Supplementary Information for:

Abnormal brain activation during speech perception and production in children and adults with reading difficulty

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Results-behavioral tests

A group (ACs, RDs) by age (children, adults) ANCOVA was conducted for each behavioral test with the Raven score as a covariate (Table 1). For the three screening tests, significant main effects of age were observed, with adults better than children on character naming ($F(1,81) = 153.93$, $p_{FDR} < 0.001$, $\eta_p^2 = 0.67$), sentence reading fluency ($F(1,81) = 16.91$, $p_{FDR} < 0.001$, $\eta_p^2 = 0.18$), and one-minute character naming ($F(1,81) = 82.47$, $p_{FDR} < 0.001$, $\eta_p^2 = 0.52$ for regular character naming, $F(1,81) = 68.72$, $p_{FDR} < 0.001$, $\eta_p^2 = 0.48$ for irregular character naming). The main effect of group was significant with controls better than individuals with RD on character naming ($F(1,81) = 90.80$, $p_{FDR} < 0.001$, $\eta_p^2 = 0.54$), sentence reading fluency ($F(1,81) = 78.89$, $p_{FDR} < 0.001$, $\eta_p^2 = 0.51$), one-minute regular character naming ($F(1,81) = 73.13$, $p_{FDR} < 0.001$, $\eta_p^2 = 0.49$), and one-minute irregular character naming ($F(1,81) = 59.20$, $p_{FDR} < 0.001$, $\eta_p^2 = 0.44$). The age by group interaction was significant for character naming ($F(1,81) = 50.57$, $p_{FDR} < 0.001$, $\eta_p^2 = 0.40$, Supplementary Figure 3), sentence reading fluency ($F(1,81) = 12.90$, $p_{FDR} = 0.002$, $\eta_p^2 = 0.15$) , and one-minute irregular character naming ($F(1,78) = 5.99$, $p_{FDR} = 0.022$, $\eta_p^2 = 0.07$) but nor for one-minute regular character naming ($F(1,81) = 3.94$, $p_{FDR} = 0.065$, $\eta_p^2 = 0.05$). Simple effect analysis showed that children with RD had a greater deficit than adults with RD on the Chinese character naming test ($F(1,81) = 154.37$, $p < 0.001$ for children; $F(1,81) = 5.36$, $p = 0.023$ for adults), while adults with RD had a greater deficit than children with RD on the sentence reading fluency test ($F(1,81) = 74.76$, $p < 0.001$ for adults; $F(1,81) = 20.02$, $p < 0.001$ for children) and the one-minute irregular character naming test ($F(1,81) = 49.98$, $p < 0.001$ for adults; $F(1,81) = 18.81$, $p < 0.001$ for children).

