Novel Word Acquisition and Remediation in Children with Developmental Dyslexia

Authors: Xuejun Bai, Ma Jie, Li Xin, Kunyu Lian, Tan Ke, Yang Yu, Liang Feifei, Bai Xuejun

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Abstract

This study investigated new word acquisition and improvement pathways in children with developmental dyslexia by comparing changes in individuals' eye movement patterns during repeated learning of new words. Experiment 1 employed a repeated new word learning paradigm with participants consisting of children with developmental dyslexia and chronological age- and reading ability-matched controls to explore new word acquisition in children with developmental dyslexia. The results revealed that, compared to the matched groups, children with developmental dyslexia required more contextual exposures to exhibit significant decreases in first fixation duration and gaze duration on new words, and showed a slower decline in total fixation time. This indicates that new word acquisition is slower in children with developmental dyslexia than in typically developing children. Experiment 2 utilized two text presentation formats—inter-word spacing and normal unspaced text—while maintaining the repeated new word learning paradigm to investigate whether inter-word spaces could facilitate new word acquisition in children with developmental dyslexia. The findings demonstrated that under the inter-word spacing condition, new word acquisition in children with developmental dyslexia could reach the level of typically developing children. This suggests that inter-word spaces, as visual word segmentation cues, can promote new word acquisition in children with developmental dyslexia. The results of this study provide a novel approach for new word acquisition in children with developmental dyslexia.

Full Text

Preamble

Novel Word Acquisition in Children with Developmental Dyslexia and Its Improvement

BAI Xuejun[1,2], MA Jie[1], LI Xin[1], LIAN Kunyu[1], TAN Ke[1], YANG Yu[1], LIANG Feifei[2]

[1]Academy of Psychology and Behavior, Tianjin Normal University, Tianjin 300074
[2]School of Educational Science, Tianjin Normal University, Tianjin 300387

Abstract

This study investigated novel word acquisition in children with developmental dyslexia and potential improvement approaches by examining changes in eye movement patterns during repeated exposure to new words. Experiment 1 compared dyslexic children with chronological age- and reading level-matched controls using a repeated novel word learning paradigm. Results showed that dyslexic children required more contextual exposures to show significant decreases in first fixation duration and gaze duration on novel words, and exhibited a slower decline in total fixation time compared to matched groups, indicating slower novel word acquisition. Experiment 2 manipulated text presentation format (word-spaced vs. normal unspaced) using the same paradigm to examine whether inter-word spacing could facilitate novel word acquisition in dyslexic children. Results revealed that under word-spaced conditions, dyslexic children' s novel word acquisition reached the level of normal children, suggesting that inter-word spacing as a visual word segmentation cue can promote novel word acquisition in developmental dyslexia. These findings provide a new avenue for improving novel word acquisition in children with developmental dyslexia.

Keywords: developmental dyslexia; novel word acquisition; word segmentation; Chinese reading

1 Introduction

Developmental dyslexia refers to a learning disability characterized by inefficient word recognition in individuals without organic brain damage or mental disorders, with at least average intelligence, and who have received equivalent education as their peers. Specific manifestations include: (1) poor fluency and accuracy in word recognition; (2) poor vocabulary spelling and decoding abilities (Lyon, Shaywitz, & Shaywitz, 2003). Numerous studies have found that due to word recognition difficulties, children with developmental dyslexia have significantly lower character recognition and vocabulary than normal children (Meng, Cheng-Lai, Zeng, Stein, & Zhou, 2011; Pan, Yan, Laubrock, Shu, & Kliegl, 2014; Shu, McBride-Chang, Wu, & Liu, 2006; Zhang, Xie, Xu, & Meng, 2018). Therefore, character recognition quantity serves as a primary indicator for identifying children with developmental dyslexia (Chen et al., 2018; Pan et al., 2014; Yan, Pan, Laubrock, Kliegl, & Shu, 2013; Zhou et al., 2014).

