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Brain Changes Following Two Reading Interventions in Chinese Children With Reading Disability

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ABSTRACT

Most behavioral interventions on reading disability (RD) have been developed in alphabetic languages and are phonologically-based. Chinese is a morpho-syllabic language in which each character represents a morpheme and a syllable. Therefore, phonologically-based interventions may not be most helpful in Chinese. In this study, we compared a phonological and a morphological intervention (MI) in Chinese children with RD both behaviorally and neurologically. We recruited 80 fifth-grade Chinese children, including 18 typically developing children as age controls (AC), and 62 children with RD, 22 of whom received the phonological intervention (PI), 22 of whom received the MI, and 18 served as waiting-list controls (WL). An auditory rhyming task and a visual spelling task were employed to examine brain activation before and after the intervention. We found that the PI and MI both effectively improved character naming, sentence reading fluency, one-minute irregular character reading and phonological awareness compared with the WL group. At the brain level, the PI group showed greater increase of brain activation in the right middle temporal gyrus than the MI and WL following the intervention in an auditory rhyming task, suggesting compensatory phonological strategies developed in PI. The MI group showed greater increase of brain activation in the left middle frontal gyrus, left inferior frontal gyrus and left fusiform gyrus than the PI and the WL group following the intervention in a visual spelling task, suggesting functional normalization, because these regions were less activated in children with RD than typical controls before the intervention. These findings suggest intervention-specific brain changes with otherwise similar effectiveness in the behavior. It provides important insights in understanding brain mechanisms underlying behavioral intervention in children with RD.

Trial Registration: This study's design was preregistered at the Chinese Clinical Trial Registry (ChiCTR2300067536), see [https://www.chictr.org.cn]

Summary

1. This study compared the efficacy of a phonological intervention (PI) and a morphological intervention (MI) in Chinese children with reading disability.
2. Both PI and MI demonstrated comparable effectiveness in behavioral outcomes, yet exhibited distinct neural changes.
3. Specifically, the PI facilitated reading improvement through functional compensation, whereas the MI achieved improvement through normalization.

1 | Introduction

Reading is one of the most important ways to obtain information in the modern society, whereas 7% of school-aged children suffer from reading disability (RD) across languages (Yang et al. 2022). Children with RD show a significant and specific impairment in reading ability, which cannot be explained by intelligence, sensory acuity, learning opportunities, or motivation (Shaywitz et al. 1990). In addition to academic underachievement, children with RD also have a greater chance to develop depression, anxiety (Maughan et al. 2003; Willcutt and Pennington 2000), and aggressive behaviors (Heiervang et al. 2001) than typically developing children. Behavioral intervention is the most prevalent treatment for children with RD.

1.1 | Behavioral Interventions

One of the most consistent findings in the literature of RD is that poor reading is associated with phonological deficits (Bradley and Bryant 1983; Pennington and Lefly 2001; Ramus and Szenkovits 2008), therefore, reading remediation has been focused on phonological skills in alphabetic languages including phonological awareness and phonics (Eden et al. 2004; Elbro and Petersen 2015; Meyler et al. 2008; Schneider et al. 2000; Soriano et al. 2011). These interventions tend to show a significant effectiveness on phonological awareness and phonological decoding (Eden et al. 2004; Meyler et al. 2008; Soriano et al. 2011), word decoding (Tilanus et al. 2019), and oral paragraph reading accuracy (Eden et al. 2004; Soriano et al. 2011), but mild improvement on reading fluency (Eden et al. 2004) or reading comprehension (Eden et al. 2004; Soriano et al. 2011).

Reading requires slightly different skills depending on the writing system, therefore, reading interventions in other languages should take this into consideration. Chinese is non-alphabetic, and none part of a character corresponds to a phoneme. Instead, the whole character, which represents a morpheme, corresponds to the whole syllable. There are also many homophones which are different characters that share the same syllable. Therefore, the direct mapping between orthography and semantics is more reliable in Chinese reading. All of these special features of Chinese encourage a reader to rely on orthographic and morphological processing during reading rather than phonological processing. Previous studies have shown that different from alphabetic languages, reading acquisition in Chinese has a greater demand on orthographic (Ho et al. 2007; McBride-Chang et al. 2005) and morphological skills (McBride-Chang et al. 2003; Shu et al. 2006) than phonological skills. An 8-year longitudinal study showed that preliterate phonological awareness only contributes to the early stage of reading and writing in Chinese, while morphological awareness also contributes to high-level literacy skills, such as reading fluency and reading comprehension in high-grade children (Pan et al. 2016). Another Chinese study using path analyses found that morphological awareness makes a greater prediction of performance on character recognition, character dictation, and reading comprehension than phonological awareness across children with RD and typical control children (Shu et al. 2006). Interventions on RD in Chinese should take these findings into account.

Research on intervention for Chinese children with RD has been scarce. There is evidence for the effectiveness of phonological intervention (PI) in Chinese RD (Ho and Ma 1999; Wang 2017). For example, onset-rime-level phonological training improved character reading, onset and rime awareness, as well as rapid naming, but the effect was smaller in children above the age of 10 than those younger than 10 (Wang 2017). Phonetic radical training improved regular character reading but not irregular character reading (Ho and Ma 1999). On the other hand, evidence also suggests that morphological awareness training might be more effective than phonological training in some areas, such as vocabulary knowledge and word reading, with phonological training only effective in promoting phonological awareness (Zhou et al. 2012). Other studies have also shown the effectiveness of morphological training on morphological awareness (Chow et al. 2008; Packard et al. 2006; Wu et al. 2009), character writing and copying (Packard et al. 2006), novel word interpretation, word dictation, and comprehension (Wu et al. 2009).

The previous studies on morphological intervention (MI), however, have been conducted in typically developing children and the morphological training was mixed with other trainings such as orthographic structure awareness training (Packard et al. 2006), dialogic reading (Chow et al. 2008), phonological training (Zhou et al. 2012), and phonetic radical training (Wang et al. 2021), which makes it difficult to identify the unique effectiveness of the MI. Therefore, a comparison of the effectiveness of a pure MI and a pure phonological training on Chinese children with RD is needed to understand how they help with reading, respectively.

In Chinese, morphological awareness is defined as the awareness of, access to, and manipulation of morphemes (Shu et al. 2006). There are three levels of morphological processing in Chinese. First, at the semantic radical level, a semantic radical could provide a clue to the meaning of the character (Shu et al. 2006). Second, at the character level, there are homographic morphemes and homophonic morphemes, and it is important but challenging for children to understand and use them correctly. Homographic morpheme is a character/morpheme that has different meanings in different compound words. Homophonic morphemes are different characters that share the same phonology. Last, at the word-level, all Chinese words are compound words which are composed of two or more morphemes/characters. It is an important skill for children to understand the relationship between different morphemes in a compound word in Chinese. To sum up, for morphological training, it is important to cover all of the three levels in order to promote reading proficiency.

1.2 | Brain Functional Differences Associated With RD

A substantial literature exists about brain functional differences in individuals with RD with some extent of consensus that RD is associated with reduced brain activation in three regions in the left reading network, including the left inferior frontal gyrus (IFG), temporoparietal area, and inferior temporal gyrus (ITG as well as increased involvement in the right hemisphere (Richlan 2012). A recent meta-analysis study showed that the most consistent reduction of brain activation across languages is at the left temporoparietal area, which may be related to phonological deficits (Yan et al. 2021), since the left temporoparietal area is associated with phonological representation and phonological mapping (Booth et al. 2002). The meta-analysis also suggests that the differences in the left IFG is more significant in Chinese than in alphabetic languages, presumably because the left IFG is involved in addressed phonological processing which is more relevant in Chinese than in alphabetic languages (Tan et al. 2005). Moreover, the left ITG is involved in rapid orthographic recognition and play an essential role in fluent reading (Langer et al. 2015). Previous studies suggest that reduced activation in the left ITG represents core signature of RD (Cao et al. 2021), which accumulates with age (Richlan 2012; Xiaohui Yan et al. 2024).

1.3 | Brain Changes Following Intervention

Any behavioral changes following intervention are accompanied by brain changes (Geng et al. 2021). Previous research suggests that there are two kinds of brain changes following intervention (Barquero et al. 2014). One is normalization, in which brain function becomes more similar to typical readers following intervention. The other is compensation, in which additional brain regions are involved to compensate for deficient functions in the classical reading network. A meta-analysis study has shown that reading remediation is associated with increased brain activation following intervention in brain regions which were less activated before the intervention in individuals with RD than in typical controls (Barquero et al. 2014), suggesting functional normalization. Specifically, changes of brain activity in the left IFG and temporo-parietal regions were found following a phonological decoding intervention (Simos et al. 2007) and an oral language training (Temple et al. 2003); increased activation in the left inferior parietal lobule (IPL) was found following a phonologically-based intervention (Eden et al. 2004); and increased activation in the left superior parietal lobule (SPL) and left angular gyrus was found following a word and comprehension instruction (Meyler et al. 2008). It suggests that deficiency in these important regions in the reading network can be remediated to some degree by interventions.