For the other meta-linguistic and cognitive tests, the main effect of age was significant for the morphological awareness ($F(1,80) = 54.89$, $p_{FDR} < 0.001$, $\eta_p^2 = 0.42$ for homographic morpheme, $F(1,80) = 39.37$, $p_{FDR} < 0.001$, $\eta_p^2 = 0.34$ for homophonic morpheme), orthographic awareness ($F(1,80) = 34.05$, $p_{FDR} < 0.001$, $\eta_p^2 = 0.31$ for delayed copy, $F(1,80) = 33.24$, $p_{FDR} < 0.001$, $\eta_p^2 = 0.31$ for character correction), working memory ($F(1,72) = 8.85$, $p_{FDR} = 0.006$, $\eta_p^2 = 0.12$ for forward digit span, $F(1,81) = 29.33$, $p_{FDR} < 0.001$, $\eta_p^2 = 0.28$ for backward digit span), and RAN ($F(1,81) = 50.66$, $p_{FDR} < 0.001$, $\eta_p^2 = 0.40$ for digits RAN, $F(1,81) = 29.81$, $p_{FDR} < 0.001$, $\eta_p^2 = 0.28$ for pictures RAN) with higher performance in adults than in children. The main effect of group was significant for initial sound deletion ($F(1,81) = 24.59$, $p_{FDR} < 0.001$, $\eta_p^2 = 0.24$), pseudoword rhyming ($F(1,81) = 22.05$, $p_{FDR} < 0.001$, $\eta_p^2 = 0.23$), homographic morpheme ($F(1,80) = 10.71$, $p_{FDR} = 0.003$, $\eta_p^2 = 0.13$), homophonic morpheme ($F(1,80) = 21.08$, $p_{FDR} < 0.001$, $\eta_p^2 = 0.22$), character correction ($F(1,70) = 12.23$, $p_{FDR} = 0.002$, $\eta_p^2 = 0.14$), delayed copy ($F(1,80) = 7.34$, $p_{FDR} = 0.011$, $\eta_p^2 = 0.09$), working memory-backward digit span ($F(1,81) = 14.74$, $p_{FDR} < 0.001$, $\eta_p^2 = 0.16$) and rapid automized naming ($F(1,81) = 24.38$, $p_{FDR} < 0.001$, $\eta_p^2 = 0.24$ for digits, $F(1,81) = 15.01$, $p_{FDR} < 0.001$, $\eta_p^2 = 0.17$ for pictured objects) with higher performance in controls than in individuals with RD. The age by group interaction was significant for the two morphological awareness tests (F(1,80) = 31.76, $p_{FDR} < 0.001$, $\eta_p^2 = 0.30$ for the homographic morpheme test, and F(1,80) = 23.53, $p_{FDR} < 0.001$, $\eta_p^2 = 0.24$ for the homophonic morpheme test), working memory forward-digit span (F(1,72) = 9.70, $p_{FDR} = 0.005$, $\eta_p^2 = 0.13$) and rapid automized naming of digits (F(1,81) = 6.07, $p_{FDR} = 0.022$, $\eta_p^2 = 0.07$) (Supplementary Figure 4). Simple effect analysis revealed deficits in children with RD in the morphological awareness tests (F(1,80) = 41.70, $p < 0.001$ for homographic morpheme, F(1,80) = 48.19, $p < 0.001$ for homophonic morpheme), working memory test (F(1,72) = 12.61, $p = 0.001$) and rapid automatized naming test (F(1,81) = 31.24, $p < 0.001$), but not in adults with RD (F(1,80) = 1.55, $p = 0.217$ for homographic morpheme, F(1,80) = 0.04, $p = 0.837$ for homophonic morpheme, F(1,72) = 0.68, $p = 0.412$ for forward digit span, F(1,81) = 3.90, $p = 0.052$ for RAN). Supplementary Figure 3 shows results on the four tests with a significant interaction.

Results- General Linear Model (GLM) results for HbR

Results for the speech perception task

We conducted a repeated measure ANOVA of group (ACs, RDs) by age (children, adults) by similarity to Chinese (high similarity, low similarity) by syllable consistency (identical, different) for each channel. A significant main effect of group was observed in CH3 (left SFG) with RDs showing greater concentration changes of HbR than ACs ($F(1,80) = 11.14$, $p_{FDR} = 0.048$, $\eta_p^2 = 0.14$). No main effect of age, similarity or syllable consistency, or interactions were significant after FDR correction.

Results for the speech production task

We conducted a repeated measure ANOVA with age and group as between-subject variables, language as a within-subject variable and Raven as a covariate for each channel. A significant main effect of group was found in CH8 (left precentral) with RDs showing greater concentration changes of HbR than ACs ($F(1,74) = 11.59$, $p_{FDR} = 0.048$, $\eta_p^2 = 0.14$). However, no significant main effects of age, language, or interaction effects were observed.

Results- Sub-group analyses with IQ-matched adults

Because in the whole sample, there was a significant difference between RD adults and AC adults on Raven, we performed sub-group analyses on both behavioral tests and fNIRS data with Raven well matched in adults with RD and AC adults. This resulted in a sub-group of 14 adults with RD and 12 age-matched AC adults, while children groups remained the same. Age and Raven scores were matched for AC adults and adults with RD (controls = 19.67 ± 1.56 years, RDs = 19.57 ± 1.09 years, $t(24) = 0.18$, $p = 0.86$ for age; controls = 123.33 ± 3.82, RDs = 116.43 ± 12.26, $t(15.87) = 1.99$, $p = 0.063$ for Raven).