Primary school years represent a critical period for vocabulary growth in children. Statistics show that children acquire approximately 3,000 new words annually, with over 80% of vocabulary learned through natural reading (Nagy, Herman, & Anderson, 1985). Based on alphabetic writing systems, Fukkink (2005) proposed a four-stage cognitive model of novel word acquisition in natural reading: (1) making a decision to trigger novel word learning; (2) investing substantial cognitive resources into the word itself and its context to search for effective cues, including intra-word cues, contextual cues, and knowledge stored in long-term memory; (3) using contextual cues to infer novel word meaning; and (4) evaluating the formed meaning of the novel word. Since Chinese text lacks explicit visual word boundary information, successful word segmentation constitutes the primary step in novel word acquisition during reading (白学军, 张慢慢, 臧传丽, 李馨, 陈璐, 闫国利, 2014; 李兴珊, 刘萍萍, 马国杰, 2011; Li, Rayner, & Cave, 2009; Liang et al., 2015, 2017). Applying Fukkink' s (2005) model to Chinese reading requires adding a word segmentation process. Therefore, when acquiring novel words in Chinese reading, readers must first segment sentences into words while simultaneously using intra-word cues and contextual information for semantic inference and integration.

Liang, Zhang, Zhang, Wang, and Bai (2017) used eye-tracking technology to examine developmental differences in natural reading of novel word acquisition between normal children and adults by analyzing changes in eye movement patterns during repeated exposure. The experiment required adults and third-grade primary school students to learn novel words across five consecutive contexts. Results showed that for gaze duration and refixation ratio on novel words, adults exhibited sharp decreases during the second exposure, whereas children only began to show decreases during the fourth exposure. For total fixation time, children showed continuous decreases across the first four exposures, while adults showed substantial decreases only during the first two exposures, with the magnitude of reduction diminishing sharply thereafter. These findings indicate that normal children' s eye movement patterns in novel word acquisition differ from adults' , with adults showing a stepwise decline and children showing a continuous decline in fixation patterns. This may be because children, as less skilled readers with lower reading proficiency, have language-cognitive processing skills that are still developing (Reichle et al., 2013), preventing them from effectively utilizing intra-word cues and contextual information for semantic inference like adults.

Compared to normal children, children with developmental dyslexia exhibit lower reading proficiency and possess several deficits that may affect novel word acquisition: (1) Phonological processing deficits, manifested as weak phonological awareness, poor phonological memory, and difficulties in phonological retrieval (Ho, Law, & Ng, 2000). (2) Orthographic awareness deficits, manifested as weak awareness of Chinese character formation rules and structures, and poor processing of character configurations (Ho, Chan, Tsang, & Lee, 2002). Since Chinese word segmentation and recognition involve interactive top-down and bottom-up processing across visual features, character, and word levels (Li et al., 2009), dyslexic children' s phonological and orthographic processing deficits may affect character-level processing, which in turn may influence activation at other levels, making it more difficult to establish connections between character form, sound, and meaning. Consequently, children with developmental dyslexia may experience greater difficulty in segmenting and recognizing novel words within sentences. (3) Rapid naming deficits, manifested as poor automatic processing in form-sound conversion for familiar visual stimuli (Yan et al., 2013). (4) Poor reading fluency, characterized by slow reading speed and low accuracy (Li & Wu, 2015; Meng et al., 2011). Both rapid naming and reading fluency involve multiple low-level reading-cognitive processes such as phonology and orthography, reflecting the degree of automatic processing (Hudson, Pullen, Lane, & Torgesen, 2009; Li et al., 2015; Wolf, Bowers, & Biddle, 2000). Children with developmental dyslexia exhibit rapid naming deficits and poor reading fluency, requiring them to concentrate more cognitive resources on low-level processes like phonology and orthography, leaving fewer resources for searching effective cues for semantic inference, which affects semantic inference and integration of novel words and reduces reading comprehension efficiency (Fukkink, 2005; Li et al., 2015). Based on these reasons, researchers infer that children with developmental dyslexia may experience greater difficulties in acquiring novel words during natural reading.