Compensations in the right hemisphere have been well reported in individuals with RD even without intervention (Richlan et al. 2011; Yan et al. 2021). Following intervention, brain regions in the right hemisphere have also been reported to be more involved than before the intervention (Barquero et al. 2014; Shaywitz et al. 2004; Temple et al. 2003). Compensations have been observed in the right temporo-parietal areas and the right frontal regions following a phonological decoding training (Simos et al. 2007); in the right IFG, right superior frontal gyrus (SFG) and right middle temporal gyrus (MTG) following an auditory processing training (Temple et al. 2003); in the right IFG and right posterior parietal areas following an orthographic training (Richards et al. 2006). However, it has also been observed that there is reduced compensation in the right hemisphere following intervention. One study found that the right MTG and the right caudate nucleus were more activated before a PI than 1 year after the intervention during a letter-identification task in children with RD, suggesting that these two right hemispheric regions might initially compensate for the disruption of the left reading systems but the compensation is no longer necessary after the intervention (Shaywitz et al. 2004a). Functional normalization or compensation following intervention are expected as a result of interactions of linguistic, cognitive and sensory neural systems in the brain (Perdue et al. 2021).

To our knowledge, there have been only two published studies that have directly compared brain activation changes following different reading interventions, and one was on English-speaking individuals with RD (Richards et al. 2006) and one was on German speakers (Heim et al. 2015). However, due to small sample size (i.e., smaller than 10 in some groups), less rigorous comparisons (i.e., each treatment was compared to a control group, and no direct comparison between the two treatments was conducted), and lack of whole brain analysis in the previous two studies, we propose a more rigorous study for Chinese children with RD. We aimed to identify general versus specific brain changes following different interventions, which would provide important insights in understanding the neurocognitive mechanisms underlying each intervention. For example, it may be possible that different interventions have similar behavioral effectiveness but different brain mechanisms. One intervention may evoke more normalization while the other may evoke more compensation. Our study would make significant contributions not only to the understanding of brain mechanisms of Chinese phonological and morphological learning through an intervention study, but also to the understanding of neural plasticity and brain principles in responding to different kinds of learning in general.

1.4 | The Current Study

In the current study, we developed a PI which focused on phonological representations, phonological awareness, and phonetic radicals, and a MI which addressed the three levels of morphological skills. We were interested in examining: (1) the effectiveness of the two interventions in promoting reading, (2) general and specific brain changes following the different interventions, and (3) whether brain activity in the pre-intervention predicts responsiveness to the intervention?

2 | Method

2.1 | Participants

We recruited 80 fifth-grade children from eight public elementary schools in the local city, including 18 typically developing children as age controls (AC), and 62 children with RD, 22 of whom were assigned to receive PI (the PI group), 22 of whom were assigned to receive MI (the MI group), and 18 were assigned to the waiting-list control group (WL). After intervention, four children with RD did not participate in the post-test, resulting in 21 participants in the PI group, 20 participants in the MI group and 17 participants in the WL group. The AC group only participated in the pre-test (Table 1).

Children with RD met the following criteria: (1) the standard score on Raven was above 80; (2) the z-score was below −1.5 on either a sentence reading fluency test or a character naming test. The inclusionary criteria for AC were: (1) the standard score on Raven was above 80; (2) the z-score was above −1 on both the sentence reading fluency and the character naming test. All of the participants were also native Chinese speakers, right-handed (Oldfield 1971), free of attention deficit hyperactivity disorder (ADHD), autism, stuttering, or any other neurological or psychiatric disorder. In an interview, all parents of children with RD reported a history of reading difficulty but no language problems though.

2.2 | Randomization and Blinding

This was a randomized controlled trial (RCT) study, with participants randomly allocated to one of the intervention groups or a waiting control group at a 1:1:1 allocation ratio. All assessments and procedures of this RCT were approved by the ethics committee of the Institutional Review Board at the Sun Yat-Sen University. An independent researcher performed randomization in the allocation to the three groups using a computer-generated pseudo-random sequence of numbers. From low to high, participants were grouped into five blocks according to their reading ability (averaged z-score of character naming, reading fluency, and one-minute character naming). Within each block, participants were randomly assigned to one of the three groups. The sequence of allocation was concealed before the intervention was conducted. Participants and experimenters who conducted behavioral testing were blinded to the experimental design and intervention allocation.

2.3 | Procedures

Parents' informed written consents were obtained before data collection. All behavioral tests were administered both before and 3 months after the intervention except Raven, which was only tested before the intervention. The intervention lasted for 4 weeks, with 5 days per week and 2 h per day, which was delivered through online meetings due to COVID19. The dosage was chosen to strike a balance between content coverage and children's motivation. The total number of hours of our study (40 h) is above the average of 28 Chinese intervention studies included in a recent meta-analysis (Ruan et al. 2024), which is 17 h (range: 3.5–131 h). Another meta-analysis found that total number of hours positively predicts intervention effect size (range: 9–125 h) (Boucher et al. 2023).

The PI included phonological awareness training (e.g., phoneme discrimination, phoneme blending, segmentation, and manipulation), and phonetic radical training. The MI included morphological awareness training (e.g., homophonic morphemes, homographic morphemes, compound word construction), and semantic radical training. For details of the intervention protocol, please see the supporting information. For the waiting control participants, they were offered the phonological or MI after the completion of the study.

2.4 | Behavioral Tests

Raven (Raven et al. 2004) was used to assess the participants' non-verbal cognitive ability. The ***sentence reading fluency*** test and the ***character naming*** test were used for screening, which are norm-based tests published previously (Song et al. 2015). We also had other reading and writing tests. ***A one-minute character reading test*** was used to measure character reading fluency, which included two subtests, a regular character test and an irregular character test. ***A character dictation test*** was used to measure spelling. Participants were asked to write down characters they heard. ***Meta-linguistic awareness tests***. Phonological awareness was tested in a pseudo-word rhyming judgment test and an initial sound deletion test. Morphological awareness was measured in a homographic morpheme test and a homophonic morpheme test. Orthographic awareness was measured in a delayed copy test and a misspelled character correction test. ***Passage Listening Comprehension***. Participants listened to a short passage, and then were asked to answer nine questions about the passage. This is a measurement of language comprehension. Details about the behavioral tests are reported in the supporting information.

2.5 | fMRI Tasks

During the fMRI session, we employed an auditory rhyming (AR) judgment task and a visual spelling (VS) judgment task. In the AR task, participants heard a pair of two-character words sequentially, and were asked to judge whether the words rhyme or not. In the VS task, a pair of two-character words were sequentially presented in the visual modality, and participants were asked to judge whether the second character of the first word had similar orthography as the second character of the second word by sharing a phonetic radical. Participants were asked to press the "Yes" button with the right index finger, and the "No" button with the right middle finger.

In both the AR and VS tasks, all characters and words were familiar to fifth-grade children, as tested in another sample of children. In addition to 96 lexical trials, we also had 24 perceptual control trials and 48 null baseline control trials. For each trial (lexical, perceptual, or null), the first stimulus was presented for 800 ms, followed by a 200 ms interval, and then the second stimulus lasted for 800 ms, followed by a jittered inter-stimulus interval (2200, 2600, or 2800 ms), during which a red cross appeared indicating that it is time to make a judgment. The presentation of trials was randomized and optimized using OptSeq (http://surfer.nmr.mgh.harvard.edu/optseq). We grouped the trials into two runs with each run lasting for 6 min and 44 s. The same fMRI tasks were administered again for the post-intervention scan. More details about the fMRI tasks and MRI data acquisition are reported in the supporting information.

2.6 | MRI Data Analysis

MRI data analysis was performed using Statistical Parametric Mapping 12 (https://www.fil.ion.ucl.ac.uk/spm/). Details of data

TABLE 1 | Demographic information and scores (mean [standard deviation, range]) on the behavioral assessments for all three groups before the intervention.