Results for behavioral tests in the subgroups

A group (ACs, RDs) by age (children, adults) ANOVA was conducted for each behavioral test in the sub-group analyses. Significant main effects of age and group were observed for all of the three screening tests (**Supplementary Table 1**), with adults better than children and AC readers better than RD readers. The age by group interaction was significant for character naming ($F(1,66) = 33.37$, $p_{FDR} < 0.001$, $\eta_p^2 = 0.35$), and sentence reading fluency ($F(1,66) = 12.18$, $p_{FDR} = 0.035$, $\eta_p^2 = 0.16$) but not for one-minute regular character naming ($F(1,66) = 2.03$, $p_{FDR} = 0.30$, $\eta_p^2 = 0.03$) or one-minute irregular character naming ($F(1,66) = 3.91$, $p_{FDR} = 0.15$, $\eta_p^2 = 0.06$). Simple effect analysis revealed a consistent pattern as in the whole sample analysis, with children with RD showing a greater deficit than adults with RD on the Chinese character naming test ($F(1,62) = 146.74$, $p < 0.001$ for children; $F(1,62) = 5.57$, $p = 0.021$ for adults), and adults with RD showing a greater deficit than children with RD on the sentence reading fluency test ($F(1,62) = 86.83$, $p < 0.001$ for adults; $F(1,62) = 35.77$, $p < 0.001$ for children).

The main effects of age and group was also significant for all the meta-linguistic and cognitive tests (Supplementary Table 1). The age by group interaction was significant for homographic morpheme test ($F(1,64) = 17.17$, $p_{FDR} < 0.001$, $\eta_p^2 = 0.22$), and homophonic morpheme test ($F(1,64) = 14.04$, $p_{FDR} = 0.002$, $\eta_p^2 = 0.19$). The interaction between age and group was not significant for working memory forward-digit span ($F(1,57) = 2.93$, uncorrected $p = 0.093$) or rapid automatized naming of digits ($F(1,66) = 1.92$, uncorrected $p = 0.171$). Simple effect analysis revealed a deficit in morphological awareness in children with RD ($F(1,60) = 34.16$, $p < 0.001$ for homographic morpheme, $F(1,60) = 47.82$, $p < 0.001$ for homophonic morpheme), but not in adults with RD (F(1,60) = 0.29, *p* = 0.59 for homographic morpheme, F(1,60) = 0.75, *p* = 0.39 for homophonic morpheme).

Supplementary Table 1. Main effects of age and group for the behavioral tests in the sub-group analyses.

	F_{age}	η_p^2	F_{group}	η_p^2
Chinese Character Naming	158.57^{***}	.72	89.28^{***}	.59
Sentence Reading Fluency	39.86^{***}	.39	121.15^{***}	.66
One-minute Character Naming (regular)	67.53^{***}	.52	68.92^{***}	.53
One-minute Character Naming (irregular)	73.59^{***}	.54	64.86^{***}	.51
Initial Sound Deletion	11.39^{**}	.18	22.06^{***}	.26
Pseudowords Rhyming	13.26^{**}	.19	23.57^{***}	.27
Homophonic Morpheme	45.92^{***}	.43	25.82^{***}	.30
Homographic Morpheme	75.48^{***}	.56	11.01^{**}	.15
Character Correction	40.34^{***}	.40	14.85^{***}	.20
Delayed Copy	42.03^{***}	.41	11.51^{**}	.16
Forward Digit Span	34.15^{***}	.39	5.93^{*}	.10
Backward Digit Span	67.85^{***}	.52	32.85^{***}	.35
RAN (digits)	50.22^{***}	.45	21.40^{***}	.26
RAN (pictures)	25.95^{***}	.29	12.41^{**}	.17

Note: * FDR $p<0.05$, ** FDR $p<0.01$, *** FDR $p<0.001$.

