain localization to words were not more dispersed among struggling readers than among  
593 typical readers. Using MVPA, we showed that, within individual subjects, the activation  
594 patterns in the VWFA in response to written words were less reproducible across runs in  
595 struggling readers than in typical readers. This was solely the case for words, not for the other  
596 visual categories. We did observe a slightly reduced activation to faces and houses in struggling  
597 readers relative to typical readers, as previously reported in illiterate subjects (Dehaene et al.,  
598 2010), as well as seen in response to non-word stimuli (numbers, abstract strings) (Boros et al.,  
599 2016) and faces in dyslexics (Gabay et al., 2017; Monzalvo et al., 2012). However, the pattern  
600 of activity for faces was stable from one run to the next, contrary to what was found for words  
601 in the MVPA analyses. This observation suggests that the reduced activation to written words  
602 may not reflect a general disorganization of the extra-striate visual areas, but rather a specific  
603 difficulty with written words.

604         Given that the site of the VWFA does not activate strongly to written words in illiterates  
605 (Dehaene et al., 2010; Hervais-Adelman et al., 2019) and in typical children before they learn  
606 to read (Dehaene-Lambertz et al., 2018), its under-activation in struggling readers may simply  
607 reflect the lack of reading practice – in other words, it might be a consequence rather than a  
608 cause of the reading deficit. Dyslexia is likely to be a heterogeneous deficit with a variety of  
609 different causes, including a phonological deficit in many children, but also visual attentional  
610 deficits, plausibly anywhere along the complex processing chain that leads from print to sound  
611 and meaning (Friedmann et al., 2010; Paulesu et al., 2014; Valdois et al., 2012). The present  
612 study cannot distinguish cause from consequence, but it does demonstrate that a reduced  
613 activation in the VWFA is one of the dominant fMRI signatures of reading disability.

614         The other major site of atypical activation reported in the dyslexia literature is the left  
615 posterior STG, a region involved in grapheme-phoneme conversion (Frost et al., 2009;  
616 Turkeltaub et al., 2003) although this location is less consistently found in children than in  
617 adults (Richlan et al., 2011). In our data, only French struggling readers had a significantly  
618 lower activation relative to their controls at this location, but in both languages, struggling  
619 readers exhibited an unstable activation pattern across fMRI runs, suggesting fragile phonetic

620 representations evoked by written stimuli. In agreement with this interpretation, Vandermosten  
621 et al (2019) also observed disrupted phonological representation in a multivariate pattern  
622 analysis but not in the univariate activation analysis in beginning readers with a family risk for  
623 dyslexia. Again, because this site is also under-activated during spoken language processing in  
624 illiterates and in preliterate children compared to adult and children readers (Dehaene et al.,  
625 2010) we cannot ascertain whether its anomalous activation is a cause or a consequence of the  
626 reading disability. Indeed, it does not have to be one or the other, but could be both, as  
627 phonological awareness is known to be both a predictor of future reading (Hulme et al., 2012;  
628 Melby-Lervåg et al., 2012), and a consequence of learning to read in an alphabetical language  
629 (Morais et al., 1986).

630 Finally, we also observed decreased activation in the left middle frontal gyrus, as first  
631 reported in Chinese dyslexics by Siok et al. (Siok et al., 2008; Siok et al., 2004). Activation at  
632 this location was modulated by both reading score and language: overall, Chinese children had  
633 larger activation than French children at this site, but in both languages, struggling readers also  
634 exhibited weaker activation than their controls. Thus, the effects of reading ability and language  
635 on that region seemed to be additive. The first reports of dysfunction in this area were obtained  
636 in Chinese dyslexics and, because of a lack of evidence for a comparable deficit in alphabetic  
637 languages, were interpreted as supporting a unique contribution of this region to Chinese  
638 reading (Siok et al., 2008; Siok et al., 2004). Here, however, we observed reduced activations  
639 in struggling readers relative to typical readers in Chinese, but also in French. The language  $\times$   
640 reading ability interaction was not significant, and Bayesian analyses confirmed the moderate  
641 evidence for a null interaction. Those Bayesian analyses, together with the fact that we easily  
642 detected strong differences between groups (mainly related to reading ability, but also, in a few  
643 regions, to the children's native language) support the hypothesis that our study, with 96  
644 subjects, was sufficiently powered and that cross-linguistic differences in neural deficits in  
645 struggling readers were indeed minimal or absent, in this region as well as elsewhere in the  
646 brain. While a null effect can never be firmly asserted, the present results positively indicate  
647 that atypical activation in this region is not unique to Chinese struggling readers, but can be  
648 found in alphabetic readers as well and is therefore part of a universal phenotype of reading  
649 disability. Note that convergent results were also found in our previous study of French children,



650 where LMFG exhibited significant activation to words relative to other visual categories in  
651 typical readers, but not in dyslexics in an ROI analysis (Monzalvo et al., 2012).

652 Unlike readers of alphabetic languages who only have to acquire a small set of letters and  
653 of grapheme–phoneme correspondences, readers of Chinese must learn a few thousands of  
654 characters. To overcome this difficulty, Chinese readers may rely more on a motor memory of  
655 writing gestures as a means for memorizing the large number of characters, and as noted earlier,  
656 writing skills predict reading ability in Chinese children (Tan et al., 2005b). The greater  
657 activation of the left MFG may therefore reflect the greater reliance of Chinese children on  
658 writing, and the dysfunction of this region in Chinese struggling readers may reflect an  
659 underlying deficit in memorizing writing gestures (Ziegler, 2006). This strategy is not unique  
660 to Chinese, however: novice readers in alphabetic languages also benefit from a motor memory  
661 for hand gestures when recognizing written words (Bara et al., 2004), and a recent study found  
662 that a motor representation of handwriting gestures is automatically accessed for subliminal  
663 written words in both Chinese and French adult readers (Nakamura et al., 2012). Our findings  
664 on children further suggest that the left MFG is likely to play a pivotal role in successful reading  
665 acquisition independently of the writing system.

666

### 667 **Limitations and future direction**

668 Several limitations of the present study need to be considered. First, our task was  
669 orthogonal to reading, and involved the mere detection of a picture of a star. This choice was  
670 made to avoid any effect due to performance itself. A task that is more difficult for some  
671 children than from others could have induced greater activation, but also greater movement in  
672 the scanner. The disadvantage is that participants were not explicitly instructed to attend to  
673 words, which could have increased the differences between typical and struggling readers, and  
674 between French and Chinese readers. Note, however, that our results indicate a strong  
675 sensitivity of our procedure to reading proficiency, since reading performance was correlated  
676 with activation in all key areas of the reading circuit (VWFA, posterior STG, MFG and pre-  
677 central (Fig 2 and Table 3).

678 Although our groups were larger than in any previous study comparing Chinese and  
679 alphabetic writing systems, and were also more homogeneous in age, whole-brain analyses at



680 corrected-level of significance failed to show significant differences between typical and  
681 struggling readers. Our conclusions are therefore based primarily on analyses of ROIs that were  
682 previously established in the literature as being critical to reading proficiency. Our small effect  
683 size may be due to the definition of our groups, which included struggling readers that were not  
684 full-blown dyslexics. Indeed, the reading delay in Chinese children was less than in French  
685 children (Table 1), but even in French children who were typical French dyslexics (more than  
686 2 years of delay in the LUM test), whole-brain analyses were poorly sensitive, which underlines  
687 the difficulties of pediatric research. Constraints on experiment duration are severe with young  
688 children, and make it difficult to collect the same extensive datasets as in adults. A lack of  
689 sensitivity could also have arisen from the greater variance between children in terms of  
690 maturation, learning experience, attention and concentration on the task compared to adults  
691 who can remain attentive, perform more consistently, and are generally at the peak of the skill  
692 being tested (i.e., no longer learning). Furthermore, the difference between typical and  
693 struggling readers may be smaller in children than in adults because even the normal children  
694 are still in the process of learning and are therefore not fully competent, whereas the adult  
695 typical readers (often recruited at university) are at ceiling. Finally, as has been shown in  
696 alphabetic languages, the slope of normal reading acquisition in children depends on the  
697 transparency of the writing system. In other words, a typical 10-year-old reader would not  
698 perform equally well in English, French, German or Italian (even if we could use exactly the  
699 same test) because he or she has not yet attained the same level of reading fluency. Thus,  
700 comparing languages and assessing equivalent reading delay in different writing systems, while  
701 still matching for age and education, raises complex issues and increases the difficulties of  
702 intercultural comparisons in children compared to adults.