Assessment	AC	PI	MI	WL	$T_{(PI\ vs.\ MI)}$	$T_{(MI\ vs.\ WL)}$	$T_{(PI\ vs.\ WL)}$
N	18 (eight males)	22 (18 males)	22 (15 males)	18 (12 males)			
Age	11.44 (0.51, 11.19–11.70)	11.27 (0.63, 10.99–11.55)	11.14 (0.47, 10.93–11.34)	11.11 (0.76, 10.73–11.49)	0.81	0.13	0.74
Raven	102.93 (12.83, 82–133)	98.23 (9.45, 83.00–113.00)	98.95 (7.74, 84.00–120.00)	98.61 (7.84, 86.00–115.00)	0.32	0.64	−0.35
Sentence reading fluency (3505) [0.74]	1212.14 (407.60, 45.00–3328.00)	523.91 (195.99, 217–929)***	537.52 (223.44, 125.00–978.00)***	435.88 (160.58, 135.00–748.00)***	0.02	1.23	1.54
Character naming (150) [0.94]	131.43 (7.03, 12.00–146.00)	90.57 (16.57, 52.00–114.00)***	87.52 (23.32, 18.00–123.00)***	80.59 (22.06, 29.00–113.00)***	1.25	0.35	1.62
One-minute character reading (regular) (150) [0.81]	78.81 (16.45, 37.00–113.00)	40.91 (16.84, 5.00–66.00)***	41.09 (19.37, 7.00–75.00)***	30.53 (15.15, 7.00–56.00)***	0.46	1.32	1.96
One-minute character reading (irregular) (150) [0.81]	60.71 (16.92, 27.00–96.00)	21.91 (12.11, 5.00–50.00)***	23.10 (13.63, 2.00–63.00)***	17.82 (13.01, 4.00–45.00)***	−0.23	0.75	0.61
Initial sound deletion (30) [0.70]	23.34 (7.67, 4.50–40.00)	9.95 (8.03, 0.00–25.00)***	6.25 (6.80, 0.00–23.50)***	9.44 (8.40, 0.00–21.00)***	1.35	−1.35	−0.11
Pseudoword rhyming (40) [0.56]	33.40 (4.55, 18.00–40.00)	28.09 (5.13, 17.00–35.00)***	28.10 (4.04, 20.00–35.00)***	29.24 (4.64, 17.00–36.00)***	0.40	−1.16	0.70
Homographic morpheme (30) [0.72]	25.54 (2.09, 21.00–29.00)	18.27 (4.11, 11.00–26.00)***	16.75 (3.11, 10.00–22.00)***	17.65 (2.52, 14.00–23.00)***	1.50	−0.74	0.85

(Continues)

TABLE 1 | (Continued)

Assessment	AC	PI	MI	WL	$T_{(PI\ vs.\ MI)}$	$T_{(MI\ vs.\ WL)}$	$T_{(PI\ vs.\ WL)}$
Homophonic morpheme (30) [0.65]	28.67 (1.12, 25.00–30.00)	22.05 (3.57, 16.00–26.00)***	19.10 (6.17, 8.00–27.00)***	21.18 (4.99, 10.00–27.00)***	1.67	−1.06	0.40
Character dictation (40) [0.85]	33.56 (3.67, 22.00–39.00)	16.59 (6.79, 6.00–31.00)***	15.15 (8.53, 2.00–33.00)***	14.71 (6.18, 4.00–24.00)***	0.47	0.03	0.56
Delayed copy (30) [0.68]	22.74 (4.47, 12.00–30.00)	18.33 (4.26, 4.00–24.00)***	17.60 (3.91, 9.00–23.00)***	19.82 (3.11, 14.00–24.00)***	0.31	−1.95	0.64
Misspelled-character correction (60) [0.74]	39.38 (6.88, 23.50–54.00)	30.62 (5.34, 21.00–39.00)***	28.10 (6.51, 11.00–40.00)***	30.94 (5.60, 21.00–40.00)***	0.88	−2.07	−1.58
Passage listening comprehension (9) [0.53]	6.59 (1.53, 3.00–9.00)	4.00 (1.73, 2.00–8.00)***	4.85 (2.35, 2.00–13.00)***	5.06 (1.28, 2.00–7.00)***	−1.37	−1.95	−2.02
Digit span-positive order (45) [0.76]	8.29 (1.30, 5.00–12.00)	7.57 (1.47, 5.00–10.00)***	6.82 (1.01, 5.00–9.00)***	7.44 (1.20, 6.00–9.00)***	1.97	−1.80	0.29
Digit span-reverse order (40) [0.58]	4.76 (1.25, 3.00–8.00)	3.27 (1.20, 2.00–5.00)***	3.64 (1.50, 2.00–8.00)***	3.56 (1.50, 2.00–6.00)***	−0.89	0.19	−0.76

Notes: The number in the parentheses following each assessment representing the full score for each test. The number in the brackets is the reliability of each test. ***Indicates that AC was significantly higher than PI, MI, and WL ($p < 0.001$).

Abbreviations: AC, the age control group; PI, the phonological intervention group; MI, the morphological intervention group; WL, the waiting-list control group.

pre-processing and individual-level analysis are reported in the supporting information. For the group-level analysis, we first conducted a one-way analysis of variance (ANOVA) of group (AC, RD) for the pre-intervention data on the contrast of lexical minus null to examine RD effect in each task. PI, MI, and WL were combined into RD in this analysis because they did not differ significantly. Then we conducted a flexible factorial ANOVA of group (PI, MI, WL) by time (pre-intervention, post-intervention) to examine the intervention effect in each task. In addition, we performed a brain-behavioral correlation analysis in the whole brain level between the pre-intervention brain activation in the AR and VS task and the amount of improvement on the character naming test (i.e., post-test minus pre-test), separately for the three intervention groups, to examine whether brain data can predict responsiveness. In the correlation model, we regressed out age, gender, Raven, and pre-test score. All reported significant results were uncorrected $p < 0.001$ at the voxel level, and $p < 0.05$ FDR-corrected at the cluster level unless specifically mentioned. This threshold was chosen because one previous study suggested that false positive results are more likely to happen at the cluster level and it is essential to do multiple comparison correction at the cluster level, and the voxel level threshold can be set at the uncorrected 0.005 or 0.001 level (Eklund et al., 2016). Our data and study materials are available based on request.

3 | Results

3.1 | Behavioral Results

3.1.1 | Behavioral Tests Before the Intervention

One-way ANOVA of group (AC, PI, MI, WL) showed a significant main effect of group for all behavioral tests. Post-hoc analyses revealed that the AC group was significantly higher than the PI, the MI, and the WL group, while there were no significant differences between any two of the PI, MI, and WL groups for any of the tests (Table 1).

3.1.2 | Behavioral Improvement After the Intervention

We conducted an ANOVA of group (PI, MI, WL) by time (pre-intervention, post-intervention) to examine intervention effect for each test. The interaction between group and time was significant for the sentence reading fluency test ($F(2,56) = 4.025$, $p_{corr} = 0.023$, $\eta^2 = 0.126$), the character naming test ($F(2,56) = 6.326$, $p_{corr} = 0.031$, $\eta^2 = 0.184$), the one-minute irregular character reading test ($F(2,56) = 5.747$, $p_{corr} = 0.005$, $\eta^2 = 0.170$), and the initial sound deletion test ($F(2,56) = 9.908$, $p_{corr} = 0.000$, $\eta^2 = 0.261$), while no significant interactions were found for the other tests (Table 2). All results were corrected using the false discovery rate (FDR) method ($p < 0.05$).

Simple effect analysis showed that before the intervention, the PI, the MI, and the WL groups were not significantly different on any of the four tests ($p > 0.05$), while after the intervention, the PI group and the MI group were significantly higher than the WL group on all of the four tests (for the sentence reading fluency test, $t(40) = 2.995$, $p_{corr} = 0.030$, Cohen's $d = 0.949$ for PI > WL, and $t(40) = 2.654$, $p_{corr} = 0.036$, Cohen's $d = 0.856$ for MI > WL; for the character naming test $t(40) = 3.211$, $p_{corr} = 0.018$, Cohen's $d = 1.026$ for PI > WL, and $t(40) = 1.538$, $p_{corr} = 0.042$, Cohen's $d = 0.494$ for MI > WL; for the one-minute irregular character reading test, $t(40) = 2.663$, $p_{corr} = 0.048$, Cohen's $d = 0.843$ for PI > WL, and $t(40) = 2.183$, $p_{corr} = 0.050$, Cohen's $d = 0.698$ for MI > WL; for the initial sound deletion test, $t(40) = 2.777$, $p_{corr} = 0.024$, Cohen's $d = 0.888$ for PI > WL, and $t(40) = 3.308$, $p_{corr} = 0.012$, Cohen's $d = 1.047$ for MI > WL). There was no significant difference between the PI and the MI group for any test after the intervention ($t(44) = -0.076$, $p_{corr} = 0.960$, Cohen's $d = 0.023$ for the sentence reading fluency test; $t(44) = 1.002$, $p_{corr} = 0.483$, Cohen's $d = 0.318$ for the character naming test; $t(44) = 0.218$, $p_{corr} = 0.849$, Cohen's $d = 0.066$ for the one-minute irregular character reading test; $t(44) = -0.179$, $p_{corr} = 0.886$, Cohen's $d = 0.054$ for the initial sound deletion test) (Figure 1). Therefore, the interaction effects were driven by greater increase in the PI and the MI group than in the WL group following the intervention.

For the other tests, all three groups had similar amount of improvement. We reported detailed results in the supporting information.

