Orthographic-Phonological Integration Ability in Chinese Children with Developmental Dyslexia: The Interaction Between Orthography and Phonology

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Abstract

The purpose was to investigate whether abnormalities exist in the mutual influence of orthographic and phonological information during orthography-phonology integration in Chinese children with developmental dyslexia. Experiment 1 employed 30 Chinese children with developmental dyslexia and 29 age-matched control children as participants, using a cross-modal visual-auditory orthographic judgment task. The results revealed that congruent phonology exhibited a significant facilitatory effect on orthographic processing, and no significant group difference was found in the influence of phonology on orthographic processing. Experiment 2 employed 32 Chinese children with developmental dyslexia and 32 age-matched control children as participants, using a cross-modal visual-auditory phonological judgment task. The results revealed that congruent orthography exhibited a significant facilitatory effect on phonological processing, while incongruent orthography exhibited a significant inhibitory effect on phonological processing. The influence of orthography on phonological processing in the age-matched control group was significantly greater than that in the developmental dyslexia group. These results indicate that during orthography-phonology integration, Chinese children with developmental dyslexia exhibit abnormalities in the influence of orthography on phonological processing, but not in the influence of phonology on orthographic processing.

Full Text

Orthography-Phonology Integration of Chinese Children with Developmental Dyslexia: The Mutual Influence of Orthography and Phonology

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Abstract

Previous studies have revealed that individuals with developmental dyslexia (DD) experienced an orthography-phonology integration deficit. Using functional magnetic resonance imaging, researchers have observed hypoactivation in the superior temporal area when individuals with DD performed an orthography-phonology integration task. Additionally, individuals with DD exhibited a delayed and reduced mismatch negative wave in an audiovisual oddball paradigm when using event-related potentials. However, some studies have found no significant differences between normal readers and DD readers when making decisions about a phoneme preceded by a grapheme.

These controversial results may be attributed to the varying manifestations of the mutual influence between orthography and phonology during orthography-phonology integration in DD. Nevertheless, there is a lack of comprehensive research on this topic. The present study aims to explore the mutual influences between orthography and phonology during orthography-phonology integration in Chinese children with DD.

Two experiments were designed to separately investigate the mutual influence between orthography and phonology during orthography-phonology integration in individuals with DD. In Experiment 1, we explored the influence of phonology on orthographic processing. 30 children with DD and 29 age-matched (CA) children participated in Experiment 1. Participants were asked to decide whether a grapheme was real or one invented for the purposes of this study. Each grapheme was accompanied by the presentation of a phoneme, which was either congruent or incongruent with the grapheme. This experiment also included a baseline condition in which only a grapheme was presented. In Experiment 2, we examined the influence of orthography on phonological processing. 32 children with DD and 32 CA children participated in Experiment 2. Participants were asked to decide whether a phoneme was real or invented. Each phoneme was presented with either a congruent or incongruent grapheme. This experiment also included a baseline condition in which only a phoneme was presented.

The results of Experiment 1 revealed a facilitating effect in the congruent condition compared to the grapheme only condition, but no inhibitory effect was observed in the incongruent condition. Furthermore, no significant group difference was found in the influence of phonology on orthography after controlling for the effect of the only grapheme condition. These findings indicate that Chinese children with DD do not exhibit a deficit in the influence of phonology on orthography during orthography-phonology integration. In Experiment 2, a facilitating effect was observed in the congruent condition and an inhibitory effect was observed in the incongruent condition compared to the only phoneme condition. These effects were significantly lower in children with DD than in CA children. These results indicate that Chinese children with DD exhibit a deficit in the influence of orthography on phonology after controlling for the effect of the only phoneme condition. The collective findings from Experiment 1 and Experiment 2 suggest that Chinese children with DD only exhibit a deficit in the influence of orthography on phonology when integrating a phoneme and a grapheme, while the influence of phonology on orthographical processing remains intact.

In conclusion, the present research provides insights into the mechanism of dyslexics' deficit in orthography-phonology integration. Notably, this study revealed that this deficit primarily manifests in the influence of orthography on phonological processing. These findings suggest orthography-phonology integration deficit in Chinese children with DD may be attributed to an impaired effect of graphemes on phonological processing.