703       However, since we had a particular interest in understanding the role of previously  
704 identified brain regions, an analysis based on ROIs was a reasonable choice, having the great  
705 advantage of mitigating the problem of multiple comparisons and reducing the risk of false  
706 negatives, but also allowing us to examine activation patterns at an individual level, as in the  
707 MPVA analyses. These targeted analyses were able to show the role of MFG in alphabetic  
708 languages. As usual in science, the results will need to be confirmed in future studies using  
709 larger samples to obtain more robust inferences.

710 In conclusion, with several convergent analyses, we revealed that the neural bases of  
711 reading in typical and struggling children are largely similar, but partly language-specific, in  
712 French and Chinese readers. Across these very different writing systems, the cultural invention  
713 of reading relies on similar brain resources. As previously noted in an adult fMRI study  
714 (Nakamura et al., 2012), cultural variability is merely reflected in the variable emphasis that  
715 different writing systems put on phonemes, syllables and whole words, which in turn may  
716 modulate the severity of dyslexia and the degree of anomaly that can be detected at different  
717 locations along the brain's reading circuitry.

718

## 719 **Materials and Methods**

### 720 **Participants**

721 Ninety-six children participated in the current study, including 24 Chinese struggling  
722 readers (mean age = 123 months, standard deviation (SD) = 10), 24 Chinese typical readers  
723 (mean age = 123 months, SD = 11), 24 French struggling readers (mean age = 123 months, SD  
724 = 10) and 24 French typical readers (mean age = 123 months, SD = 11). All children reported  
725 normal hearing and corrected-to-normal vision and no history of neurological or psychiatric  
726 disorder. Nonverbal IQ, assessed by Raven's Standard Progressive Matrices in Chinese children  
727 and Wechsler Intelligence Scale in French children, was in the normal range for all participants.  
728 The study was approved by local institutional review boards in Beijing (China) and Kremlin-  
729 Bicêtre (France), respectively. Written consent was obtained from all children and their parents.

730 **Chinese participants:** Because standardized tests of dyslexia are not available in Chinese,  
731 we tested a large population of 2554 primary school children in Beijing (3rd grade- 5th grade,  
732 10-13 years of age) to calculate the standard norms in the following tests. The first round of  
733 tests involved: (1) Chinese Character Recognition Test (CCRT) (Wang and Tao, 1993), (2)  
734 Reading Comprehension Test (RCT) (You et al., 2011), (3) Raven Progressive Matrices Test  
735 (Raven et al.), and (4) Digit Cancellation Test (Mirsky et al., 1991). Children with a CCRT Z-  
736 score below -1.25 SD were identified as potential struggling children. We then invited these  
737 children and their parents to take part in a second-round of tests, which involved MRI scanning  
738 and several individually-administered tests: (5) Chinese Phonological Awareness Test (CPAT),  
739 (6) Character Reading Test (CRT) (Li et al., 2012), and (7) Rapid Automatized Naming Test. A

740 total of 103 children with different age and reading abilities were scanned and more information  
741 about these children can be found in a previous paper (Li et al., 2018). We considered struggling  
742 readers whose CCRT Z-score, or CPAT Z-score, was consistently low in both rounds of tests  
743 (specifically  $<-1.25$  SD in the first and  $<-1.5$  in the second) and obtained 24 children. We then  
744 selected an equal number of typically developing children ( $> -0.5$  SD in all reading-related tests)  
745 whose age, sex and non-verbal IQ matched those of the reading-struggling group (Table 1 and  
746 Supplementary file 1). By definition of the groups, the two groups were significantly different  
747 (CCRT:  $t = 18.03$ ,  $p < 0.001$ ).

748 **French participants:** To match the Chinese children, we selected 24 struggling readers  
749 and 24 typical readers from two previously published French studies: 21 struggling readers and  
750 18 typical readers from the Monzalvo et al's study (Monzalvo et al., 2012), and 3  
751 struggling readers and 6 typical readers from the population of Altarelli et al's (2013) study.  
752 French children struggling with reading were diagnosed in a dedicated learning disability center  
753 based on extensive behavioral testing with nationally established criteria following INSERM  
754 recommendations (clinical examination, full-scale IQ, standardized tests for working memory,  
755 meta-phonology, spelling, rapid automatic naming, etc.). At the time of fMRI scanning, we  
756 checked their current reading level with "L'alouette", a standardized reading test classically  
757 used to detect dyslexia in French speaking children (Lefavrais, 1967). It consists in reading as  
758 fast and accurately as possible a meaningless text of 265 words within 3 min (Lefavrais, 1967).  
759 All French struggling readers included in this study had at least  $-1.25$  SD below in this test.  
760 French and Chinese children were matched in age and sex in each group (see also Table 1 and  
761 Supplementary file 2). By definition of the groups, the two groups were significantly different  
762 ("Alouette":  $t = 14.66$ ,  $p < 0.001$ ).

763 Due to differences in writing systems, the reading skills expected at a given age are  
764 different in alphabetic languages and Chinese. Here, French children were assessed by reading  
765 a text and Chinese by character recognition. Therefore, the direct comparison of children's  
766 performance across languages provides an indication of the distance between typical readers  
767 and the children with reading difficulties, rather than an absolute assessment of dyslexia. While  
768 reading scores were similar in French and Chinese typical readers ( $t < 1$ ), French struggling  
769 readers tended to have worse scores than Chinese struggling readers ( $t = 2.45$ ,  $p = 0.07$ ), leading

770 to an interaction between language and group ( $F(1,92)=3.91, p=0.051$ ).

771

## 772 **Stimuli and task**

773 For French children, the experimental procedure was identical to Monzalvo et al. (2012).  
774 The procedure was adapted to Chinese children by replacing French words and Caucasian faces  
775 by Chinese words and Asian faces. While being scanned, Chinese and French children viewed  
776 short blocks of words, faces and houses and of a revolving checkerboard (30 frequent regular  
777 words known by young readers and 30 black and white pictures in each category) followed by  
778 a fixation cross during 10.5 s (total bloc duration 28.5 s). In each block, 10 pairs of different  
779 images belonging to the same category (200 ms presentation for the first picture/word, 200 ms  
780 inter-stimulus, 500 ms presentation for the second picture/word) were presented, separated by  
781 a 600 ms fixation period. Besides, two stars were randomly inserted in each block, 1500 ms for  
782 each star. Children were instructed to press a button with their right index finger whenever a  
783 target star appeared. This task was designed to keep their attention focused on the visual stimuli,  
784 but without any explicit reading requirement. For Chinese children and the older French  
785 children, a supplementary category (tools) was added but not included in the present analyses  
786 as this category was not presented in the original study (Monzalvo et al., 2012) and thus missing  
787 in most of the French children reanalyzed here.

788 In each run, there were two blocks of each visual category and only one block of  
789 checkerboard. All the blocks were presented in a random order. Chinese children performed  
790 two runs and French children performed four runs in Monzalvo et al (2012), and only one run  
791 in Altarelli et al (2013).

792

## 793 **fMRI Acquisition Parameters**

794 fMRI data were acquired on two Siemens 3T scanners using a 12-radiofrequency-channel  
795 head coil and the same gradient-echo planar imaging sequence in France and China with the  
796 following parameters: 40 contiguous 3mm isotropic axial slices, TE/TR = 30/2400 ms, flip  
797 angle = 81°, voxel size = 3 × 3 × 3 mm, matrix = 64 × 64. A high-resolution T1 weighted volume  
798 was also acquired with the following parameters: 176 1mm isotropic axial slices, TE/TR =  
799 4.18/2300 ms, flip angle = 9°, matrix = 256 × 256.

800 Prior to the scanning session, all children underwent a training session in a mock scanner.  
801 This training session aimed to help children become familiar with the MRI environment and  
802 task instructions, and to teach them to keep their head motionless during the scan.

803

#### 804 **Data pre-processing and statistical analyses**

805 Preprocessing and analyses of the data were done using SPM12. The French and Chinese  
806 data were processed together. The functional images were first corrected for differences in slice-  
807 acquisition time and realigned to the first volume in the scanning session. ArtRepair toolbox  
808 was used to detect and repair bad volumes (Mazaika et al., 2007). Two criteria were used to  
809 detect bad volumes: (1) 1.5 % variation in the global average BOLD signal from scan to scan  
810 and (2) 0.5 frame-wise displacement, reflecting the sum of all head movements from scan to  
811 scan (calculated from realignment parameters). The damaged volumes that exceeded these  
812 criteria were replaced by linear interpolation of previous and subsequent images or by nearest-  
813 neighbor interpolation when several consecutive images were affected.

814 For the anatomical image, we first checked for scanner artefacts and gross anatomical  
815 abnormalities, then we manually set the origin of T1 image to the anterior commissure for each  
816 subject. We normalized each child's anatomy to the Montreal Neurological Institute (MNI)  
817 template using the DARTEL approach to improve segmentation accuracy and local registration  
818 among participants. Functional images were co-registered to their corresponding anatomy.  
819 Then the parameters obtained during the DARTEL wrapping process were applied to the  
820 functional images which were finally smoothed using a 6 mm Gaussian kernel.