We calculated the correlation between scores of the pre-intervention behavioral tests and the amount of behavioral improvements to examine what factors may predict responsiveness. In order to simplify data analysis, using principal component analysis (PCA), we compressed similar tests into a factor score. Specifically, we compressed the two phonological awareness tests (i.e., initial sound deletion and pseudoword rhyming) into a phonological awareness factor, the two orthographic awareness tests (i.e., delayed copy, and misspelled character correction) into an orthographic awareness factor, the two morphological awareness tests (i.e., homographic morpheme and homophonic morpheme) into a morphological factor, the two RAN tests (i.e., digit RAN and picture RAN) into an RAN factor, the two one-minute character reading tests (i.e., regular character and irregular character reading) into a one-minute character reading factor. We included these five factor scores as well as character naming and sentence reading fluency in the correlation analysis. We calculated the correlation between the pre-intervention score on these seven variables and the change score on these variables separately in the PI, MI, and WL group. We found a positive correlation between the pre-intervention phonological awareness score and the change on sentence reading fluency in the PI group ($r = 0.638$, $P_{FDR} = 0.032$). We also found a negative correlation between the pre-intervention morphological awareness score and the change on morphological awareness score in the PI group ($r = -0.663$, $P_{FDR} = 0.032$).

3.1.3 | Performance on the In-Scanner Tasks

Before the intervention, a one-way ANOVA of group (AC, PI, MI, and WL) was conducted separately for accuracy and corrected reaction time (RT) on the AR task and the VS task. Corrected RT was calculated by dividing the RT by the accuracy, to account for possible trade-offs between speed and accuracy (Townsend and Ashby 1983). In both tasks, the AC group had higher accuracy than the other three RD groups; however, no group differences were found for the corrected RT. After the intervention, a repeated-measure ANOVA of group (PI, MI, WL) by time

TABLE 2 | Improvement (mean [standard deviation, range]) on the behavioral assessments from the pre-intervention test to the post-intervention test.

	PI group ($n = 21$) **Post-Pre**	**MI group ($n = 20$)** **Post-Pre**	**WL group ($n = 17$)** **Post-Pre**	**Interaction group × time F (η^2)**
Sentence reading fluency	344.82 (159.10, 105.00–677.00)	353.68 (166.61, 54.00–669.00)	227.50 (168.79, 5.00–511.00)	5.61* (0.13)
Character naming	18.32 (10.36, 2.00–49.00)	16.73 (7.96, 5.00–38.00)	8.72 (8.39, −9.00–26.00)	9.54** (0.20)
One-minute character reading (regular)	20.36 (11.57, 0.00–50.00)	14.59 (11.07, 4.00–51.00)	15.78 (11.94, 0.00–46.00)	0.11 (0.00)
One-minute character reading (irregular)	12.36 (6.08, 2.00–25.00)	10.73 (8.70, −2.00–34.00)	4.11 (8.58, −22.00–19.00)	5.79* (0.13)
Initial sound deletion	10.30 (6.76, −5.00–20.00)	14.00 (8.33, −7.00–27.50)	4.00 (5.42, −6.00–12.50)	19.25*** (0.34)
Pseudoword rhyming	4.27 (6.63, −15.00–14.00)	2.73 (5.20, −12.00–11.00)	0.94 (6.12, −12.00–14.00)	0.99 (0.03)
Homographic morpheme	2.64 (4.07, −5.00–8.00)	2.77 (4.43, −6.00–13.00)	2.94 (3.37, −2.00–8.00)	0.02 (0.00)
Homophonic morpheme	2.64 (2.28, −1.00–7.00)	4.32 (4.45, −2.00–13.00)	2.72 (3.20, −3.00–11.00)	1.62 (0.04)
Character dictation	2.55 (3.80, −5.00–9.00)	1.68 (5.02, −13.00–10.00)	4.33 (3.76, −2.00–10.00)	3.44 (0.08)
Delayed copy	1.05 (3.01, −5.00–6.00)	0.90 (0.77, −0.66–2.46)	0.59 (0.83, −1.11–2.28)	0.08 (0.00)
Misspelled-character correction	0.33 (3.65, −6.00–7.00)	1.40 (0.97, −0.58–3.37)	−0.82 (1.06, −2.97–1.32)	2.40 (0.06)
Passage listening comprehension	0.82 (1.18, −2.00–3.00)	0.36 (2.04, −6.00–4.00)	−0.61 (2.20, −5.00–2.00)	2.11 (0.05)

Abbreviations: PI, the phonological intervention group; MI, the morphological intervention group; WL, the waiting-list control group; Post-Pre, the change of score from the pre-intervention to the post-intervention.
***$p < 0.001$, **$p < 0.01$, *$p < 0.05$.

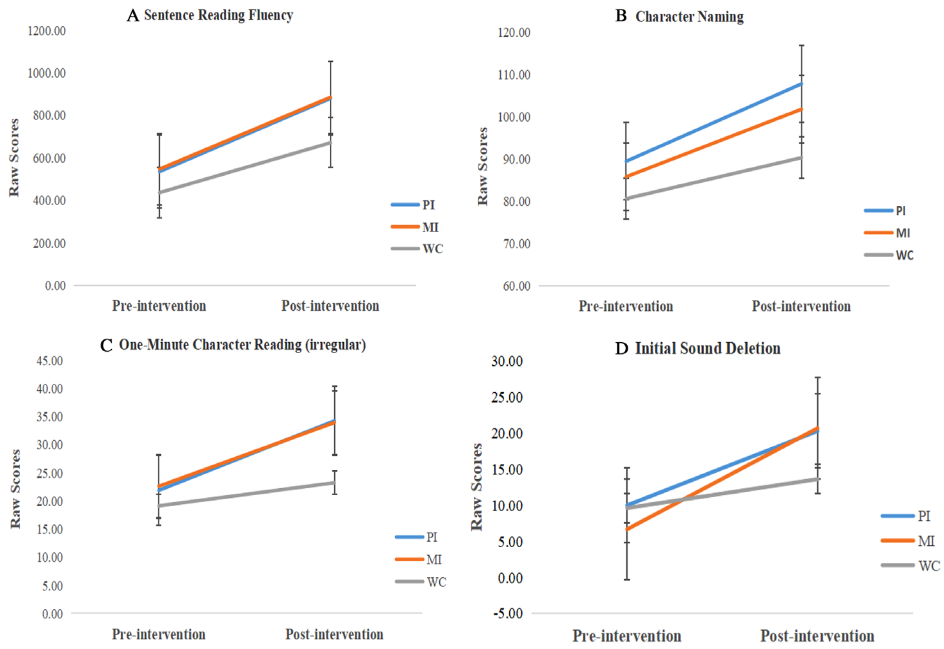

FIGURE 1 | Significant interactions between time and group on the behavioral tests, driven by greater increase in the PI and MI group than in the WC group. PI, phonological intervention; MI, morphological intervention; WC, waiting controls.

(pre-intervention, post-intervention) was conducted separately for accuracy and corrected RT in the AR and VS task. No main effect or interaction were found, suggesting that performance on the in-scanner tasks did not change following the intervention (Figure 2). Detailed results from the ANOVAs are presented in the supporting information.

3.2 | Brain Results

3.2.1 | Group Comparisons Before the Intervention

Before the intervention, a one-way ANOVA of group (AC, RD) revealed that for the AR task, the AC group had significantly greater activation than the RD group at the bilateral cingulate gyrus, the left middle frontal gyrus (MFG), left IFG, right insula, left cuneus, bilateral thalamus, left IPL, right lingual gyrus, right cuneus, right middle occipital gyrus (MOG), and left precuneus (Table 3, Figure 3A).

For the VS task, before the intervention, the AC group had significantly greater activation than the RD group at the left MOG, right SPL, left MFG, bilateral lingual gyrus, right cuneus, left precuneus, right IFG, and left precentral gyrus (Table 3, Figure 3B).

In both the AR task and the VS task, the AC group had significantly greater activation at the left MFG than the RD groups (Table 3, Figure 3C). There were no differences between any two of the PI, the MI, and the WL group before the intervention on either the AR task or the VS task. Brain activations in each group for each task are presented in the supporting information (Figure S1).

When task accuracy was added as a covariate, ANCOVA of group showed greater activation in AC than in RD in the left IFG/MFG and bilateral SFG in the AR task, in the right SPL and left lingual gyrus in the VS task. There was no conjunction between the two tasks for the AC > RD contrast.

3.2.2 | Intervention Effects

For the AR task, the ANOVA of group (PI, MI, WL) by time (pre-intervention, post-intervention) revealed a significant interaction between group and time at the right MTG at a lower threshold ($p < 0.005$ uncorrected) (Figure 4A). For the VS task, the ANOVA of group (PI, MI, WL) by time (pre-intervention, post-intervention) revealed significant interactions between group and time at the left parahippocampal gyrus. When the threshold was lowered to $p < 0.005$ uncorrected, the left IFG, left MFG, and left fusiform gyrus also showed a significant interaction (Table 4, Figure 4B). The main effects of group and time are also reported in Table 4.