The first purpose of this study was to examine the characteristics of novel word acquisition in children with developmental dyslexia during natural reading and their performance. Inter-word spacing as a visual-level word boundary cue can strengthen connections between morphemes in novel words in terms of form, sound, and meaning, facilitating successful visual word segmentation. Readers then only need to utilize intra-word cues and contextual cues for semantic inference and integration (梁菲菲等, 2017; Bai et al., 2013; Blythe et al., 2012; Liang et al., 2015, 2017). Previous studies have found that inter-word spacing facilitates reading in English (Rayner, Fischer, & Pollatsek, 1998), Thai (Winskel, Radach, & Luksaneeyanawin, 2009), Chinese (Bai et al., 2013), German (Inhoff & Radach, 2002), Japanese (Sainio, Hyönä, Bingushi, & Bertram, 2007), Spanish (Perea & Acha, 2009), and other languages. The magnitude of this facilitation is modulated by readers' reading skill level, with greater benefits for lower-skilled readers (Blythe et al., 2012; Shen et al., 2012). Compared to normal children, children with developmental dyslexia have lower reading skills (Shu et al., 2006) and exhibit deficits in recognizing and connecting morpheme form, sound, and meaning (Lyon et al., 2003). Therefore, they may rely more heavily on visual word boundary cues (such as inter-word spacing) during reading. The second purpose of this study was to investigate the facilitative effect of inter-word spacing on novel word acquisition in children with developmental dyslexia.

Using a repeated novel word learning paradigm, Experiment 1 examined the processing characteristics and performance at each stage of novel word acquisition in children with developmental dyslexia by comparing eye movement pattern changes during repeated learning with chronological age- and reading level-matched controls. Building on this, Experiment 2 manipulated text presentation format (inter-word spaced vs. normal unspaced) using the same paradigm to explore how inter-word spacing facilitates novel word acquisition in children with developmental dyslexia. Based on previous findings on novel word acquisition characteristics in normal readers (梁菲菲等, 2017; Blythe et al., 2012) and the deficits in phonology, orthography, rapid naming, and reading fluency in children with developmental dyslexia (Ho et al., 2002; Meng et al., 2011; Yan et al., 2013), this study hypothesized: (1) Children with developmental dyslexia would perform worse than normal children on all eye movement measures reflecting various processing stages, particularly in the early processing stages of novel word acquisition; (2) Inter-word spacing would facilitate novel word acquisition in all three groups, with the greatest effect for children with developmental dyslexia.

Since the reading development of children with developmental dyslexia follows two patterns (薛锦, 舒华, 杨剑锋, 陆建平, 2008): (1) Delayed development, where dyslexic children' s reading level is similar to younger children; and (2) Atypical development, where dyslexic children' s reading behavior is dissimilar to normal children of any age group (including same-age and younger children). To examine whether novel word acquisition in developmental dyslexia follows a delayed or atypical pattern, this study included both chronological age-matched and younger reading level-matched children as control groups. If the eye movement pattern changes during novel word acquisition in children with developmental dyslexia are similar to younger reading level-matched children but differ substantially from chronological age-matched children, this would indicate a delayed developmental pattern. If their eye movement patterns differ from both reading level-matched and chronological age-matched children, this would indicate an atypical developmental pattern.

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2 Experiment 1: Novel Word Acquisition in Children with Developmental Dyslexia

Using a repeated novel word learning paradigm, each novel word (a two-character pseudoword) was embedded in eight different contexts. By comparing eye movement pattern changes across learning stages between children with developmental dyslexia and matched controls, this experiment examined the characteristics of novel word acquisition in children with developmental dyslexia.

2.1.1 Participants

A total of 881 fifth-grade and 951 third-grade primary school students from three schools in Tianjin and one school in Fujian were screened, yielding 41 children with developmental dyslexia (a prevalence rate of 4.65%), as shown in Table 1 . Due to school and personal reasons, 22 children with developmental dyslexia participated in the experiment (16 boys, 6 girls).

The selection criteria for the developmental dyslexia and matched groups were as follows. First, the following tests were administered (Meng et al., 2011; Shu et al., 2006): (1) Class-wide administration of the Primary School Chinese Character Recognition Test (王孝玲, 陶保平, 1996) and the Combined Raven' s Reasoning Test (李丹, 胡克定, 陈国鹏, 金瑜, 李眉, 1988) to third- and fifth-grade students; (2) Individual administration of language and cognitive ability tests (林传鼎, 张厚粲, 1986; 凌文铨, 滨治世, 1988; 王晓辰, 2010; 邹艳春, 2003; Cheng, Li, & Wu, 2015; Denckla & Rudel, 1974; Li et al., 2015; Shu, Meng, Chen, Luan, & Cao, 2005), including orthographic awareness test, phonological awareness test (syllable judgment, phoneme deletion, onset/rime/tone discrimination), verbal short-term memory test (digit span, character span), rapid automatized naming test, and reading fluency test (one-minute word reading, three-minute sentence reading).