821 The pre-processed functional images were then submitted to a first level statistical analysis:  
822 in each subject, a general linear model was built in which a hemodynamic response function  
823 and its time derivative were convolved with block onsets for each category and the 6 motion  
824 parameters entered as regressors of non-interest.

825

#### 826 **Data-driven Analyses**

827 **Whole brain analyses:** We implemented a mixed-model analysis of variance (ANOVA)  
828 with language (French vs. Chinese) and reading skill (typical vs. struggling readers) as between-  
829 subject factors, and Category (Words vs. Faces vs. Houses) as a within-subject factor. We

830 recovered category-specific activations through the contrasts [category X > mean of the other  
831 two categories] across the whole group (N = 96). We report effects at a threshold of  $p < 0.001$   
832 at the voxel level and  $p < 0.05$  family wise error (FWE) corrected for multiple comparisons at  
833 the cluster level (denoted  $p_{\text{FWE\_corr}}$ ).

834 To deepen our analyses of the effect of reading performances, we studied the correlation  
835 between reading performance (standard scores in reading test) and the word and face activation  
836 in the 96 children. We report effects at a threshold of  $p < 0.001$  at the voxel level and  $p < 0.05$   
837 FWE corrected for multiple comparisons at the cluster level.

838 For these analyses, we displayed in the corresponding figures the results in each of the four  
839 groups (N = 24) or in each language (N = 48) at a threshold of  $p < 0.001$  at the voxel-level, non-  
840 corrected at the cluster-level to provide the reader with the full information on the activation  
841 patterns in each group.

842

843 **Mask-restricted analyses:** To maximize the sensitivity to differences between groups, we  
844 focused our analyses on a restricted mask of voxels corresponding to the word-specific  
845 activation across all children determined by the [Words > Faces + Houses] contrast ( $p < 0.001$   
846 voxel level and  $p_{\text{FWE}} < 0.05$  cluster level, size  $\sim 7497 \text{ mm}^3$ ). We performed an ANOVA with  
847 language (French vs. Chinese) and reading skill (typical vs. struggling readers) as between-  
848 subject factors. To provide readers with full information, we report these results at the threshold  
849 of voxel-level  $p < 0.001$ , non-corrected at the cluster-level.

850

### 851 **Literature driven Analyses**

852 As the number of comparisons at the voxel-level might decrease the sensitivity to small  
853 differences between typical and struggling readers, we focused on Regions of Interest (ROI),  
854 which have been repeatedly shown in the literature to show a reduced activation in dyslexics.  
855 We first searched published meta-analyses of imaging studies reporting brain regions showing  
856 functional dysfunction in dyslexics in alphabetic languages (Linkersdorfer et al., 2012; Maisog  
857 et al., 2008; Richlan et al., 2009; Richlan et al., 2011). To create representative ROIs for these  
858 dyslexia-related regions, we collected all of the foci reported in each meta-analysis  
859 corresponding to the anatomical location under consideration (see Supplementary file 4), and

860 averaged the reported coordinates (x, y, z respectively) to create a 6-mm-radius sphere of the  
861 averaged locus as a ROI (see Figure 3).

862 Due to the limited number of published neuroimaging studies of Chinese dyslexia, no  
863 meta-analysis was available to summarize the available evidence into a pooled estimate.  
864 However, atypical activation in a lateral prefrontal region within BA 9 has been reported in  
865 Chinese children with reading disability (Siok et al., 2004; Siok et al., 2009) and this region  
866 was repeatedly found to be more involved in reading Chinese than alphabetic languages (Bolger  
867 et al., 2005; Nakamura et al., 2012; Tan et al., 2005a). Besides, previous studies also often  
868 reported that Chinese reading networks are more symmetrical in the ventral visual system. We  
869 thus included the foci in both left middle frontal gyrus and right occipital cortex that were  
870 reported in several meta-analyses on Chinese typical reading (Bolger et al., 2005; Tan et al.,  
871 2005a; Wu et al., 2012; Zhu et al., 2014) and created representative ROIs as above (see  
872 Supplementary file 5). In total, we obtained 10 ROIs related to dyslexia in alphabetic languages  
873 and 3 additional ROIs potentially related to Chinese typical reading and dyslexia (**Figure 3**).

874 We extracted the mean contrast-weighted beta values for the words vs. fixation contrast in  
875 each ROI in each child and first considered whether these values were correlated with the  
876 reading score across all participants (figure 3), second entered these values in an ANOVA with  
877 language (Chinese vs. French) and reading skills (typical vs. struggling readers) as between-  
878 subject factors. The false discovery rate (FDR) multiple-comparison method was implemented  
879 to take into account the multiple ROIs. We did the same analyses in the same ROIs for the  
880 contrasts of faces vs fixation and houses vs fixation. The FDR corrected p value is denoted as  
881  $p_{FDR\_corr}$ .

882 Because some of our analyses evaluated the null hypothesis of no difference between two  
883 factors, we also performed Bayesian analyses on the same data, with the same factors as the  
884 ANOVA above, using the JASP software (<https://jasp-stats.org>). These analyses yield a Bayes  
885 Factor (denoted BF10), which estimates the likelihood ratio of the positive (1) over the null (0)  
886 hypothesis. A BF10 of 0.20, for instance, indicates a five-times (1/0.20) greater likelihood in  
887 favor of the null hypothesis and is equivalent to the inverse notation BF01=5.

888

889 **Individual analyses**



890       **Peak analyses:** We further investigated whether children struggling with reading might  
891 have a greater inter-individual variability in brain localization, which could putatively explain  
892 a lower activation at the group level in each voxel. We focused on those regions showing  
893 significant main effects of reading ability or language in the group activation analysis (i.e. left  
894 FFG, MFG, precentral, STS, pSTG, and SPL) and searched for active voxels (Words > fixation)  
895 in each participant in a sphere (radius = 12 mm) centered on the whole group peak coordinates  
896 in the [Words > Faces + Houses] contrast. We eliminated voxels with t-value inferior to 1 and  
897 then selected the 10 strongest activated voxels within the search area. We first derived the  
898 individual center of mass of these voxels by averaging their x, y, z coordinates and calculated  
899 the distance between this center of mass and the group peak coordinates in each child. Second,  
900 we averaged the beta values measured in these voxels to obtain the maximal activation in each  
901 child. We then separately entered distance and activation into language  $\times$  reading ability  
902 frequentist and Bayesian ANOVAs to investigate whether children struggling with reading  
903 differed in peak location and activation intensity compared to typically developing children.  
904 We performed a similar analysis on the face responses in the bilateral fusiform face areas (FFA)  
905 to investigate whether struggling readers had greater inter-individual variability in the location  
906 and intensity of face activations.

907

908       **Multivariate Pattern Analysis (MVPA):** Our final investigation of putative differences  
909 related to language or to reading ability was based on MVPA analysis. We focused on the  
910 regions showing significant main effects of reading ability or language in the univariate  
911 activation analysis and drew a 9-mm radius sphere centered on the averaged coordinates of foci  
912 reported in meta-analyses, and then intersected each sphere with the mask [Words > Faces +  
913 Houses] described above to obtain a fair representation of the group activations in the mask.  
914 All the voxels within the mask were included for MVPA analysis.

915       Secondly, within each ROI, we quantified the within-subject reproducibility of the patterns  
916 of activation by calculating in each subject the correlation coefficients between the pattern of  
917 response evoked by words relative to fixation during the first run and the pattern of response  
918 evoked by each category (words, faces and houses) relative to fixation during the second run.  
919 The correlation coefficients were converted into Z-scores and entered into a separate ANOVA



920 for each ROI with language (Chinese vs French), reading ability (typical vs struggling readers),  
921 and condition (within-category correlation (i.e. words with words), vs between category  
922 correlation (i.e. words with faces, words with houses, faces with houses) as factors.

923 We performed a similar analysis in the bilateral face fusiform areas to investigate whether  
924 struggling readers showed reproducible activation patterns to faces. Bilateral face ROIs were  
925 spheres with a 9-mm radius centered on the reported peak coordinates in the face-selective  
926 activation in previous studies (left [-39, -45, -18], right [39, -45, -18]) (Downing et al., 2005).  
927 We intersected each sphere with the whole group activations [Face > Words + Houses] to obtain  
928 a mask (~1318 mm<sup>3</sup>). All the voxels within the mask were included for MVPA analysis. We  
929 then calculated the correlation coefficients between the pattern of response evoked by faces  
930 relative to fixation during the first run and the pattern of response evoked by each category  
931 (faces, houses and words) relative to fixation during the second run in each subject.