We conducted ROI analyses at the five regions with a significant interaction to examine what drove the interaction. We extracted beta values at each ROI which was defined as a sphere centered at the peak with a radius of 6 mm. For the right MTG in the AR task, we found that the PI group had a greater increase in brain activation after the intervention than the MI group and the WL group (Figure 4A).

For the VS task, we found a greater increase in brain activation following the intervention in the MI group at the left parahippocampal gyrus, the left IFG, the left fusiform gyrus, and the left MFG than the PI group and the WL group (Figure 4B).

3.2.3 | Brain-Behavioral Correlations

For the PI group, we found that brain activation in the AR task in the right precentral gyrus/postcentral gyrus at the

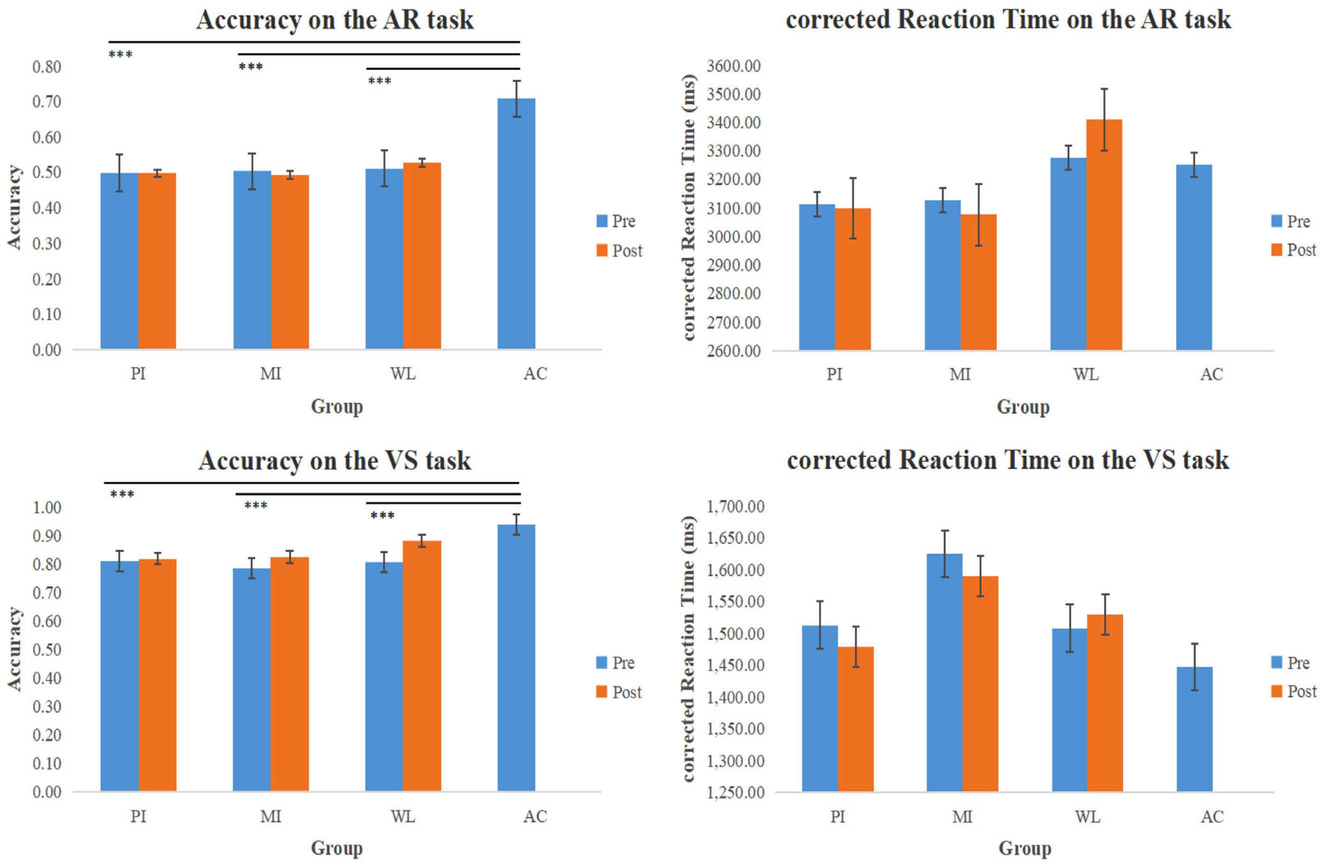

FIGURE 2 | Accuracy and corrected reaction time on the AR and VS task before and after intervention in each group. AC, the age control group; MI, the morphological intervention group; PI, the phonological intervention group; pre, before intervention; post, after intervention; WC, the waiting-list control group. Significant group main effects in repeated measures ANOVA: ***$p < 0.001$.

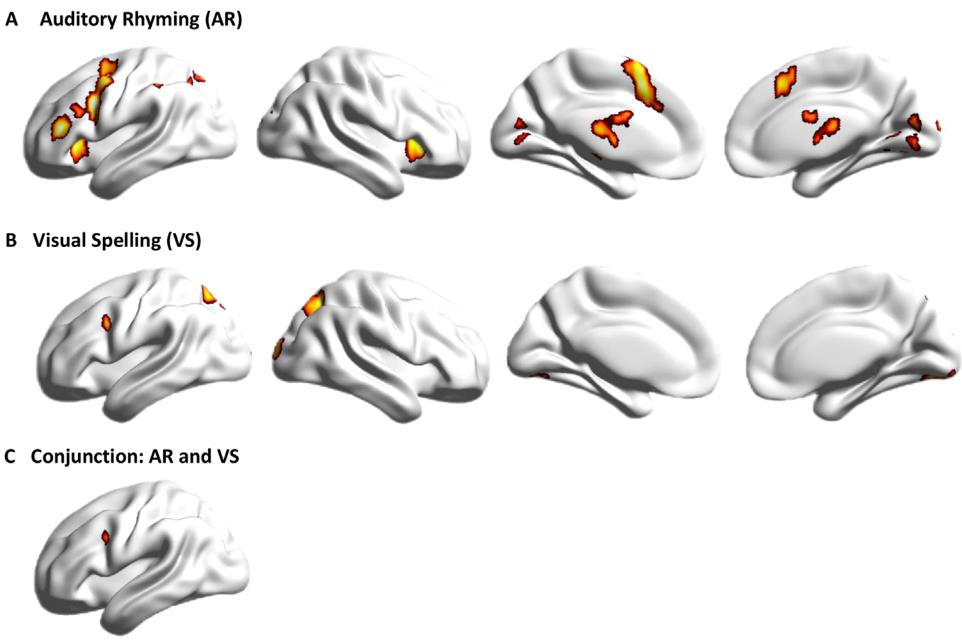

FIGURE 3 | Greater activation in ACs than in children with RD before the intervention for the AR task (A), and the VS task (B). The conjunction of AC > RD in the AR task and in the VS task is shown in C.

TABLE 3 | Group comparisons for brain activation before the intervention.

Anatomical region	H	BA	Voxels	*x*	*y*	*z*	*Z*
AC > RD in the AR task							
Cingulate gyrus	R/L	32	975	8	20	44	6.53
Middle frontal gyrus/inferior frontal gyrus/insula	L	8/46	2606	−42	36	17	6.10
Insula	R	13	301	32	20	7	5.45
Cuneus	L	18	796	−2	−74	11	5.10
Thalamus	L/R	/	771	−10	−16	4	4.90
Inferior parietal lobule	L	40	183	−50	−38	54	4.22
Lingual Gyrus	R	18	232	21	−58	2	4.13
Cuneus/middle occipital gyrus	R	19/18	94	21	−96	20	3.96
Precuneus	L	7	127	−22	−72	50	3.86
AC > RD in the VS task							
Middle occipital gyrus	L	18	135	−16	−102	10	5.49
Superior parietal lobule	R	7	565	26	−68	52	5.48
Middle frontal gyrus	L	46	184	−44	16	28	5.45
Lingual gyrus	R	19	288	24	−74	−8	5.45
Lingual gyrus	L	18	217	−22	−76	−10	5.43
Middle occipital gyrus/cuneus	R	18/19	126	24	−94	23	5.38
Precuneus	L	7	257	−21	−72	56	5.30
Conjunction of AC > RD in the AR task and AC > RD in the VS task							
Middle frontal gyrus	L	46	281	−44	15	28	5.58

Abbreviations: AC, the age control group; BA, Brodmann area; H, hemisphere; L, left hemisphere; R, right hemisphere; RD, children with RD including the PI group, the MI group, and the WL group; *x*,*y*,*z*, Montreal Neurological Institute (MNI) coordinates.

pre-intervention scanning positively predicted improvement on the character naming test (Table 5, Figure 5A).