Second, participants were grouped based on test scores: (1) Developmental dyslexia group: average or above-average intelligence, character recognition score 1.5 standard deviations below grade mean, reading fluency score 1 standard deviation below grade mean, and at least one individual test score 1 standard deviation below the chronological age-matched group; (2) Chronological age-matched group: same age and comparable intelligence as the dyslexia group, with character recognition within 0.5 standard deviations of grade mean; (3) Reading level-matched group: comparable intelligence and character recognition as the dyslexia group, but two grades lower.

The final sample consisted of 22 children in each of the three groups: developmental dyslexia, chronological age-matched, and reading level-matched. The mean age and test scores for each group are presented in Table 2 .

Statistical analyses revealed no significant age difference between the developmental dyslexia and chronological age-matched groups ($t(42)=1.25$, $p>0.05$), but both were significantly older than the reading level-matched group ($t(42)=10.60$, $p<0.001$, $d=3.27$). The developmental dyslexia group performed significantly worse than both matched groups on phoneme deletion ($ts>3.31$, $ps<0.002$, $ds>1.02$). On character recognition, orthographic awareness, verbal working memory, digit/letter/color rapid naming, one-minute word reading, and three-minute reading tests, the dyslexia group performed significantly worse than the chronological age-matched group ($ts>2.11$, $ps<0.041$, $ds>0.65$) but did not differ from the reading level-matched group ($ts<1.70$, $ps>0.05$). No significant differences were found among the three groups on intelligence, syllable judgment, or onset/rime/tone discrimination ($Fs<2.56$, $ps>0.05$). These results indicate that the selected children with developmental dyslexia primarily exhibited deficits in orthographic awareness, phonological awareness, verbal working memory, and rapid naming.

2.1.2 Experimental Design

A 3 (participant group: developmental dyslexia, chronological age-matched, reading level-matched) × 4 (learning stage: 1, 2, 3, 4) mixed design was employed. Participant group was a between-subjects variable, and learning stage was a within-subjects variable. Stage 1 included Context 1, Stage 2 included Context 2, Stage 3 included Contexts 3, 4, and 5, and Stage 4 included Contexts 6, 7, and 8.

2.1.3 Experimental Materials

Based on the SUBTLEX-CH corpus (Cai & Brysbaert, 2010), 96 high-frequency Chinese characters (frequency > 100 per million) were selected as morphemes for constructing novel words. Fifteen third-grade students who did not participate in the formal experiment were asked to provide pronunciations and word formations for the selected characters. Eighty characters with correct pronunciations and formations were chosen as target characters, with a mean character frequency of 323 per million, mean stroke count of 8.6, and equal probability (50%) of appearing in initial or final morpheme positions.

Target characters were paired to create 40 pseudowords as novel words. The degree of “pseudoword-ness” was controlled by: (1) ensuring all pseudowords were non-existent in the Modern Chinese Dictionary; (2) presenting correct pronunciations of pseudowords and asking 15 university students who did not participate in the formal experiment to write corresponding words based on pronunciations, resulting in selection of 30 pseudowords that could not be written out.

Each novel word was described as a new member of a common semantic category across eight sentences. Ten semantic categories were used: buildings, medicines, furniture, stationery, flowers, animals, occupations, fruits, transportation, and clothing, with three pseudowords per category. Fifteen university students who did not participate in the formal experiment rated the association strength between pseudowords and their semantic categories on a 4-point scale (1 = very difficult to associate; 4 = very easy to associate). The mean association value was 1.04 (SD = 0.07), indicating low association between pseudowords and real words.

Target words were placed in the middle of sentences ranging from 13 to 14 characters in length. Fifteen third-grade students who did not participate in the formal experiment rated sentence fluency and difficulty on 5-point scales (1 = very disfluent and very difficult to understand; 5 = very fluent and very easy to understand). To exclude the influence of novel words on sentence fluency and difficulty, following Liang et al. (2015, 2017), each novel word in sentence frames was replaced with a familiar member of the same semantic category (e.g., replacing “环米” with “牡丹” in “富丽端庄的环米的花瓣不易脱落”) before rating. Mean sentence fluency was 4.31 (SD = 0.29) and mean difficulty was 4.47 (SD = 0.35), indicating sentences were fluent and easy to understand.