932 Note that six French typical readers and three French struggling readers from Altarelli et  
933 al's study (2013) completed only one run of the visual task, so that they were not included in  
934 this MVPA analysis. For those children who had 4 runs, we used their first two runs to calculate  
935 the correlation coefficients between runs. The FDR multiple-comparison method was again  
936 used as a correction for the multiple ROIs tested.

937

### 938 **Anterior-to-Posterior organization of the ventral temporal cortex**

939 In the following analyses, we focused on the ventral occipito-temporal region, because it  
940 is the site of one of the major changes related to reading: the emergence of a specific response  
941 to words in literates and also the site of the most reproducible hypoactivation in dyslexics  
942 compared to typical readers in alphabetic writing (Richlan et al., 2011). Because activations to  
943 words, faces and houses display a gradient both along the anterior-to-posterior (i.e. "y") axis  
944 and lateral-to-medial (i.e. "x") axis (Baker et al., 2007; Scherf et al., 2007), we averaged the  
945 activity in successive spheres along the anterior-posterior axis at the "x" privileged position for  
946 each visual category and compared typical and struggling readers in Chinese and French  
947 participants. The spheres had a 6-mm-radius and were regularly spaced with the center  
948 positioned at y = -73, -64, -55, -46, -37, -28 respectively, x and z positions being kept constant  
949 (z = -16). The x position was based on the peak of the category-specific activation (category >

950 others) in all participants, i.e. for Words:  $x = \pm 48$ ; Faces:  $x = \pm 39$ ; and Houses:  $x = \pm 30$  (see  
951 Table 2)

952 We performed a separate ANOVA for each visual category with language and reading  
953 ability as between-subject factors, ROI (6 y-axis positions) and Hemisphere (left and right) as  
954 within-subject factors. In each ANOVA, we corrected for multiple comparisons using the FDR  
955 method.

956

957

958 **Conflict of interest** The authors declare no conflict of interest

959

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964

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1241 **Table 1. Characteristics of the four groups**

	<b>Chinese</b>		<b>French</b>	
	<b>Typical</b>	<b>Struggling</b>	<b>Typical</b>	<b>Struggling</b>
Sample size	24	24	24	24
Age in months (SD)	123 (11)	123 (10)	123 (11)	123 (10)
Sex	13M/11F	16M/8F	13M/11F	16M/8F
Reading ability	0.67	-1.74	0.73	-2.16
(CI 95%)	(0.49~0.86)	(-1.95~-1.54)	(0.39~1.07)	(-2.38~-1.94)

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1244 **Table 2. Regions of significant activations for each visual category vs the two others across**  
 1245 **all participants**

<b>Region</b>	<b>MNI coordinates</b>	<b>Peak <i>p</i>-value</b>	<b>Peak <i>z</i>-value</b>
<b>Words &gt; others</b>			
Left inferior frontal gyrus	-48 12 30	2.06e-19	8.93
Left precentral	-39 0 36	1.45e-18	8.72
	-51 6 39	2.91e-14	7.51
Left superior temporal gyrus/sulcus	-57 -30 3	2.39e-19	8.92
Left middle temporal gyrus	-51 -42 6	7.89e-18	8.52
Left fusiform gyrus	-48 -57 -15	1.69e-17	8.43
Left Inferior parietal sulcus	-45 -39 42	4.29e-14	7.46
Right superior temporal sulcus	57 -27 3	8.94e-10	6.02
<b>Faces &gt; others</b>			
Left fusiform gyrus	-39 -48 -21	3.28e-17	8.35
Right fusiform gyrus	42 -54 -18	6.14e-26	10.47
Right amygdala/ hippocampus	18 -9 -18	6.11e-22	9.56
Left amygdala/ hippocampus	-18 -9 -18	3.91e-15	7.77
<b>Houses &gt; others</b>			
Left fusiform gyrus	-30 -48 -6	9.01e-53	15.24
Right fusiform gyrus	30 -45 -9	2.90e-50	14.86
	27 -63 -9	2.40e-22	9.65
Left calcarine	-18 -54 9	8.66e-10	6.02

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1252 **Table 3. Regions significantly correlated with reading scores across all participants at the**  
1253 **whole-brain level**

<b>Region</b>	<b>MNI coordinates</b>	<b>Peak <i>p</i>-value</b>	<b>Peak <i>z</i>-value</b>	<b>R-value</b>
Left fusiform gyrus	-42 -45 -18	6.65e-6	4.36	0.490
Right fusiform gyrus	42 -66 -24	9.96e-6	4.27	0.512
Left precentral	-36 -3 57	2.75e-6	4.54	0.467
Right precentral	54 18 33	1.29e-5	4.21	0.432
Left middle frontal gyrus	-36 12 27	1.92e-5	4.12	0.468
Right middle frontal gyrus	45 6 54	7.72e-6	4.32	0.460
Left superior temporal sulcus	-57 -24 0	1.00e-5	4.26	0.510
Right middle occipital gyrus	27 -69 42	6.34e-6	4.37	0.448

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1257 **Table 4. Bayes factor (BF10) in language × reading ability Bayesian ANOVA analysis of**  
 1258 **children’s activation to words versus fixation**

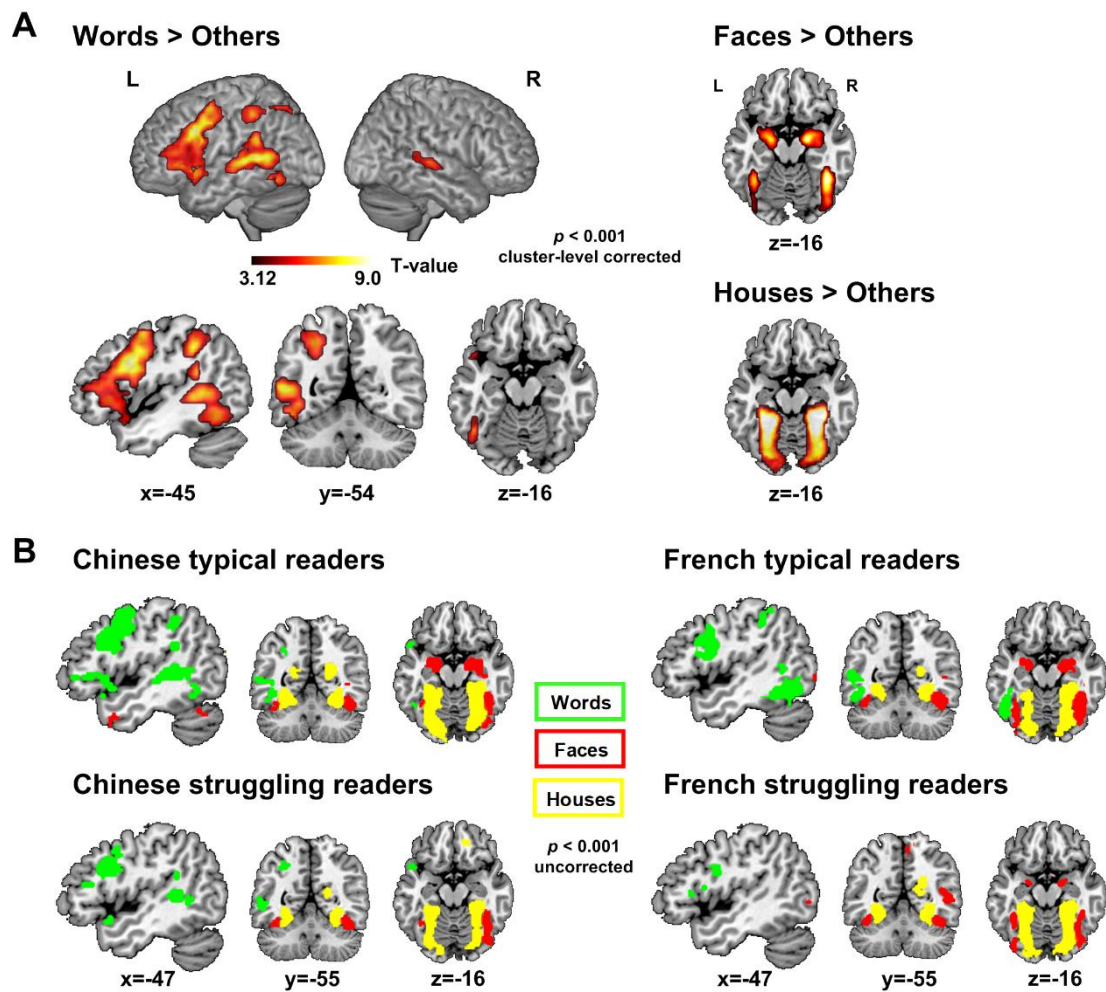
ROIs	Main effect of language	Main effect of reading ability	Interacti on	Post-hoc analysis			
				Typical (Chinese vs French)	Struggling (Chinese vs French)	Chinese children (typical vs struggling)	French children (typical vs struggling)
FFG	0.216	1528.966	0.313	0.227	0.337	13.577	93.163
MFG	80.211	9.948	0.305	2.837	309.651	1.616	29.351
STS	0.220	37.507	0.309	0.387	0.259	6.933 <sup>a</sup>	5.076
PCG	1.532	5.625	0.275	1.782	1.075	2.662	2.661
SPL	7.052	0.562	0.323	4.486	1.782	0.822	0.332
pSTG	9.908	0.289	1.054	0.616	74.014	0.215	23.744