For the MI group, the brain activation in the AR task in the right lingual gyrus/fusiform gyrus/MOG positively predicted improvement on the character naming test (Table 5, Figure 5B); and activation in the VS task in the left fusiform gyrus positively predicted improvement on the character naming test (Table 5, Figure 5C).

We also correlated improvement on the initial sound deletion test with brain changes following the intervention separately in each group and each MRI task. We found that in the PI group, brain activation changes in the bilateral lingual gyri in the AR and the VS task had a positive correlation with changes in the initial sound deletion test. In the MI group, brain activation changes in the right precentral gyrus in both tasks had a negative correlation with changes in the initial sound deletion test (Figure 6).

4 | Discussion

The aim of the current study was to examine the effectiveness of a phonological and a MI in Chinese children with RD both behaviorally and neurologically. We found evidence for both. As the first study that examined brain changes following different interventions in Chinese children with RD, our findings provide both theoretical and practical insights to the field of RD.

4.1 | Behavioral Evidence

We found that the phonological and MIs are equally effective. Specifically, both the PI and the MI group had greater

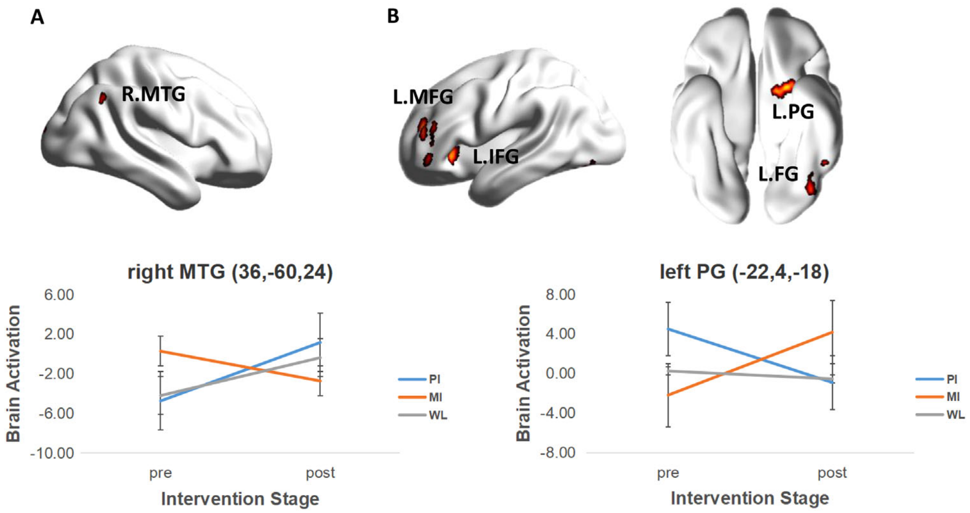

FIGURE 4 | Brain regions where there was an interaction between group and time in the AR task (A) and the VS task (B). Only the left PG was significant at $p < 0.001$ uncorrected, and the other regions were significant at a lower threshold ($p < 0.005$ uncorrected). FG, fusiform gyrus; IFG, inferior frontal gyrus; MFG, middle frontal gyrus; MTG, middle temporal gyrus, PG, parahippocampal gyrus.

improvement than the WL group on character naming, sentence reading fluency, one-minute irregular character reading, and initial sound deletion. This finding is different from a previous study which found greater improvement on word reading and vocabulary after morphological but greater improvement on phonological awareness after PI (Zhou et al. 2012). The study by Zhou et al. (2012) is different from ours in many aspects which may explain different findings in these two studies. Their intervention was mostly based on spoken language since their participants were typically developing kindergarteners. Our intervention focused on character reading in fifth-grade children with RD. Each Chinese character has a phonetic radical and a semantic radical, so when the phonetic radical is taught, the semantic radical also stands out, and vice versa. That may be why we found similar effects in phonological and MI. Both phonological and MI strengthened the connection among orthography, phonology and semantics in character representation.

We also found both interventions are effective in improving phonological awareness. Previous reading intervention studies in other languages also found that morphological training improved phonological awareness (Arnbak and Elbro 2000; Lyster 2002). In Chinese, a study also found improvement on syllable representation in children with RD following a metalinguistic training including morphological and phonological components (Wang et al. 2021a).

Our study further suggests that MI may improve phonological awareness via different mechanisms than PI. Specifically, we found that increased phonological awareness was correlated with increased brain activation in the bilateral lingual gyri in both the AR and the VS tasks in the PI group, but decreased brain activation in the right precentral gyrus in both tasks in the MI group, suggesting different mechanisms in the two interventions in improving phonological awareness. In the PI group, we taught Pinyin which is an alphabetic system indicating the pronunciation of the character. This may encourage co-activation of Pinyin in the bilateral lingual gyri as a visual aid during character processing in the two tasks. Previous studies have shown the reciprocal relationship between Pinyin learning and phonological awareness (Lin et al., 2020). Our study tends to suggest that this reciprocal relationship may be due to the visual strategy of activating Pinyin during phonological processing. On the other hand, in the MI group, those with greater phonological awareness increase showed reduced activation in the right precentral gyrus. The right precentral gyrus has been found to play a compensatory role in phonological processing in previous studies (Yan et al. 2021), due to the involvement of the articulation-related strategies. Our study suggests that those with a greater improvement in phonological awareness tend to show reduced involvement of this compensation, which is consistent with a previous study showing that after intervention, less compensation is needed (Huber et al. 2018).

Furthermore, there is a trend that the MI group had a greater improvement than the other two groups on the homophonic morpheme test and the misspelled character correction test, even though it did not reach a significance. Future research is needed to have a larger sample size to examine if MI has a specific effect on homophone discrimination and orthographic skills.

4.2 | Neurological Evidence

4.2.1 | Abnormalities Before the Intervention

Before the intervention, children with RD showed reduced activation in the left MFG (BA9) than typical children during both the AR and the VS task. This left MFG has been found to play an important role in Chinese reading (Tan et al. 2005), as compared to alphabetic languages. This might be related to the addressed phonological procedure in Chinese due to fact that each character maps to the whole syllable in Chinese. It might also be associated with lexical integration and selection because there are many homophones in Chinese, and there is a higher demand on lexical selection. Research has consistently shown that this important region is less involved in Chinese individuals with RD than in typical readers, such as in a visual homophone judgment and

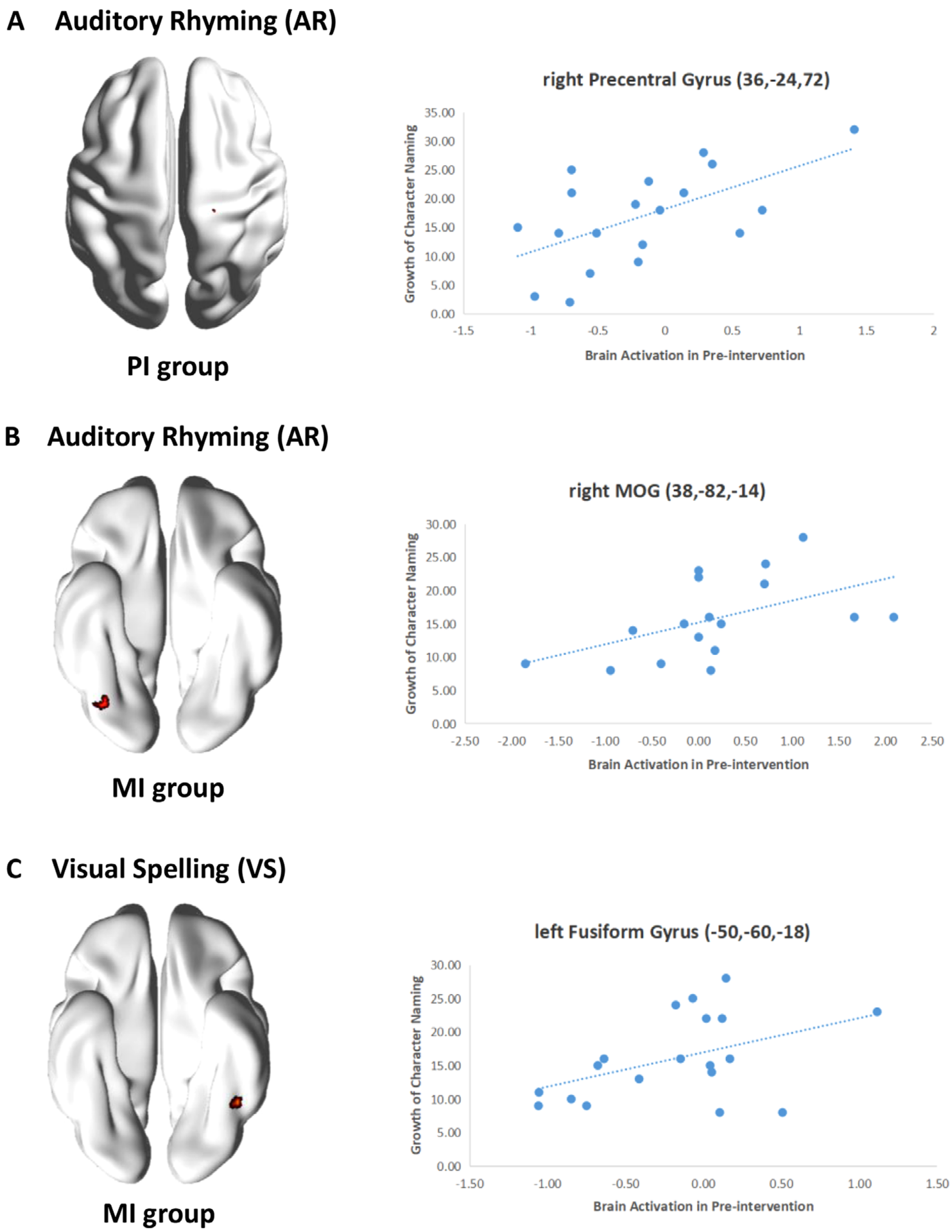

FIGURE 5 | Regions with a positive correlation between brain activation in the AR task before the intervention and improvement on the character naming tests in the PI group (A), and the MI group (B), and the positive correlation between brain activation in the VS task and improvement on character naming in the MI group (C).