fNIRS results for the speech perception task in the sub-group analysis

We conducted a repeated measure ANOVA of group (AC, RD) by age (children, adults) by similarity to Chinese (high similarity, low similarity) by syllable consistency (identical, different). Results showed no significant main effect of age, group, similarity or syllable consistency. The three-way (age×group×similarity) interaction was significant in CH31 (right IFG, $F(1,69) = 10.86$, $p = 0.002$, $\eta_p^2 = 0.14$) and CH37 (right DLPFC, $F(1,69) = 10.36$, $p = 0.002$, $\eta_p^2 = 0.13$). Simple effect analyses showed that adults with RD had a greater hemodynamic response than AC adults in perception of Spanish syllables with high similarity to Chinese in CH31($F(1,69) = 4.73$, $p = 0.033$), while no significant differences were found between AC children and children with RD. For CH37, children with RD showed lower hemodynamic response in perception of Spanish syllables with high similarity to Chinese ($F(1,69) = 4.56$, $p = 0.036$) and greater hemodynamic response in perception of Spanish syllables with low similarity to Chinese than AC children ($F(1,69) = 5.40$, $p = 0.023$), while no significant differences were found between AC adults and adults with RD. Another way to explain the interaction was a greater developmental increase in tACs for the perception of Spanish syllables with low similarity to Chinese ($F(1,69) = 5.03$, $p = 0.028$ for CH31, $F(1,69) = 5.28$, $p = 0.025$ for CH37) and a greater developmental increase in RDs for the perception of Spanish syllables with high similarity to Chinese ($F(1,69) = 5.09$, $p = 0.027$ for CH31, $F(1,69) = 5.49$, $p = 0.022$ for CH37).

fNIRS results for the speech production task in the sub-group analysis

A repeated measure ANOVA was conducted with language as a within-subject factor, and group and age as between-subject factors. No main effect of age or group was significant; neither was the interaction effect between age and group. The main effect of language was significant in CH10 (left postcentral, $F(1,63) = 9.66$, $p_{FDR} = 0.045$, $\eta_p^2 = 0.13$), CH32(right IFG, $F(1,63) = 17.81$, $p_{FDR} = 0.004$, $\eta_p^2 = 0.22$), and CH43 (right postcentral, $F(1,63) = 12.26$, $p_{FDR} = 0.020$, $\eta_p^2 = 0.16$), with the activation for Chinese greater than that for Spanish. The language by group interaction was significant for CH22 ($F(1,63) = 7.75$, $p = 0.007$,$\eta_p^2 = 0.11$). Simple effect analyses showed that individuals with RD exhibited greater hemodynamic response for Spanish than Chinese ($F(1,63) = 4.84$, $p = 0.031$), whereas no significant language differences was found in ACs ($F(1,63) = 3.05$, $p = 0.086$). Another way to explain the interaction is that individuals with RD had greater hemodynamic response than controls for Spanish production ($F(1,63) = 7.92$, $p = 0.007$), while no significant group difference was observed for Chinese production ($F(1,63) = 0.10$, $p = 0.92$).

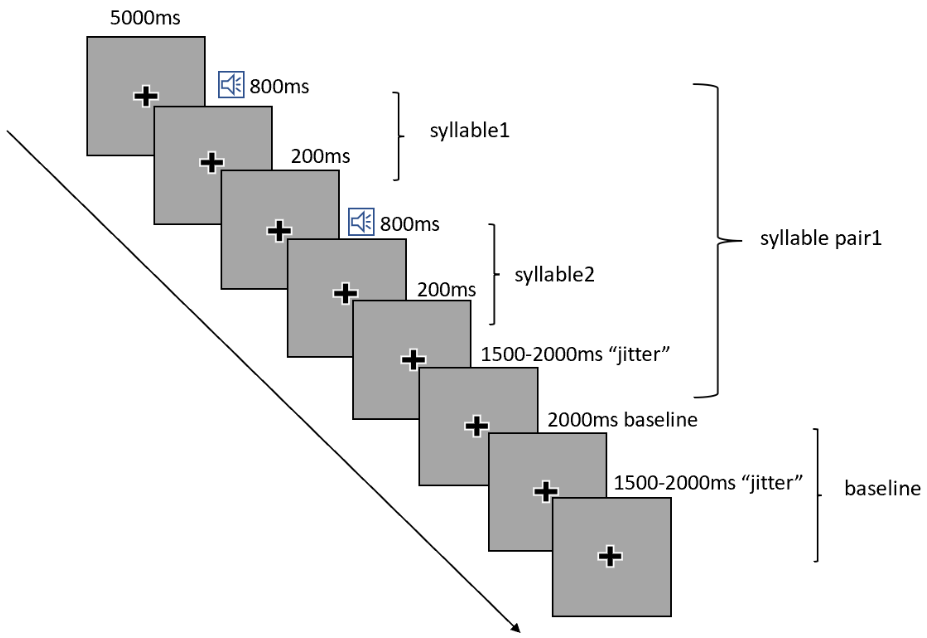
The sub-group analyses showed basically the same results as the whole group analyses for both the behavioral and fNIRS data.