Keywords: developmental dyslexia, audiovisual integration, orthography, phonology

Introduction

Reading is a crucial pathway for acquiring information from the external world. However, individuals with developmental dyslexia (DD) struggle to achieve fluent reading despite normal intelligence, adequate educational opportunities, and absence of organic damage (Lyon et al., 2003). Successful reading requires the visual system to process orthographic information and the auditory system to process phonological information, with subsequent integration of these two channels into a unified audiovisual representation (Beech, 2002; Law et al., 2018; Macoir et al., 2012). Research has demonstrated that individuals with DD exhibit deficits in audiovisual integration (Blau et al., 2009; 2010), which refers to the process whereby visual and auditory signals presented with temporal and spatial proximity tend to be bound into a unified representation (Koelewijn et al., 2010). In the context of reading, this deficit manifests as difficulty integrating orthographic and phonological information. Blomert (2011) proposed the orthography-phonology automatic integration hypothesis, suggesting that the root cause of DD lies in the failure to automatically integrate orthographic and phonological information.

Neuroimaging studies have provided substantial support for orthography-phonology integration deficits in DD. Using functional magnetic resonance imaging (fMRI), Blau et al. (2009; 2010) employed letter-speech sound stimuli under congruent, incongruent, and unisensory (visual and auditory) conditions. After controlling for unisensory processing, they found that individuals with DD showed significantly reduced activation in bilateral superior temporal cortex under congruent conditions compared to chronological age-matched (CA) controls, though no group differences emerged under incongruent conditions, indicating an orthography-phonology integration deficit. Subsequent research extended these findings to the lexical level. Kast et al. (2011) examined adult DD and CA participants using real and pseudowords with corresponding speech sounds under congruent and unisensory conditions, requiring word/pseudoword judgments. Results revealed that DD individuals exhibited significantly weaker activation in the left supramarginal gyrus and right superior temporal sulcus under congruent conditions, with no group differences in unisensory conditions. Kronschnabel et al. (2014) reported similar findings in adolescent DD. Research on Chinese DD using analogous paradigms has also demonstrated atypical activation in superior temporal regions during orthography-phonology integration tasks (Yang et al., 2020). Collectively, these findings suggest that DD is characterized by orthography-phonology integration deficits associated with abnormal activation in superior temporal brain regions, exhibiting cross-linguistic consistency.

Event-related potential (ERP) studies have further elucidated the temporal dynamics of orthography-phonology integration deficits in DD. Froyen et al. (2011) employed audiovisual crossmodal and auditory unisensory conditions, using congruent orthography-phonology stimuli as standards and incongruent pairs as deviants in the crossmodal condition, while using the sounds of letters "a" and "o" as standard and deviant in the unisensory condition. Participants passively viewed and listened to stimuli while the researchers compared mismatch negativity (MMN) responses to deviants across conditions. The results showed that CA children exhibited significantly enhanced MMN amplitudes in the crossmodal compared to the unisensory condition, whereas the DD group did not show this effect but instead displayed enhanced late discrimination negativity (LDN). The researchers argued that both early MMN and late LDN reflect orthography-phonology integration capacity, with the presence of only enhanced LDN in DD indicating slower and less automatic integration. Mittag et al. (2013) replicated these findings in adult DD and CA participants, additionally using picture-sound pairs as deviants. They found that DD showed weaker MMN amplitude enhancement and longer latencies than CA for both incongruent orthography-phonology and picture-sound pairs. Moreover, CA participants showed significant MMN enhancement only for incongruent orthography-phonology pairs, not for picture-sound pairs, whereas DD showed no differential MMN responses across deviant types, further confirming orthography-phonology integration deficits.

However, contradictory findings have also emerged. Nash et al. (2016) tested DD children, CA controls, and reading-level matched (RL) controls using an orthographic priming task where letters or shapes were presented 500 ms before speech sounds, requiring participants to judge whether the presented sound corresponded to a real letter. While DD children showed longer reaction times overall than both control groups, their performance under congruent orthography-phonology conditions did not differ significantly from controls. Building on this work, Clayton and Hulme (2018) added an incongruent condition to investigate whether DD exhibits abnormal resistance to interference during phonological judgment. They found that although DD children had longer reaction times than CA controls across all conditions, they did not differ from RL controls. Importantly, the facilitatory effect under congruent conditions and inhibitory effect under incongruent conditions were comparable across DD, CA, and RL groups, suggesting intact orthography-phonology integration capacity in DD. These behavioral findings stand in contrast to neuroimaging studies (Blau et al., 2009; 2010; Froyen et al., 2011; Kast et al., 2011; Kronschnabel et al., 2014; Mittag et al., 2013; Yang et al., 2020).