1259 The value of Bayes factor BF10 means that data are n times more likely under alternative  
 1260 hypothesis (H1) than null hypothesis (H0). The alternative hypothesis in comparisons between  
 1261 typical and struggling readers is group 1 (typical) > group2 (struggling); the alternative  
 1262 hypothesis in comparisons between languages is group 1 (Chinese) > group2 (French);

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1265 **Figures**

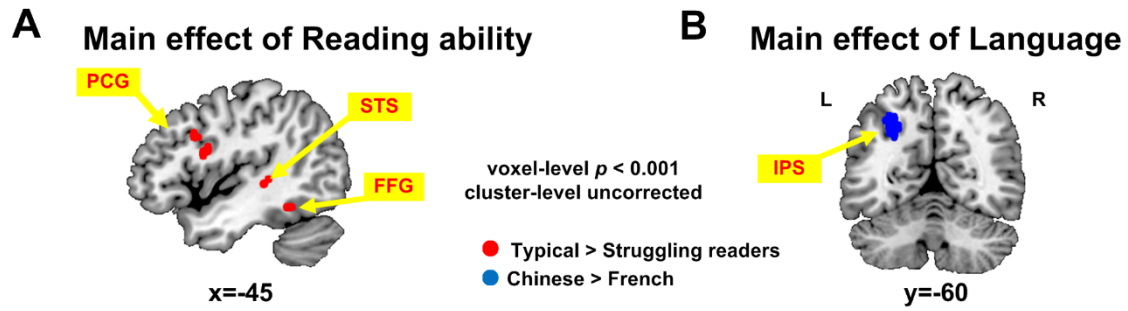


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1267 **Figure 1. (A) Category-specific circuits across all participants** (voxel-level  $p < 0.001$ ,  
 1268 cluster-level FWE corrected  $p < 0.05$ ). On the left, the reading circuit identified by the contrast  
 1269 Words > [Faces, Houses] and on the right: Face-selective (Faces > [Words, Houses]) and House  
 1270 selective regions (Houses > [Words, Faces]). (B) **Category-specific circuits in each of the**  
 1271 **four groups** (voxel-level  $p < 0.001$ , cluster-level uncorrected). On the left, category-specific  
 1272 activations in Chinese typical readers (above) and Chinese struggling readers (below). On the  
 1273 right, category-specific activations in French typical readers (above) and French struggling  
 1274 readers (below). Green: regions selectively activated by words (Words > [Face, House]); Red:  
 1275 regions selectively by faces (Face > [Word, House]); Yellow: regions selectively activated by  
 1276 Houses (House > [Word, Face]);

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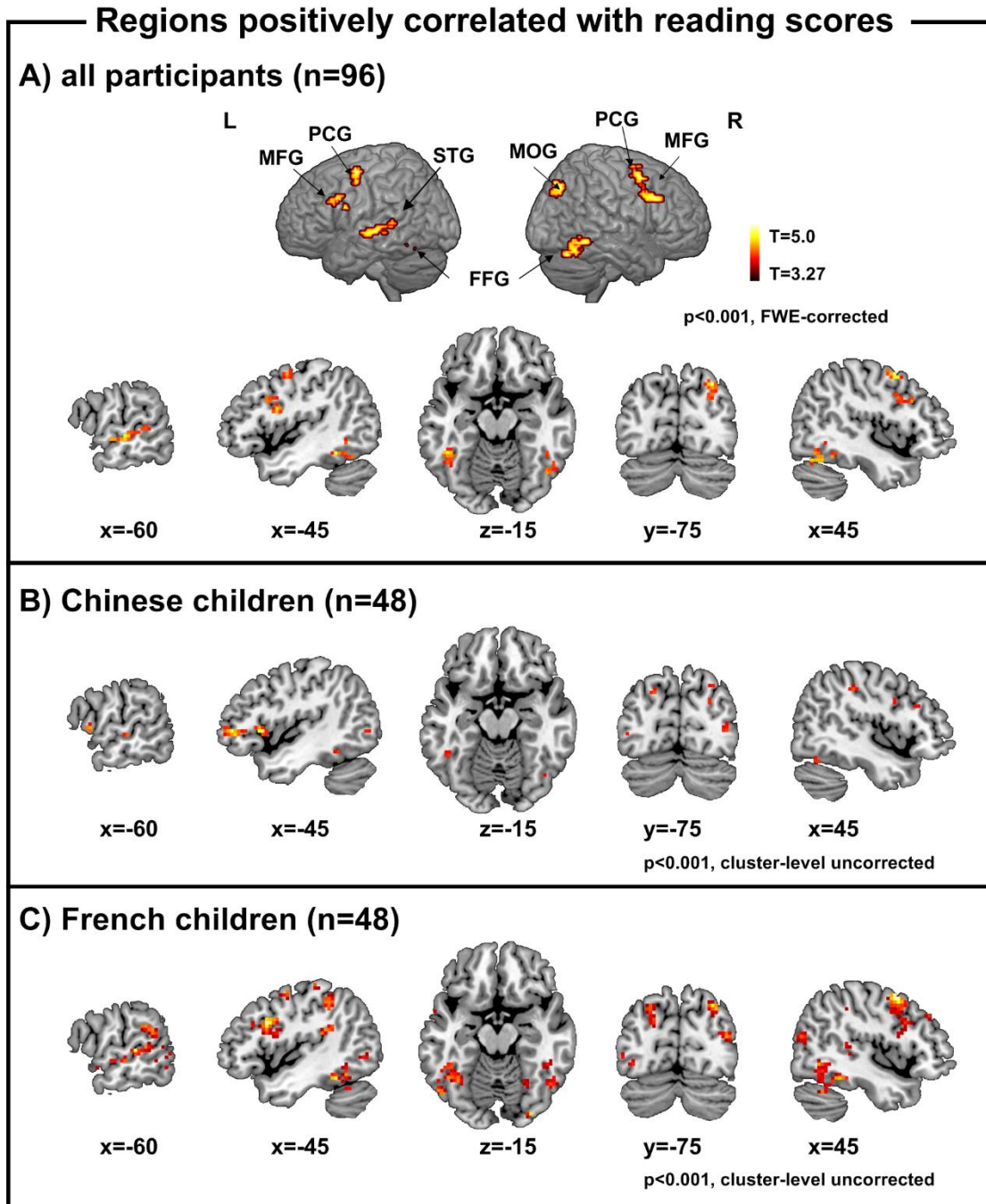
1278 The following figure supplements are available for figure 1:



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1281 **Figure 1—Figure supplement 1.** (A) A few voxels in the left fusiform gyrus, left precentral  
1282 and left superior temporal sulcus reached the voxel threshold ( $p = 0.001$ ) in the  $2 \times 2$  language  
1283  $\times$  reading ability ANOVA analysis. Only the left precentral region survived the multiple  
1284 comparisons within the mask of word-specific voxels. (B) A main effect of language was  
1285 observed in the left intra-parietal sulcus (55 voxels,  $p_{\text{FWE}_{\text{corr}}} = 0.004$ ,  $z = 4.29$  at  $[-30 -60 39]$ ),  
1286 significant at corrected level within the mask of word-specific voxels, due to larger activation  
1287 in Chinese than French children.