visual lexical decision task (Siok et al. 2004), in an auditory rhyming task (Cao et al. 2017), in a visual rhyming task (Cao et al. 2021), and in a morphological task (Liu et al. 2012). A recent meta-analysis showed that this region has greater functional and structural abnormalities in individuals with RD in Chinese than in alphabetic languages (Yan et al. 2021), due to greater specialization of this region to Chinese than to alphabetic languages in typical readers. Our finding is consistent with these previous studies in showing reduced activation in this region in Chinese children with RD across both the AR task and the VS task.

4.2.2 | Intervention Effects

We found intervention-specific effect in the brain. Specifically, the MI group increased brain activation in the left parahippocampal gyrus following the intervention, compared to the PI and WL group. When a more lenitent threshold was applied, left IFG/MFG and left fusiform gyrus also showed greater increase in the MI than the PI and WL group, and the PI group showed greater increase in the right MTG than the MI and WL groups. It suggests that different interventions affect different parts of the brain, even though behaviorally they had similar effects in improving reading and phonological awareness.

4.2.2.1 | The MI-Specific Effects.

The left parahippocampal gyrus is more activated following the MI than the PI or the WL. The parahippocampal gyrus is involved in declarative memory (Aminoff et al. 2013; Bonner et al. 2015), and our morphological training had a focus on the connections between orthography and semantics, which might explain why this region showed

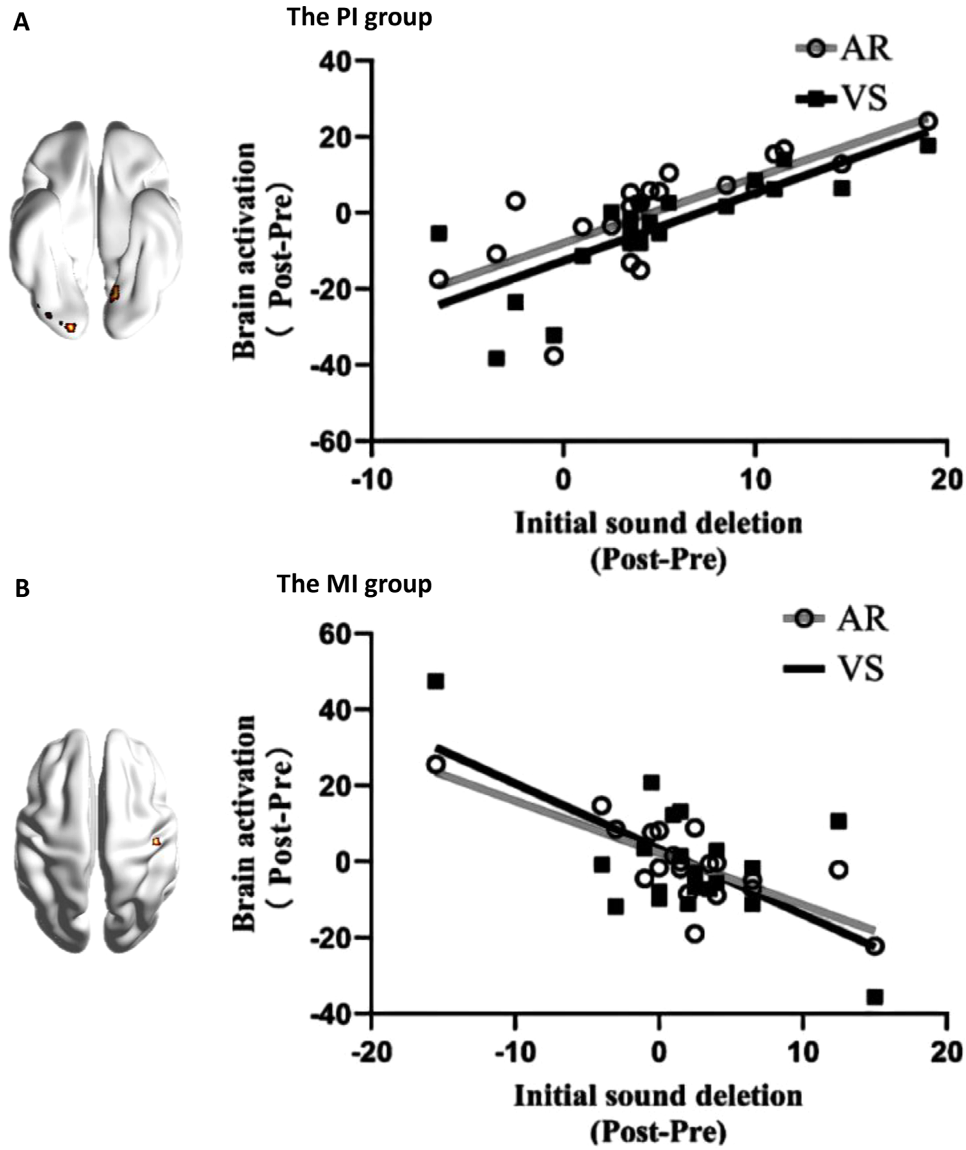

FIGURE 6 | Correlations between brain change and behavioral change. (A) a positive correlation between brain activation changes in the AR and VS tasks and behavioral changes in the initial sound deletion test in the PI group (averaged across all clusters in the bilingual gyri that had a significant positive correlation). (B) a negative correlation between brain activation changes in the right precentral gyrus in the AR and VS tasks and behavioral changes in the initial sound deletion test in the MI group.

a MI-specific effect. A previous morpheme-based intervention study also found training-specific brain activation increase in the bilateral parahippocampal gyri (Gebauer et al. 2012).

When the threshold was lowered, we also found greater increase in the brain activation at the left fusiform gyrus in the MI group than in the PI and the WL group following intervention. The left fusiform gyrus has been found to be specialized for orthographic processing and part of the fusiform gyrus was named visual word form area (VWFA) (Booth et al. 2002; Cohen et al. 2000; Cohen et al. 2002; Dehaene et al. 2002; McCandliss et al. 2003; Olulade et al. 2015; Richlan et al. 2011; Warrington and Shallice 1980). However, some researchers have argued that this region is actually an interactive region between orthography, phonology, and semantics which is associated with prediction-making during reading (Price and Devlin 2011). Evidence suggests that the left FG plays an essential role in fluent reading because this region is more involved when reading fluency is more demanded (Benjamin and Gaab 2012; Langer et al. 2015). According to the reading development model by Pugh (2000), there is a developmental shift from phonological reading in the dorsal pathway to orthographic reading in the ventral pathway (Pugh et al. 2000), and the left fusiform gyrus is an important region in the ventral reading pathway. Consistent with this model, previous studies have found greater involvement of this region in adults than in children during reading (Bitan et al. 2009; Cao, Lee, et al. 2010; Shaywitz et al. 2007; Siok et al. 2020).

The left fusiform gyrus has been found to be less activated in readers with RD than control readers in multiple tasks, such as in auditory rhyming judgment tasks (Desroches et al. 2010; Zou et al. 2015), in visual word reading tasks (Cao et al. 2021; Hoeft et al. 2007), and in a visual semantic category task (Shaywitz et al. 2002), suggesting that neural differences in the left FG

TABLE 4 | Results from the ANOVA of group (PI, MI, WL) by time (pre-intervention, post-intervention) in the whole brain analysis for both the AR and the VS task.