Two potential explanations may account for these inconsistent findings. First, the discrepancies may reflect different manifestations of the mutual influence between orthography and phonology during integration. Most neuroimaging studies have employed passive tasks or required judgments only on congruent pairs, preventing direct assessment of abnormalities in orthography-phonology mutual influence. Only one fMRI study with Chinese DD children and CA controls used a crossmodal orthographic judgment task with congruent, incongruent, and visual unisensory conditions (Yang et al., 2020). While this study revealed atypical brain activation related to orthography-phonology integration, no behavioral group differences emerged, suggesting potential abnormalities in phonological influence on orthographic processing that require further behavioral validation. Conversely, Nash et al. (2016) and Clayton and Hulme (2018) used phonological legality judgment tasks and found no group differences in orthographic influence on phonological processing. These contradictory results may stem from investigating different aspects of mutual influence: DD may show deficits in phonology-to-orthography influence while orthography-to-phonology influence remains intact.

Second, both orthographic and phonological influences may be impaired in DD, but variations in stimulus onset asynchrony across studies could mask these deficits. Research on orthographic influence has typically presented orthography 500 ms before phonology (Clayton & Hulme, 2018; Nash et al., 2016), whereas studies of phonological influence have used simultaneous presentation (Yang et al., 2020). Evidence suggests that DD exhibits a larger audiovisual temporal integration window, showing better integration than typical readers at longer intervals (Francisco et al., 2017; Hairston et al., 2005). The null findings regarding orthographic influence in DD (Clayton & Hulme, 2018; Nash et al., 2016) may thus reflect enhanced integration due to larger temporal intervals, compensating for underlying deficits. Whether DD exhibits abnormalities in both directions of influence or only in phonology-to-orthography processing requires further investigation controlling stimulus timing parameters.

Based on these considerations, the present study examined Chinese children with DD and age-matched typically developing controls (CA group) using simultaneous orthography-phonology presentation in two experiments to behaviorally investigate potential abnormalities in mutual influence during orthography-phonology integration. Experiment 1 examined the influence of phonology on orthographic processing, while Experiment 2 investigated orthographic influence on phonological processing. Behavioral investigation of these mutual influences will deepen understanding of the cognitive mechanisms underlying orthography-phonology integration deficits in DD, suggesting that such deficits may stem from abnormalities in the mutual influence between orthographic and phonological representations. Furthermore, this research extends Blomert's (2011) orthography-phonology automatic integration hypothesis by examining the specific contributions of orthography-phonology mutual influence to reading difficulties.

Experiment 1: The Influence of Phonology on Orthographic Processing

Method

Participants Experiment 1 employed G*Power 3.1 software (Faul et al., 2007) to calculate the required sample size, with effect size set at 0.25 and α at 0.05. Results indicated that a minimum of 54 participants were needed to achieve statistical power of 0.95. Given concerns about diagnostic uncertainty in DD children below third grade (Shaywitz, 2019), Experiment 1 included 59 children from grades 3-6, comprising 30 children with DD (25 males, 5 females) and 29 chronological age-matched (CA) control children (18 males, 8 females). Chi-square analysis revealed no significant differences in grade distribution between groups (^{2} = 0.47, p = 0.93). All participants were right-handed, had normal intelligence, no organic brain damage, and normal or corrected vision. DD children met inclusion criteria: standard score > 85 on the Combined Raven's Test (Li et al., 1988) and character recognition performance at least 1.5 standard deviations below grade-level norms (Wang & Tao, 1996). The study received ethical approval from relevant institutions, and informed consent was obtained from all children's guardians. Descriptive statistics for participant characteristics are presented in Table 1 .