One to three reading comprehension questions were randomly placed across the eight contexts for each novel word to assess whether participants truly understood sentence meanings. Additionally, one semantic category selection question was created for each novel word to assess participants’ mastery of the word’ s semantic category. Fifteen of the 30 novel words were selected as materials for Experiment 1, with examples presented in Table 3 .

2.1.4 Apparatus

An SR Research Eyelink 1000 eye tracker (Canada) was used with a sampling rate of 1000 Hz, screen resolution of 1024×768 pixels, and refresh rate of 120 Hz. Viewing distance was 65 cm from the screen. The font was SimSun 18 pt, with each character measuring 25×

2.1.5 Procedure

A five-point calibration mode was used with average error less than 0.5°. After successful calibration, participants read eight contexts containing novel words one by one and completed reading comprehension and semantic category selection questions via mouse button presses. Fifteen novel words were learned in two sessions with a 10-minute break between sessions. The entire experiment lasted approximately 50 minutes.

2.2 Results

No significant differences were found among the three groups in reading comprehension accuracy (developmental dyslexia group: 81%, chronological age-matched group: 87%, reading level-matched group: 85%), $F(2,63)=2.39$, $p>0.05$, indicating all groups read sentences carefully. No significant differences were found in semantic category selection accuracy (developmental dyslexia group: 95%, chronological age-matched group: 99%, reading level-matched group: 96%), $F(2,63)=2.48$, $p>0.05$, indicating all groups correctly mastered semantic categories of novel words. Data were excluded based on the following criteria (梁菲菲等, 2017): (1) sentences with fewer than 3 fixations (0.88%); (2) lost eye-tracking data (0.05%); (3) data beyond 3 standard deviations (0.4%). A total of 1.33% of data were excluded.

Novel words were designated as interest areas. The following eye movement measures were selected as dependent variables (梁菲菲等, 2017; Bai et al., 2013; Blythe et al., 2012): (1) First fixation duration: the duration of the first fixation on the interest area during first-pass reading, reflecting early processing stages; (2) Gaze duration: the sum of all fixation durations from first entering to first leaving the interest area, reflecting early lexical access stages; (3) Total fixation duration: the sum of all fixation durations within the interest area, reflecting later processing characteristics (闫国利, 熊建萍, 臧传丽, 余莉莉, 崔磊, 白学军, 2013).

2.2.1 Eye Movement Results Eye movement data for the three groups across learning stages are presented in Table 4 and Figure 1 [Figure 1: see original paper].

(1) Learning stage. Main effects were significant for first fixation duration, gaze duration, and total fixation time ($Fs>20.89$, $ps<0.001$, $p^2>0.25$).

Further analyses revealed significant differences between adjacent learning stages ($ts>2.40$, $ps<0.023$, $ds>0.64$), indicating that fixation times on novel words gradually decreased as learning stages progressed.

(2) Group. The main effect of group was not significant in participant analysis but significant in item analysis for first fixation duration ($F1(2,63)=0.76$, $p1>0.05$; $F2(2,58)=11.52$, $p2<0.001$, $p^2=0.28$), and significant for both gaze duration and total fixation time ($Fs>3.61$, $ps<0.033$, $p^2>0.10$). Since the interaction between group and learning stage was significant across all three measures, the primary focus was on analyzing this interaction.

(3) Interaction between learning stage and group. The interaction was not significant in participant analysis but significant in item analysis for first fixation duration ($F1(6,189)=1.22$, $p1>0.05$; $F2(6,174)=2.36$, $p2=0.032$, $p^2=0.08$), and significant for both gaze duration and total fixation time ($Fs>4.17$, $ps<0.001$, $p^2>0.12$). Simple effects analyses revealed significant differences among the three groups across all four learning stages ($Fs>3.72$, $ps<0.014$, $p^2>0.06$).