Discussion

Age differences in the behavioral tests

In this study, we found significant age by group interactions in character naming, sentence reading fluency, one-minute irregular character naming, morphological awareness, forward digit span and digit RAN. Further analysis indicated that children with RD exhibited significant impairments in these tests compared to their typically developing peers; however, adults with RD showed no impairment in morphological awareness, working memory or digit RAN compared to the age-matched controls, and they showed less deficits on character naming than children with RD. In contrast, for sentence reading fluency and one-minute irregular character naming, there was an even greater deficit in adults than children with RD. These patterns of age differences are consistent with previous research in that adults catch up on word decoding accuracy but show an even greater deficit in reading fluency [1, 2]. This is because typical readers have a greater improvement with age in reading fluency (both single character and sentence level) than RD readers. Specifically, our sentence reading fluency test is a comprehensive measure of reading ability, which taps into word decoding, reading comprehension, working memory and processing speed. When the basic word decoding skills are impaired, it accumulates and slows down the development of sentence reading fluency which is a higher-order reading skill.

For tests that did not show an interaction between age and group, such as phonological awareness and one-minute regular character naming, it suggests a persistent deficit over development. The persistence of phonological awareness deficits is consistent with prior findings [3-6]. The persistent deficits in one-minute regular character naming suggest that even tough word decoding accuracy can be improved by adulthood, decoding speed is still a challenge in adults with RD, which might be due to poor quality of lexical representations or poor connections between representations [7]. These findings serve as important evidence for age differences in reading and related skills in Chinese RD.