Materials The visual stimuli consisted of 30 real characters and 45 pseudocharacters. To ensure familiarity, all real characters were selected from third to fifth grade Chinese language textbooks. Pseudocharacters were created by rearranging components of real characters to form orthographically legal but nonexistent characters (e.g., 扌同). All characters had left-right structure, presented in 3 cm × 3 cm SimHei font. Real characters and pseudocharacters were matched for stroke number and component frequency. Each real character appeared once in each of three conditions (orthography-phonology congruent, incongruent, and visual unisensory), with 30 trials per condition (90 trials total). Each pseudocharacter appeared once in crossmodal (pseudocharacter with speech sound, e.g., 扌者-jiǎ) and visual unisensory conditions (90 trials total). The formal experiment comprised 180 trials (90 real characters, 90 pseudocharacters). Auditory stimuli consisted of 105 real speech sounds: 30 congruent with real characters, 30 incongruent with real characters, and 45 paired with pseudocharacters. Sounds were recorded by a female native Mandarin speaker using DELL laptop recording software and processed with GoldWave (sampling rate: 44,100 Hz, 16-bit).

Design Experiment 1 employed a 3 (orthography-phonology correspondence: congruent, incongruent, visual unisensory) × 2 (group: DD, CA) mixed factorial design. Orthography-phonology correspondence was a within-subjects factor with three levels: orthography-phonology congruent (hereafter "congruent"), orthography-phonology incongruent (hereafter "incongruent"), and visual-only orthographic presentation without auditory input (hereafter "visual unisensory"). Group served as a between-subjects factor (CA vs. DD).

Procedure The experimental procedure was programmed and run using E-Prime 2.0. Stimuli were presented on a 14-inch DELL laptop display (resolution: 1024$×$768 pixels, refresh rate: 62.5 Hz). The task required real/pseudocharacter judgments. Each trial began with a 500 ms black fixation cross (+), followed by a real character or pseudocharacter presented for 1200 ms. After stimulus offset, an 800 ms blank screen appeared before the next trial. For real characters, participants heard either a congruent or incongruent speech sound, or no sound; for pseudocharacters, a speech sound was either present or absent. Participants judged whether the visual stimulus was a real character, pressing "T" for yes and "Y" for no. Responses could be made during the 2000 ms response window (from visual stimulus onset to blank screen offset), with the next trial beginning immediately after a response. Prior to the formal experiment, participants completed practice trials with different stimuli to familiarize themselves with the task. The practice procedure matched the formal experiment. The experimental procedure is illustrated in Figure 1 [Figure 1: see original paper].

Data Analysis

Data were analyzed using SPSS 20.0. Accuracy and reaction times were submitted to a 2 (group: DD, CA) × 3 (orthography-phonology correspondence: congruent, incongruent, visual unisensory) repeated-measures ANOVA. Greenhouse-Geisser correction was applied to adjust for violations of sphericity, with corrected p-values and original degrees of freedom reported. Post-hoc comparisons used Bonferroni correction. Trials with pseudocharacters served as filler items and were excluded from analysis.

Results

Descriptive statistics for accuracy and reaction times are presented in Table 2 .

For accuracy, the main effect of orthography-phonology correspondence was significant [$F(2, 114) = 6.21$, $p=0.003$, 2= 0.10], with higher accuracy in the congruent condition than in both incongruent and visual unisensory conditions ($ps< 0.01$), while the latter two conditions did not differ significantly ($p>0.05$). The main effect of group was significant [$F(1, 57) = 5.73$, $p= 0.02$, 2= 0.09], with CA group showing higher accuracy than the DD group. The interaction between orthography-phonology correspondence and group was not significant [$F(2, 114) = 0.48$, $p= 0.62$].

For reaction times, the main effect of orthography-phonology correspondence was significant [$F(2, 114) = 11.74$, $p< 0.001$, 2= 0.17], with faster responses in congruent and visual unisensory conditions compared to the incongruent condition ($ps< 0.001$), while congruent and visual unisensory conditions did not differ ($p> 0.05$). The main effect of group was significant [$F(2, 57) = 4.18$, $p= 0.046$, 2= 0.07], with CA group responding faster than DD group. The interaction between orthography-phonology correspondence and group was not significant [$F(2, 114) = 0.76$, $p= 0.47$].