Further examination of changing patterns across learning stages for each group (Figure 1) revealed: The developmental dyslexia group showed significant decreases from Stage 2 to Stage 3 in both first fixation duration and gaze duration ($ts>2.39$, $ps<0.026$, $ds>0.93$), with no significant differences between other adjacent stages ($ts<1.31$, $ps>0.05$). The chronological age-matched group showed significant decreases from Stage 1 to Stage 2 and Stage 3 to Stage 4 in gaze duration ($ts>4.07$, $ps<0.001$, $ds>1.61$), with first fixation duration showing non-significant decreases in participant analysis but significant decreases in item analysis ($ts<1.80$, $ps>0.05$; $ts>2.01$, $ps<0.054$, $ds>0.75$); no significant decreases were observed from Stage 2 to Stage 3 for either measure ($ts<1.51$, $ps>0.05$). The reading level-matched group showed significant decreases from Stage 1 to Stage 2 and Stage 3 to Stage 4 in both first fixation duration and gaze duration ($ts>2.38$, $ps<0.024$, $ds>0.89$); from Stage 2 to Stage 3, first fixation duration showed no significant decrease ($t1(21)=0.89$, $p1>0.05$; $t2(29)=0.97$, $p2>0.05$), but gaze duration showed a significant decrease ($t1(21)=3.04$, $p1=0.006$, $d=1.33$; $t2(29)=2.92$, $p2=0.007$, $d=1.08$).

For total fixation time, all three groups showed continuous decreases from Stage 1 to Stage 4 ($ts>2.09$, $ps<0.046$, $ds>0.78$), demonstrating time savings during learning, as shown in Figure 2 [Figure 2: see original paper].

From Stage 1 to Stage 2, the developmental dyslexia group showed longer time savings than both chronological age-matched and reading level-matched groups ($ts>2.77$, $ps<0.009$, $ds>0.86$). From Stage 2 to Stage 3, the dyslexia group's time savings were longer than the chronological age-matched group (significant only in participant analysis: $t1(42)=2.18$, $p1=0.035$, $d=0.67$; $t2(29)=1.76$, $p2>0.05$). From Stage 3 to Stage 4, the reading level-matched group showed longer time savings than both the dyslexia and chronological age-matched groups ($ts>2.78$, $ps<0.008$, $ds>0.86$). No significant differences in time savings were found between groups at other adjacent learning stages (ts<1.76, ps>0.05).

2.2.2 Correlation Analysis Between Behavioral Tests and Eye Movement Measures Correlation results between behavioral tests and eye movement measures are presented in Table 5 .

Results showed that reading fluency test scores (including one-minute word reading and three-minute reading) were significantly negatively correlated with gaze duration on novel words (|rs|>0.25, ps<0.044), indicating that higher reading fluency was associated with shorter gaze durations. Digit and letter rapid naming reaction times were significantly positively correlated with total fixation time (|rs|>0.27, ps<0.029), indicating that shorter rapid naming times were associated with shorter total fixation times. No other individual tests showed significant correlations with eye movement measures (|rs|<0.23).

Experiment 1 results revealed that eye movement patterns during novel word acquisition in children with developmental dyslexia differed from normal children, specifically: (1) In early processing stages of novel word acquisition, decreases in first fixation duration and gaze duration occurred later for dyslexic children compared to both chronological age-matched and reading level-matched groups; (2) In later processing stages, although the decrease in total fixation time for the dyslexia group was not later than matched groups, their time savings during the first two learning stages were significantly shorter than matched children. These findings indicate that eye movement pattern changes during novel word acquisition in children with developmental dyslexia differed from both chronological age-matched children and younger reading level-matched children, suggesting that their novel word acquisition in natural reading follows an atypical rather than delayed developmental pattern.

Considering that the primary cognitive processing stage in Chinese novel word acquisition is the "decision to trigger learning," which presupposes successful segmentation of novel words from continuous character strings, and that Chinese word segmentation and recognition involve interactive top-down and bottom-up processing (Li et al., 2009), novel word processing resembles extremely low-frequency words where readers lack corresponding lexical representations in memory and cannot effectively engage in top-down processing, thus relying more on bottom-up processing (Blythe et al., 2012; Liang et al., 2015, 2017). Previous research has found that providing low-level visual word segmentation cues (such as inter-word spacing) significantly facilitates Chinese readers' novel word acquisition in natural reading, with this facilitative effect being particularly pronounced in lower-reading-skill children. This is because children' s language-cognitive processing skills are relatively underdeveloped, preventing them from effectively utilizing high-level intra-word cues (such as linguistic cues like word frequency and morpheme position probability; see Liang et al., 2015, 2017) for novel word identification and segmentation, making them more dependent on visual word segmentation cues. Compared to normal children, children with developmental dyslexia have even lower language-cognitive processing skills. Do they depend more on visual word segmentation cues during novel word segmentation and identification? That is, does inserting inter-word spacing promote novel word acquisition in children with developmental dyslexia? Experiment 2 addresses this question.