5000ms
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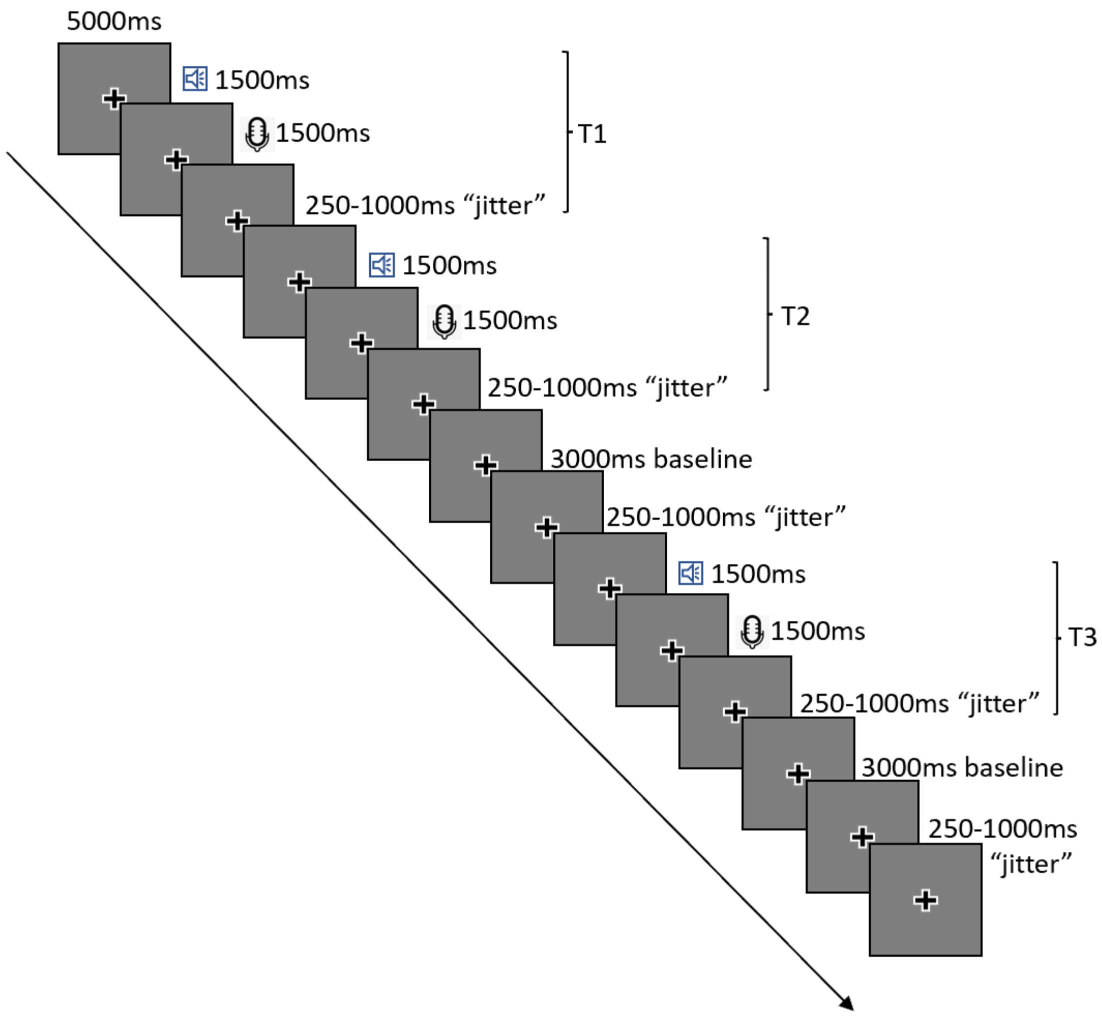
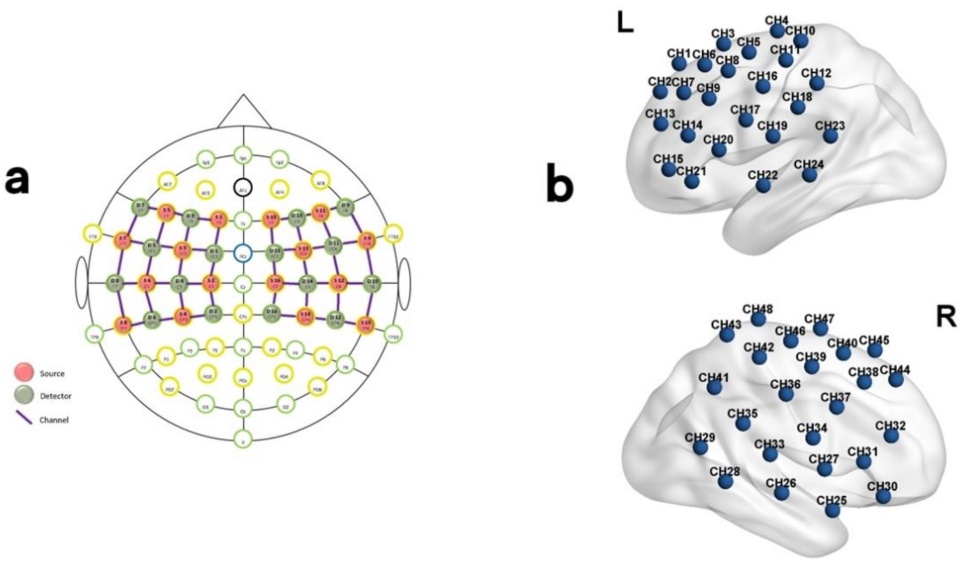
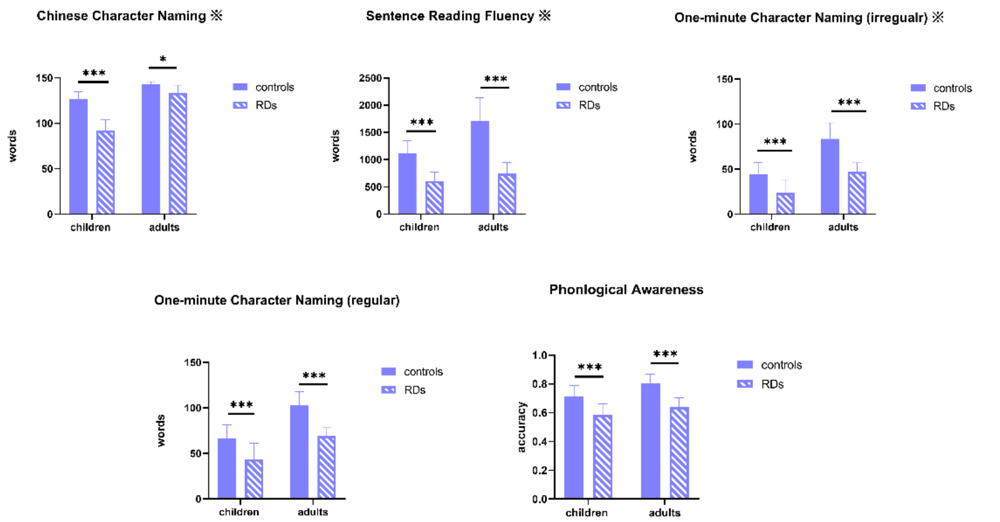