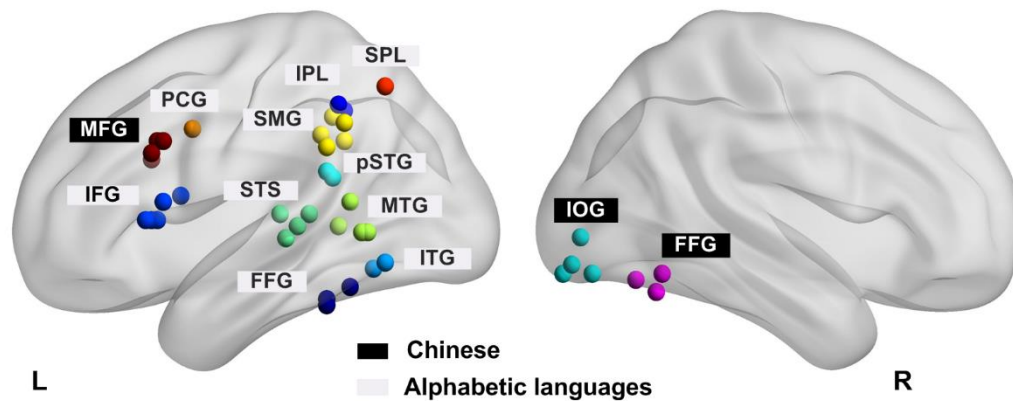


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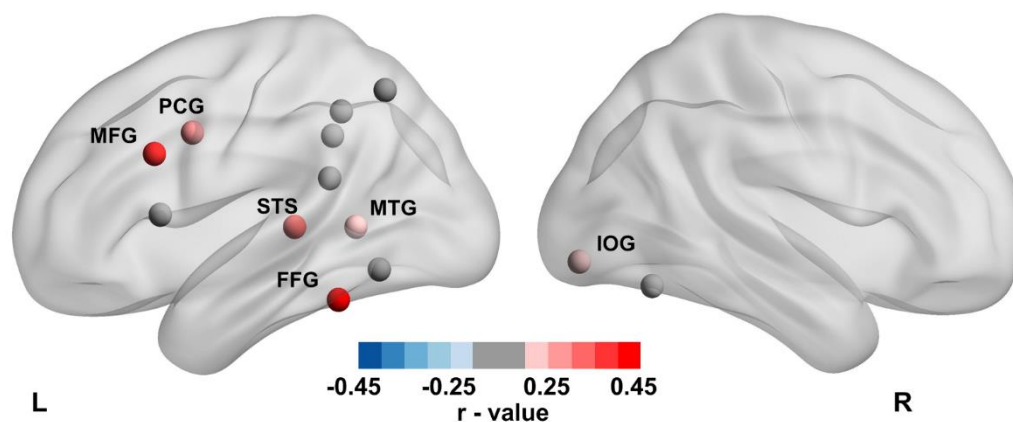
**Figure 2. Neural correlates of inter-individual variability in reading scores.** (A) The figure shows the regions whose activation in the words versus fixation contrast was positively correlated with reading scores across all participants at the whole-brain level (voxel-wise  $p < 0.001$  and cluster-wise  $p < 0.05$  FWE corrected). (B)(C) Regions positively correlated with reading scores in Chinese and French children (voxel-wise  $p < 0.001$ , cluster-level uncorrected).



### A Dyslexia-sensitive foci reported in different meta-analyses



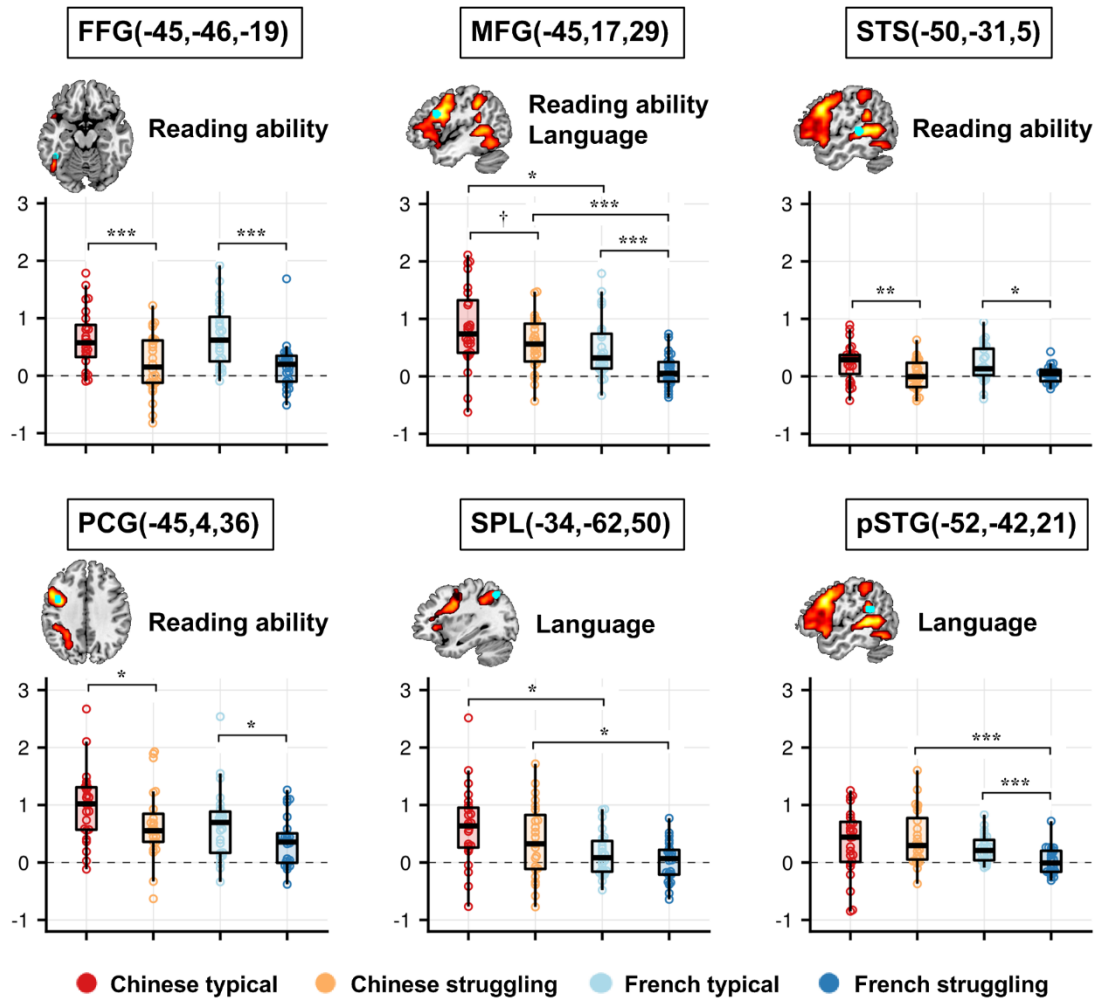
### B ROI seeds generated by averaging foci belonging to the same region



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1296 **Figure 3: Regions of interest (ROIs) used to analyze the data.** (A) Each sphere represents a  
1297 peak reported in the literature; Labels in white background indicate foci reported in meta-  
1298 analyses of dyslexia in alphabetic languages; Labels in black background indicate foci reported  
1299 in meta-analyses of Chinese reading. (B) ROIs used in the current study. Coordinates of foci  
1300 (see the upper graph) belonging to the same functional region were averaged to create 6-mm-  
1301 radius spheres at the averaged coordinates. Dots are colored according to their correlation with  
1302 reading scores across all children. Red dots represent ROIs whose activation to words versus  
1303 fixation were positively correlated with individual children's reading scores, while grey dots  
1304 represent non-significant ROIs ( $pFDR < 0.05$ ). MFG: Middle Frontal Gyrus, PCG: Pre-Central  
1305 Gyrus, STS: Superior Temporal Sulcus, MTG, Middle Temporal Gyrus, FFG: Fusiform gyrus,  
1306 IOG: Inferior Occipital Gyrus.

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1309 **Figure 4. Effects of Reading ability and language on the words versus fixation contrast in**

1310 **the selected ROIs.** Brain slices showed the literature-based ROIs (cyan) overlaid on the reading

1311 circuit (red-yellow) in our participants (Words > [Faces, Houses]). Plots show the mean

1312 activation for words > fixation, in each of the four groups and ROIs. The words “Reading ability”

1313 and “Language” indicate a significant main effect of reading ability and a main effect of

1314 language in the ANOVA (after FDR correction for a total of 13 ROIs). Note that no ROI showed