Anatomical region	H	BA	Voxels	x	y	z	Z
Main effect of group—AR							
PI > WL							
Superior frontal gyrus	L/R	6	129	−6	17	63	4.42
Fusiform gyrus	R	19	140	34	−72	−18	4.31
Insula/precentral gyrus	L	13/6	90	−40	−18	18	4.11
Middle frontal gyrus	L	6	139	−26	−4	50	3.94
Precentral gyrus	L	6	87	−42	−8	50	3.93
WL > PI							
—							
MI > WL							
—							
WL > MI							
—							
PI > MI							
—							
MI > PI							
Postcentral gyrus	R	3	92	66	−18	34	4.41
Main effect of time-AR							
Pre > Post							
—							
Post > Pre							
—							
Interaction of group (PI, MI, WL) × time (pre, post)-AR							
—							
Main effect of group-VS							
PI > WL							
—							
MI > WL							
—							
PI > MI							
Fusiform gyrus	R	37/20	253	34	−48	−18	4.15
MI > PI							
—							
WL > PI							
—							
WL > MI							
—							
Main effect of time-VS							
Pre > Post							
—							
Post > Pre							
—							
Interaction of group (PI, MI, WL) × time (pre, post)-VS							
Parahippocampal gyrus	L	34	192	−22	4	−18	4.79

(Continues)

TABLE 4 | (Continued)

Abbreviations: BA, Brodmann area; H, hemisphere; L, left hemisphere; MI, the morphological intervention group; PI, the phonological intervention group; R, right hemisphere; WL, the waiting-list control group; *x,y,z*, Montreal Neurological Institute (MNI) coordinates.

may be a central signature of RD. A previous study further suggests that functional differences at this region may represent a developmental deviance rather than a developmental delay, because even reading-matched younger control children showed greater activation than children with RD in this region (Cao et al. 2021). A recent study further suggests that differences in this region are more severe in adults with RD than in children with RD, suggesting an accumulative RD effect in this region, which is because there is a much larger developmental increase in the involvement of this region in typical readers than in RD readers (Xiaohui Yan et al. 2024). Taken together, the left fusiform gyrus is a very important region in fluent reading with the assumed function of rapid whole-word recognition, which is affected in RD and our MI can effectively increase brain activation in this region.

Consistent with our finding, a previous intervention study also found that brain function at the left fusiform gyrus can be effectively modulated (Heim et al. 2015). This study found that German children with RD exhibited increased activation in the left ventral occipito-temporal cortex (i.e., the VWFA) in a visual overt single word reading task following phonological training, attention training, or visual word recognition training, but not in the control group who received no training. In this German study, this region showed less activation in children with RD than in controls before the intervention, therefore, it suggests functional normalization. Our study adds to the literature that morphological training also effectively normalizes brain function at the left FG, presumably because morphological training enhances rapid word recognition at the left FG by strengthening the connection from orthography to semantics.

4.2.2.2 | The PI-Specific Effect. When we used a more lenient threshold of $p < 0.005$ uncorrected, the PI group showed greater increase in the right MTG than the MI and WL group. The right MTG has been found to be involved in phonological processing in previous research (Heim et al. 2015; Reilhac et al. 2013; Sandak et al. 2004), especially in learning phonetic variation associated with a specific talker (Luthra et al. 2023). A previous intervention study has also found compensation in the right temporal-parietal area following a phonological decoding intervention in English readers with RD (Simos et al. 2007). Children who receive phonological training may develop some new phonological strategies by involving the right MTG. As the first study that has examined brain changes following PI in Chinese RD, our study further suggests that the increased compensation in the right MTG is specific to the PI and not shared by other interventions that do not have a focus on phonological skills.

TABLE 5 | Correlations between brain activation (pre-intervention) and growth of behavioral performance (post-intervention minus pre-intervention) on the character naming test separately for the PI and MI group.

Anatomical region	H	BA	Voxels	*x*	*y*	*z*	*Z*
***Positive correlations in the* AR task—PI**							
Precentral gyrus/postcentral gyrus	R	6/1	103	36	−24	72	4.55
***Positive correlations in the* AR task—MI**							
Middle occipital gyrus/lingual gyrus/fusiform gyrus	R	18	109	38	−82	−14	4.08
***Positive correlations in the* VS task—MI**							
Fusiform gyrus	L	37	104	−50	−60	−18	4.12

Taken together, we found significant functional normalization in the left FG, left IFG, and MFG in the MI group during the VS task and compensation mechanisms in the right MTG area in the PI group during the AR task. It suggests that the MI may address reading processes that typical Chinese readers involve, such as the direct mapping between orthography and semantics. On the other hand, the PI emphasized on the print-sound mapping which may be an alternative way of reading Chinese characters which is only compensatory in typical Chinese reading. Future replication is needed to confirm greater normalization in the MI and greater compensation in the phonological intervention in Chinese RD using larger samples. Furthermore, at the current threshold level, we did not find any shared brain regions that respond similarly to the two interventions, suggesting a lack of general intervention effect. However, future research is needed to have a more comprehensive examination of the brain responses to interventions by including multiple scanning sessions, because the intervention-general effect may appear early on and then disappear with intervention.

4.2.3 | Prediction of Responsiveness

In addition, we found that brain activation at the right pre/postcentral gyrus in the AR task before the intervention predicted greater improvement on character naming in the PI group. This region is actually involved in phonological processing (Bamiou et al. 2003; Cao, Khalid et al. 2010; Cao et al. 2017; Sandak et al. 2004). The pre-postcentral gyrus is associated with the articulatory strategies during phonological processing (Bamiou et al. 2003), which tends to be a compensatory mechanism used in readers with RD (Yan et al. 2021). It seems to suggest that greater function in the phonological region at the baseline predicts greater responsiveness to the PI. This is also consistent with the finding that greater baseline phonological awareness is correlated with greater reading improvement in the PI group. Taken together, those with greater phonological skills tend to have better responsiveness to the PI.

Furthermore, activation in the left FG before the intervention during the VS task positively predicted improvement on character naming in the MI group, suggesting that children with better function at the left FG benefit more from the MI. The cluster in the left FG with a prediction effect actually overlaps with the cluster where there was a significant increase following the MI than the PI or WL (i.e., [−50, −60, −18] for the prediction effect, and [−46, −60, −22] for the intervention effect). It suggests that this region is not only responsive specifically to MI, but also its greater function at the baseline predicts better responsiveness following MI. This finding aligns with previous studies. For example, one intervention study found that adequate responders exhibited greater activation in the left ventral occipitotemporal regions than inadequate responders before the intervention (Rezaie et al. 2011). Another study found that activation of the left occipito-temporal VWFA in preliterate German kindergartners after an 8-week letter-speech sound correspondence training predicted their reading ability in the second grade (Bach et al. 2013). The left FG is involved in orthographic recognition and stronger orthographic skills may facilitate morphological learning because our morphological training is essentially to connect orthography with semantics. Previous studies in English have also indicated that morphological instruction needs phonological and orthographic support (Goodwin & Ahn, 2010). Taken together, better function of the left FG predicts greater responsiveness to the MI, suggesting the essential role of this region in reading and reading intervention.

Our study suggests that children with stronger phonological functions benefit more from the phonological training than those with weaker phonological functions and children with stronger FG activation benefit more from the morphological training than those with weaker activation in the left FG. This is consistent with the hypothesis that intervention should focus on strengths rather than weakness of the children (Torgesen et al., 2001). Future research is needed to confirm this finding.

4.3 | Education Implications

Our findings have important educational implications. First of all, we added an evidence-based PI and MI to the practice which can be easily integrated into regular curriculum. Second of all, our findings of responsiveness may guide implementation of these interventions in practice. For example, PI should be provided to children with better phonological skills, and MI should be provided to children with better orthographic skills. Future studies should develop intervention for children with poor phonological and orthographic skills, and future reading intervention should consider combining the phonological training and morphological training since we found them both to be effective.

4.4 | Limitations

There are several limitations in the current study. First of all, the sample of the current study did not include rural areas, therefore, future research needs to examine whether students from rural areas would also show the same patterns. Some of the key findings are only significant at a more lenient threshold level now, such as the intervention effect in the right MTG in the PI group and in the left FG, IFG, and MFG in the MI group. The study could benefit from a larger sample size with a more stringent threshold, which may have a more accurate examination on the differences between the two interventions. A follow-up session would have been valuable in understanding the long-term effects of the interventions. Last, the intervention duration may also be a factor that influences the behavioral and brain changes. Future research is needed to address these points.

5 | Conclusions

The study showed that our phonological and MIs are effective in improving reading in Chinese children with RD both behaviorally and neurologically. It suggests that the PI helps reading by developing compensation in the right phonological area, and the MI improves reading by normalizing function in the left key reading areas. Furthermore, children with better phonological functions benefit more from the PI and those with better orthographic functions benefit more from the MI, suggesting that intervention should focus on strength rather than weakness. These findings provide important insights in developing individualized intervention.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

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

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Figure S1: Brain activation in the AC and RD group for the AR task and the VS task. P<.001 uncorrected at the voxel level, FDR corrected p<.05 at the cluster level.