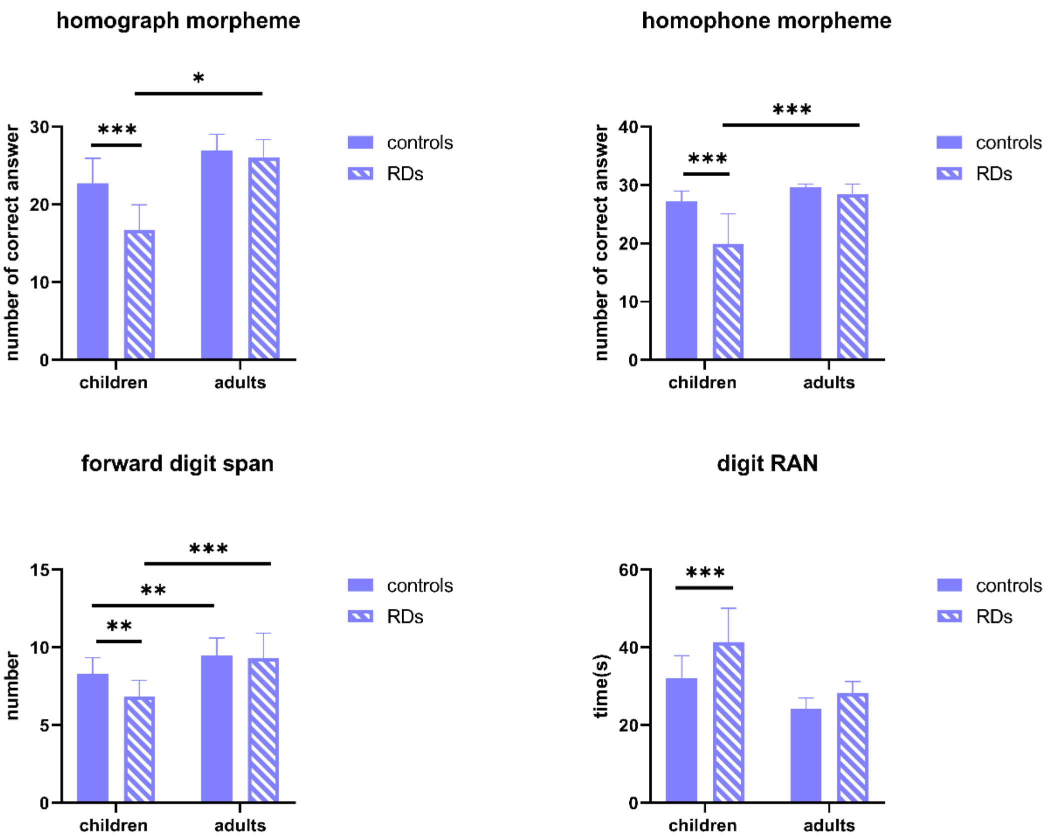
Supplementary Figure 1. Experimental procedures for the speech perception (upper) and speech production task (bottom). The speech perception task was a passive listening task, and the speech production task required participants to imitate Chinese pseudowords/Spanish words.