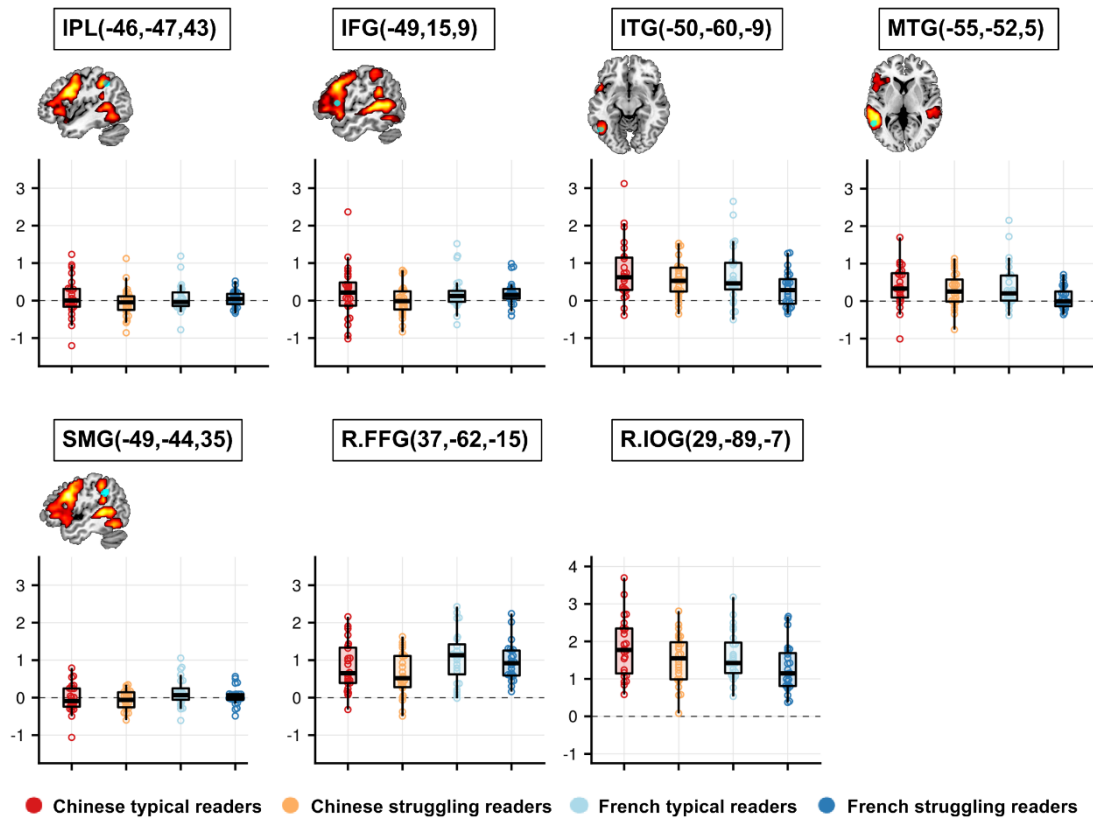
1315 a significant interaction of language × reading ability. Brackets indicate significant post hoc

1316 analyses: \*\*  $p < 0.005$ , \*  $p < 0.01$ , \*  $p < 0.05$ , † = 0.052.

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1318 The following figure supplements are available for figure 4:

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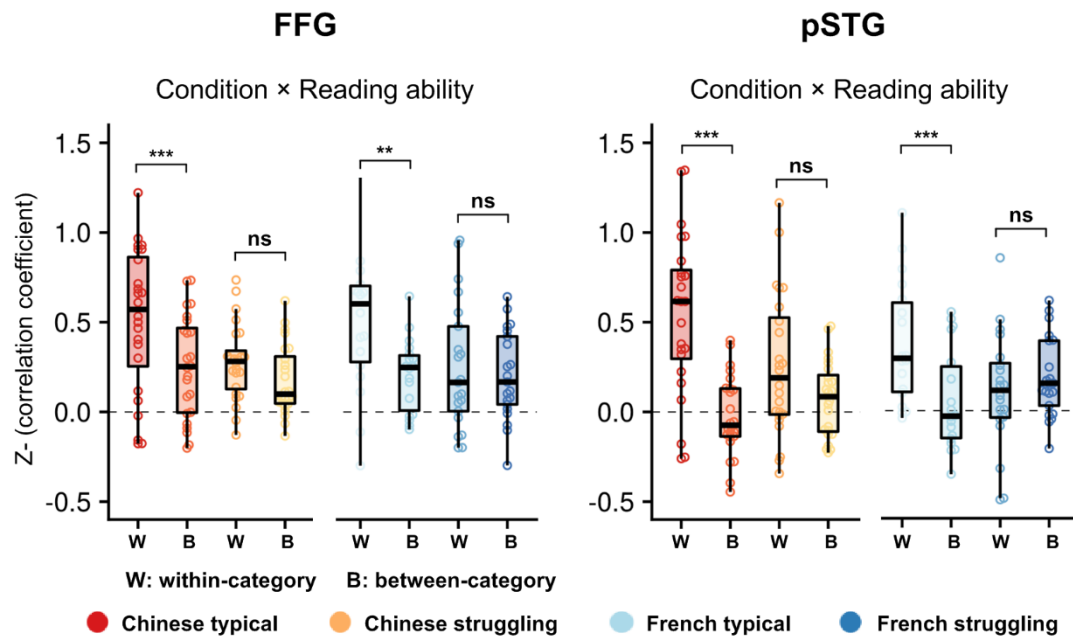


1320

1321 **Figure 4—Figure supplement 1.** Profile of activation to words (relative to fixation) in ROIs  
1322 where the ANOVA did not reveal a significant effect. Two ROIs on the right hemisphere (e.g.  
1323 R.FFG and R.IOG) were not within the reading circuit identified in our participants. Neither  
1324 the interaction of language × reading ability nor main effect of reading ability or language was  
1325 found significant in these ROIs.

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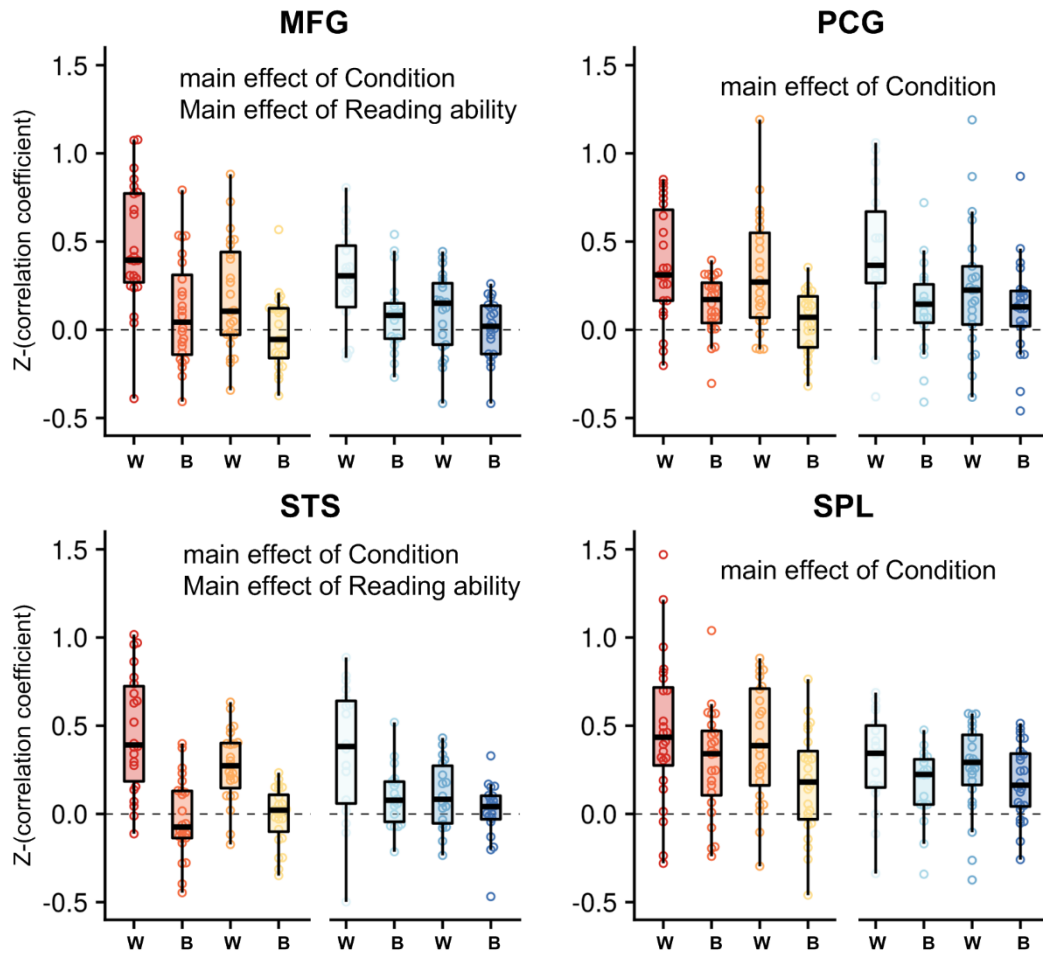
1342