Although Experiment 1 revealed poorer performance in the DD group relative to CA group on the crossmodal orthographic judgment task, the absence of a significant interaction between group and orthography-phonology correspondence could not rule out the possibility that these differences reflected impaired unisensory orthographic processing in DD. To control for individual differences in unisensory processing, we calculated Congruency Benefit Scores (CBS) following Evans (2020) as an index of orthography-phonology integration capacity [CBS = (incongruent condition - congruent condition) / incongruent condition]. Higher CBS values for accuracy indicate poorer integration, whereas higher CBS values for reaction time indicate stronger integration. CBS values are presented in Table 3 . To validate the CBS metric, one-sample t-tests confirmed that both groups' CBS values differed significantly from zero ($ps < 0.05$). Independent samples t-tests comparing CBS values between groups revealed no significant differences for either accuracy or reaction time.

Experiment 1 demonstrated that congruent phonology facilitated orthographic judgment in both groups, with CA children outperforming DD children on the visual orthographic task. However, after controlling for visual unisensory processing, the influence of phonology on orthographic processing did not differ significantly between groups.

Experiment 2: The Influence of Orthography on Phonological Processing

Method

Participants As in Experiment 1, power analysis indicated that Experiment 2 required a minimum of 54 participants. Sixty-four Chinese-speaking children from grades 4-6 participated, including 32 children with DD (26 males, 6 females) and 32 CA controls (19 males, 13 females). Chi-square analysis revealed no significant differences in grade distribution between groups ($^2 = 0$, $p = 1$). All participants were right-handed, had normal intelligence, no organic brain damage, and normal or corrected vision. DD inclusion criteria matched Experiment 1. The study received ethical approval, and informed consent was obtained from all guardians. Descriptive statistics for participant characteristics are presented in Table 4 .

Materials Auditory stimuli comprised 30 real speech sounds and 45 non-speech sounds (e.g., biáo, zèn, ruān). Each real speech sound appeared once in congruent, incongruent, and auditory unisensory conditions. Each non-speech sound appeared once in crossmodal (real character with non-speech sound) and auditory unisensory conditions, resulting in 90 presentations each for real and non-speech sounds. The formal experiment included 197 trials (including 17 catch trials), with equal probability for real and non-speech sounds. Speech sounds were recorded by a female native Mandarin speaker using DELL laptop software and processed with GoldWave (sampling rate: 44,100 Hz, 16-bit). Visual stimuli consisted of 105 real characters selected from third to fifth grade textbooks: 30 congruent with real speech sounds, 30 incongruent with real speech sounds, and 45 paired with non-speech sounds. Characters in congruent and incongruent conditions were matched for frequency (based on the Dajun Modern Chinese Character Frequency List) and stroke number. All characters had left-right structure with no repetitions, presented centrally in 3 cm × 3 cm SimHei font.

Design Experiment 2 employed a 3 (orthography-phonology correspondence: congruent, incongruent, auditory unisensory) × 2 (group: DD, CA) mixed factorial design. Orthography-phonology correspondence was a within-subjects factor with three levels: phonology-orthology congruent (hereafter "congruent"), phonology-orthology incongruent (hereafter "incongruent"), and auditory-only phonological presentation without visual input (hereafter "auditory unisensory"). Group served as a between-subjects factor (CA vs. DD).

Procedure Each trial began with a 500 ms black fixation cross (+). Following cross offset, a 1200 ms speech sound played through headphones while a visual character appeared simultaneously on screen—either a character with congruent pronunciation (congruent condition, e.g., hǎo-郝), a character with incongruent pronunciation (incongruent condition, e.g., xié-醋), or no character (auditory unisensory). After stimulus offset, an 800 ms blank screen appeared. Participants judged whether the heard sound was a real speech sound, pressing "T" for yes and "Y" for no. Responses could be made from stimulus onset through blank screen offset (2000 ms response window). If no response occurred within 2000 ms, the next trial began automatically. To maintain central fixation, the experiment included an unrelated "catch the Minion" task on 17 randomly interspersed trials, where participants pressed "B" upon seeing a Minion picture. The experimental procedure is illustrated in Figure 2 [Figure 2: see original paper].

Statistical Methods

As in Experiment 1, trials with non-speech sounds and catch trials were excluded from analysis.

Results

Descriptive statistics for accuracy and reaction times are presented in Table 5 .