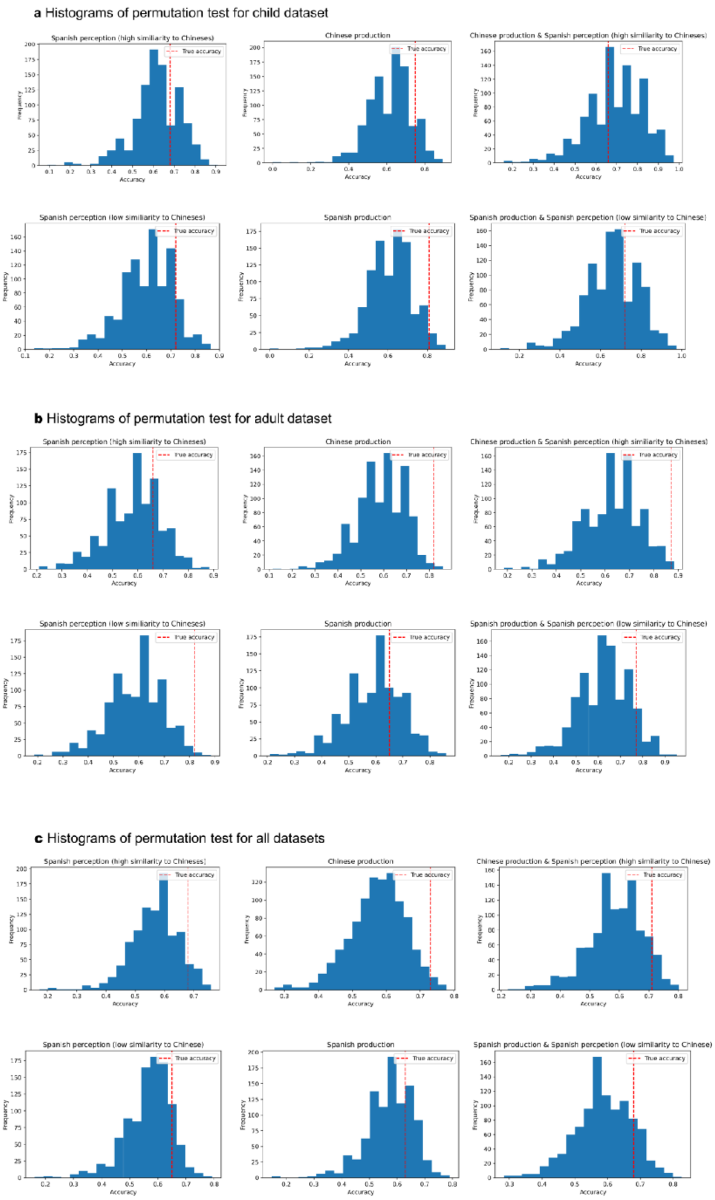
Supplementary Figure 2. (a) fNIRS probes and channels configuration. (b) Location of fNIRS channels over a brain model. The optode arrangement included 16 sources (red circles) and 16 detectors (green circles), forming a total of 48 channels (purple lines in 2(a) and blue dots in 2(b)).



Supplementary Figure 3. Behavioral performance of each group on the screening tests and the phonological awareness tests. ※ indicates a significant age by group interaction revealed by ANCOVA. Children with RD showed a greater deficit than adults with RD on the Chinese character naming test, while adults with RD showed greater deficits than children with RD on the sentence reading fluency test and the one-minute character naming (irregular) test. No significant interaction effect was found for the one-minute character naming (regular) test and the phonological awareness tests, suggesting persistent deficits on these tests. **p* < 0.05, ***p* < 0.01, ****p* < 0.001.



Supplementary Figure 4. Behavioral performance of each group on four tests that showed a significant age by group interaction. The deficits were greater in children with RD than in adults with RD in all four tests. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.



Supplementary Figure 5. Histograms of permutation test for the child dataset (a), adult dataset (b), and the combination of the two datasets (c). Red dashed line indicates the actual classification accuracy obtained by the SVM using the fNIRS data in each task.

Supplementary References

1. Shaywitz, S. E. & Shaywitz, B. A. The neurobiology of reading and dyslexia. *The ASHA Leader* **12**, 20-21 (2007).
2. Reis, A., Araújo, S., Morais, I. S. & Faísca, L. Reading and reading-related skills in adults with dyslexia from different orthographic systems: a review and meta-analysis. *Annals of Dyslexia* **70**, 339-368 (2020).
3. Bruck, M. Persistence of dyslexics' phonological awareness deficits. *Developmental Psychology* **28**, 874-886 (1992).
4. Fawcett, A. J. & Nicolson, R. I. Persistence of phonological awareness deficits in older children with dyslexia. *Reading and Writing* **7**, 361-376 (1995).
5. Nergård - Nilssen, T. & Hulme, C. Developmental dyslexia in adults: Behavioural manifestations and cognitive correlates. *Dyslexia* **20**, 191-207 (2014).
6. Moojen, S. M. P., et al. Adults with dyslexia: how can they achieve academic success despite impairments in basic reading and writing abilities? The role of text structure sensitivity as a compensatory skill. *Annals of Dyslexia* **70**, 115-140 (2020).
7. Ramus, F. & Szenkovits, G. What phonological deficit? *Q J Exp Psychol (Hove)* **61**, 129-41 (2008).