1343 The following figure supplements are available for figure 5:

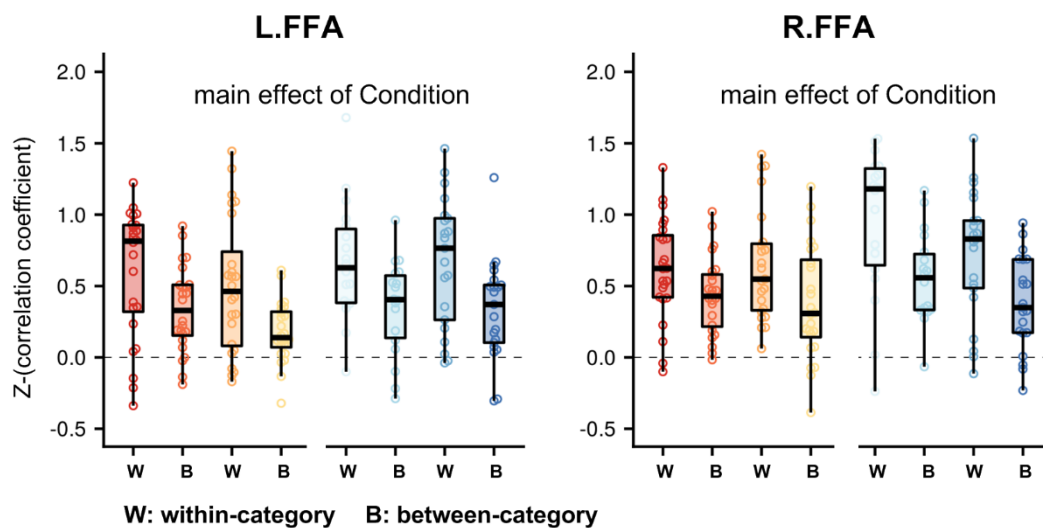
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**Figure 5. Multivariate pattern analysis indicates that the word-induced activation is not simply more anatomically variable, but is less reproducible in struggling children.** Within the designated ROISs, we computed the correlation coefficient of the multivoxel patterns for the word versus fixation contrast in run 1 and in run 2 (within-category correlation, W). For the between-category coefficient (B), the plots show the average correlation coefficient between words and faces, words and houses and faces and houses between run 1 and run 2. In each plot, the correlation is presented for the Chinese children on the left of the plot and for French children on the right. The words “Condition × Reading ability” indicate a significant interaction between condition (within vs between) and the status of children (typical vs struggling readers) (after FDR correction for a total of 13 ROIs). Typical readers, but not struggling readers, exhibited a significant similar pattern of activation to words from one run to the next in the left FFG and pSTG, suggesting that the activation pattern for words was not simply anatomically variable, but was genuinely less reproducible in struggling readers than in typical readers.

## A. MVPA analysis in reading areas



## B. MVPA analysis in faces areas



W: within-category B: between-category

● Chinese typical ● Chinese struggling ● French typical ● French struggling

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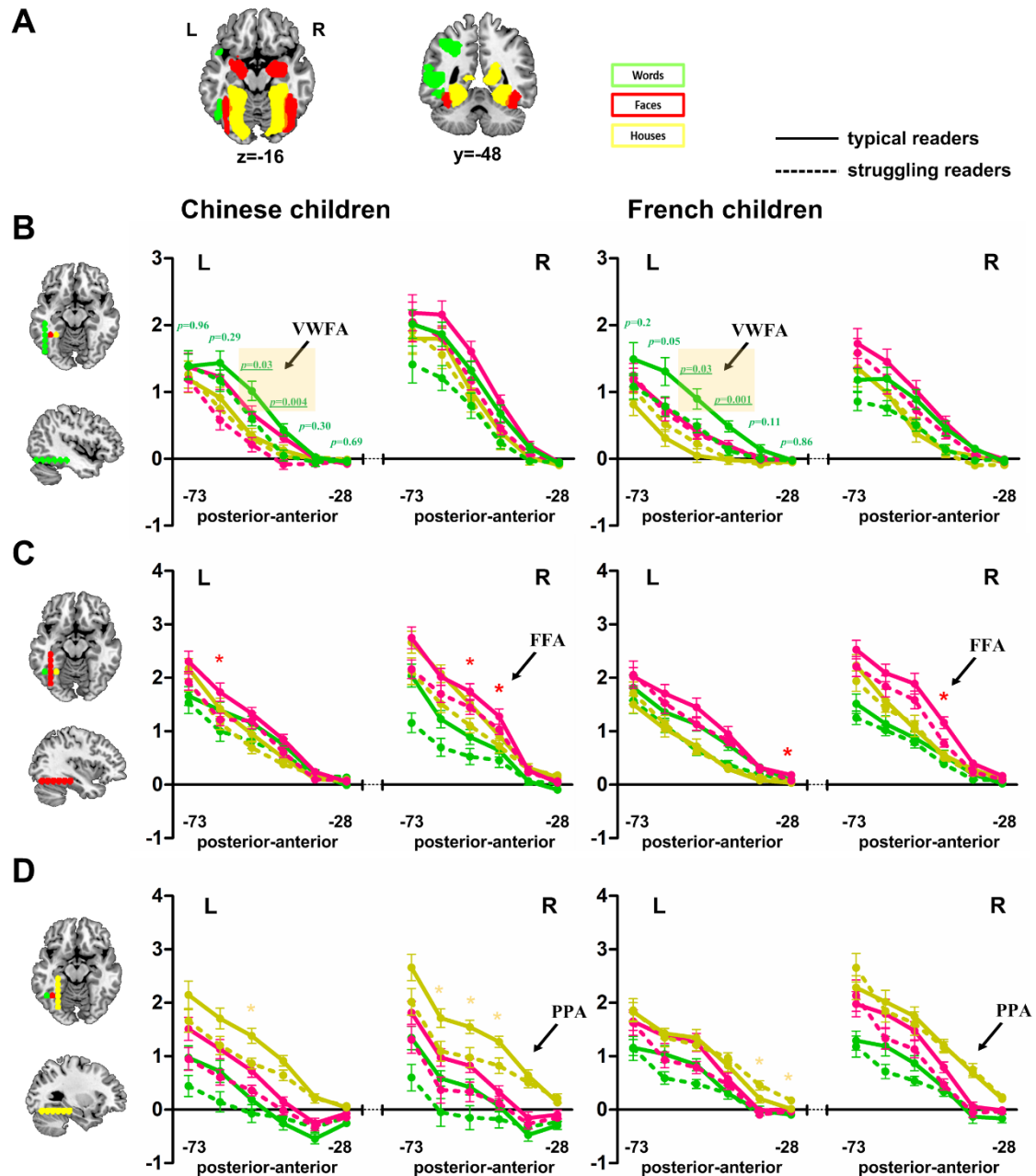
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**Figure 5—Figure supplement 1.** MVPA analysis. All these regions showed a main effect of condition, with higher correlation coefficients in within-category than between-category. Besides, the left MFG and STS showed a main effect of reading ability, with lower correlation

1349 coefficients across runs in struggling readers than typical readers. Note that neither the  
1350 interaction of condition  $\times$  reading ability nor condition  $\times$  reading ability  $\times$  language reached  
1351 significant in above regions.

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1354 **Figure 6. Mosaic of preferences for different visual categories (Words, Faces and Houses)**

1355 **in the ventral visual cortex.** (A) Slices show the activation difference between a given

1356 category and the others across all participants. (B) fMRI signal change of Words relative to

1357 fixation in both Chinese and French children in successive cortical sites along the y-axis (green

1358 dots on the left cortical slices) with constant  $x = \pm 48$  and  $z = -16$ . Both Chinese and French

1359 struggling readers have significantly lower activations relative to their controls at a specific y

1360 site of  $y = -46$  ( $p_{FDR\_corr} = 0.048$  and  $p_{FDR\_corr} = 0.012$  respectively for Chinese and French

1361 children) corresponding to the classical coordinates of the VWFA (Cohen et al., 2002). (C)

1362 fMRI signal change of Faces relative to fixation in both Chinese and French children in



1363 successive cortical sites along the y-axis (red dots on the left cortical slices) with constant  $x =$   
1364  $\pm 39$  and  $z = -16$ . (D) fMRI signal change of Houses relative to fixation in both Chinese and  
1365 French children in successive cortical sites along the y-axis (yellow dots on the left cortical  
1366 slices) with constant  $x = \pm 30$  and  $z = -16$ .  
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1369 **Additional files**

1370 **Supplementary file 1.** Demography and performance on literacy tests for Chinese children

1371 **Supplementary file 2.** Demography and performance on literacy tests for French children

1372 **Supplementary file 3.** Regions of significant activations for each visual category vs the two  
1373 others in each group (individual voxel  $p=0.001$ , cluster-level FWE corrected)

1374 **Supplementary file 4.** Summary of activation foci in meta-analyses of dyslexia in alphabetic  
1375 languages

1376 **Supplementary file 5.** Summary of foci in meta-analyses of reading in Chinese

1377 **Supplementary file 6.** Distance between individual center of 10 most activated voxels and  
1378 group peaks.

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