For accuracy, the main effect of orthography-phonology correspondence was significant [F(2, 124) = 53.11, p< 0.001, 2 = 0.46], with accuracy highest in the congruent condition, intermediate in the auditory unisensory condition, and lowest in the incongruent condition (ps < 0.05). The main effect of group was significant [F(1, 62) = 7.92, p= 0.01, 2 = 0.11], with the DD group showing lower accuracy than the CA group. The interaction between orthography-phonology correspondence and group was not significant [F(2, 124) = 0.9, p= 0.40].

For reaction times, the main effect of orthography-phonology correspondence was significant [F(2, 124) = 94.08, p< 0.001, 2 = 0.60], with faster responses in the congruent than incongruent condition (p< 0.001); incongruent and auditory unisensory conditions did not differ significantly (p> 0.1). The main effect of group was not significant [F(1, 62) = 1.66, p= 0.20]. Critically, the interaction between orthography-phonology correspondence and group was significant [F(2, 124) = 3.73, p= 0.03, 2 = 0.06]. Simple effects analysis revealed that DD group had significantly longer reaction times than CA group in the congruent condition (p = 0.04), with no group differences in incongruent or auditory unisensory conditions (ps > 0.1). Within the DD group, congruent condition responses were faster than both incongruent and auditory unisensory conditions, and incongruent condition was faster than unisensory (ps < 0.05). Within the CA group, congruent condition responses were faster than both incongruent and auditory unisensory conditions (ps < 0.001), with no difference between incongruent and unisensory conditions (p> 0.1).

Although Experiment 2 revealed poorer performance in the DD group on the crossmodal phonological judgment task, we again computed CBS values to control for individual differences in auditory unisensory processing. CBS values are presented in Table 6 . One-sample t-tests confirmed that both groups' CBS values differed significantly from zero ($ps < 0.05$). Independent samples t-tests revealed a significant group difference in reaction time CBS values, with CA group showing significantly larger CBS than DD group ($t = -2.55$, $p= 0.01$, 95% CI [–0.11, –0.01]).

Experiment 2 demonstrated that congruent orthography facilitated phonological judgment while incongruent orthography produced interference, with CA children outperforming DD children. After controlling for auditory unisensory processing, group differences emerged in orthographic influence on phonological processing, with DD showing weaker orthographic effects.

General Discussion

The present study employed two experiments to investigate whether Chinese children with DD exhibit abnormalities in the mutual influence between orthography and phonology during orthography-phonology integration. Results showed that DD children performed worse than CA controls on both phonology-to-orthography and orthography-to-phonology tasks. However, after controlling for unisensory processing using CBS scores, DD children demonstrated impairments specifically in orthographic influence on phonological processing, revealing a directional specificity in their integration deficit.

Both experiments used crossmodal judgment tasks, and combined analyses of accuracy and reaction time revealed significant facilitatory effects of congruent phonology on orthographic processing in both groups, but no significant inhibitory effects of incongruent phonology. In contrast, congruent orthography significantly facilitated phonological processing while incongruent orthography produced significant interference. Congruent and incongruent conditions engage distinct cognitive mechanisms, with congruent stimulus processing being relatively automatic and incongruent processing requiring conscious attentional control (Posner et al., 2004). The significant facilitatory effects under congruent conditions in both experiments suggest that orthography-phonology mutual influence operates automatically when stimuli are congruent. However, the significant inhibitory effect of incongruent orthography emerged only in Experiment 2, while incongruent phonology showed no significant inhibition in Experiment 1. This asymmetry may reflect differential susceptibility to crossmodal interference, as visual dominance effects make it easier to suppress auditory interference on visual processing than to suppress visual interference on auditory processing (Colavita, 1974). We speculate that the visual dominance effect rendered incongruent orthographic information particularly disruptive when participants were required to process phonology in Experiment 2, making it difficult to inhibit visual interference.

Group comparisons of CBS scores revealed that DD children exhibited abnormal orthographic influence on phonological processing but intact phonological influence on orthographic processing. These findings diverge from previous research (Clayton & Hulme, 2018; Nash et al., 2016; Yang et al., 2020). Yang et al. (2020) used the same paradigm as Experiment 1 and found atypical activation in left angular gyrus, left superior temporal gyrus, and left superior/middle frontal gyri in DD children, suggesting neural-level abnormalities in phonological influence on orthography. We propose that these discrepant results may reflect limited behavioral sensitivity to phonology-to-orthography deficits, which may be detectable only with sensitive neuroimaging techniques. Consistent with our findings, Yang et al. (2020) also found no behavioral group differences on this task. Our finding of impaired orthographic influence on phonology in DD contrasts with Nash et al. (2016) and Clayton and Hulme (2018), who used similar paradigms but presented orthography 500 ms before phonology and found no group differences. This inconsistency likely stems from variations in stimulus timing. Research indicates that DD exhibits a larger audiovisual temporal integration window, showing superior integration at longer intervals (Francisco et al., 2017; Hairston et al., 2005). When orthography preceded phonology by 500 ms, this extended temporal window may have enhanced DD integration, masking underlying deficits. In Experiment 2, simultaneous presentation eliminated this advantage, revealing abnormal orthographic influence on phonology in DD.

Three factors may explain why DD exhibited deficits only in orthography-to-phonology influence. First, phonology-to-orthography processing (Experiment 1) and orthography-to-phonology processing (Experiment 2) involve different conversion mechanisms. Snowling (1980) found that DD children showed deficits in orthography-to-phonology conversion but not in phonology-to-orthography conversion, possibly because the former is more challenging for children, obscuring group differences. Similarly, our orthography-to-phonology task (Experiment 2) may have been more sensitive to DD deficits. Second, orthography-to-phonology conversion relates primarily to reading ability, whereas phonology-to-orthography conversion relates to spelling ability (Wimmer & Mayringer, 2002). Our DD sample, defined by reading difficulties, would be expected to show deficits in orthography-to-phonology influence rather than phonology-to-orthography influence. However, we did not assess spelling ability, necessitating future research that includes spelling measures to clarify this pattern. Third, our findings may reflect Chinese language-specific characteristics. Unlike alphabetic scripts, Chinese lacks consistent grapheme-phoneme correspondence rules. With approximately 1,200 basic syllables (Lu, 2001) but over 3,500 commonly used characters, orthography-to-phonology mapping is often one-to-one (except for polyphones; e.g., "熟" → "shú"), whereas phonology-to-orthography mapping is typically one-to-many (e.g., "shú" → "熟, 塾, 赎"). Consequently, orthographic information constrains phonological processing more strongly than phonological information constrains orthographic processing. Visual processing plays a critical role in Chinese reading, and Chinese DD more readily manifests visual orthographic processing deficits (Chung et al., 2008; Meng et al., 2011; Qian & Bi, 2014). Our finding that DD showed more pronounced deficits in visual orthographic than auditory phonological unisensory tasks further supports this interpretation. The observed impairment in orthographic influence on phonology may thus stem from deficient orthographic processing that reduces its impact on phonology.

These findings hold theoretical and practical significance. Theoretically, we provide novel evidence that Chinese DD children's orthography-phonology integration deficit manifests specifically as impaired orthographic influence on phonology, with intact phonological influence on orthography. This clarifies the underlying mechanism: poor orthographic processing skills lead to reduced orthographic influence on phonology, resulting in reading difficulties. Practically, these results suggest that remediation should target orthographic recognition and the ability to use orthographic information to process phonology, thereby improving reading skills.

Several limitations warrant consideration. First, we used age-matched controls but not reading-level matched controls, leaving open whether deficits reflect inherent DD impairments or insufficient reading experience. Future research should include reading-level matched controls to determine whether orthographic influence deficits represent a core DD characteristic. Second, we did not manipulate temporal intervals. Previous research shows that DD maintains integration capacity at longer intervals while typical readers' integration declines (Francisco et al., 2017; Hairston et al., 2005). Systematic manipulation of timing parameters is needed to comprehensively characterize orthography-phonology mutual influence in DD.

In conclusion, Chinese DD children's orthography-phonology integration deficit primarily stems from poorer visual processing skills, specifically manifesting as weaker orthographic influence on phonological processing compared to typical readers, while phonological influence on orthographic processing remains intact.

Author Contributions

Menglian Liu: data analysis and manuscript writing; Yinghui Yang: research conceptualization and experiment implementation; Yifan Zhao: final manuscript revision; Hongyan Bi: research design and methodology.

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Note: Figure translations are in progress. See original paper for figures.