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3 Experiment 2: The Role of Inter-Word Spacing in Novel Word Acquisition in Children with Developmental Dyslexia

Previous research has found that visual word segmentation cues play an important role in alphabetic writing systems, not only facilitating word identification but also effectively guiding eye movements (Paterson & Jordan, 2010; Perea et al., 2009; Rayner et al., 1998). In non-spaced languages like Chinese and Thai, inter-word spacing also facilitates readers' word identification to some extent, particularly for lower-skilled readers (Shen et al., 2012; Winskel et al., 2009). This study examined the role of inter-word spacing in novel word acquisition in children with developmental dyslexia by comparing eye movement characteristics during novel word learning in unspaced and word-spaced texts across three groups.

3.1.1 Participants

Due to parental and school reasons, 18 participants from Experiment 1 (including 8 children with developmental dyslexia, 5 reading level-matched children, and 5 chronological age-matched children) were unwilling to participate in the subsequent experiment. To maintain sample size, 12 additional participants were recruited based on screening criteria (including 6 children with developmental dyslexia, 3 reading level-matched children, and 3 chronological age-matched children). Experiment 2 included 20 children in each group (developmental dyslexia, chronological age-matched, and reading level-matched), totaling 60 participants.

3.1.2 Experimental Design

A 3 (participant group: developmental dyslexia, chronological age-matched, reading level-matched) $\times$ 2 (text presentation format: normal unspaced, inter-word spaced) mixed design was employed, with participant group as a between-subjects variable and text presentation format as a within-subjects variable.

3.1.3 Experimental Materials

The 30 novel words and contexts developed in Experiment 1 were used as experimental materials. Sentences containing 15 novel words were presented in normal unspaced format, while sentences containing the other 15 novel words were presented in inter-word spaced format. The segmentation method for spaced conditions was as follows: Based on the Modern Chinese Dictionary and SUBTLEX-

CH-WF corpus (Cai et al., 2010), existing words in the dictionary or corpus were treated as word units, with spaces inserted between adjacent word units. Fifteen university students who did not participate in the formal experiment rated the reasonableness of word segmentation, achieving 96.3% agreement (SD = 0.03).

3.1.4 Apparatus and Procedure

The same as Experiment 1. Participants were required to read sentences in both normal unspaced and inter-word spaced conditions. Participants learned 7-8 novel words per session, completing learning of all 30 novel words across four sessions.

3.2 Results

No significant differences were found among the three groups in reading comprehension accuracy (developmental dyslexia group: 82%, chronological age-matched group: 88%, reading level-matched group: 86%), $F(2,57)=2.16$, $p>0.05$, indicating all groups read sentences carefully. No significant differences were found in semantic category selection accuracy (developmental dyslexia group: 96%, chronological age-matched group: 99%, reading level-matched group: 96%), $F(2,57)=1.66$, $p>0.05$, indicating all groups correctly mastered semantic categories of novel words. Data exclusion criteria were the same as Experiment 1 (梁菲菲等, 2017), with 1.74% of total data excluded. Dependent measures were identical to Experiment 1.

Eye movement data for the three groups across text presentation formats are presented in Table 6 .

(1) Text presentation format. The main effect was not significant for first fixation duration ($F1(1,57)=0.05$, $p1>0.05$; $F2(1,29)=0.03$, $p2>0.05$) but significant for gaze duration and total fixation time ($Fs>11.47$, $ps<0.001$, $p^2>0.17$), with longer gaze and total fixation times in unspaced than spaced conditions.

(2) Group. The main effect was not significant in participant analysis but significant in item analysis for first fixation duration ($F1(2,57)=0.93$, $p1>0.05$; $F2(2,58)=15.82$, $p2<0.001$, $p^2=0.35$), and significant for gaze duration and total fixation time ($Fs>3.89$, $ps<0.026$, $p^2>0.12$). Since the interaction between text presentation format and group was significant across all three measures, primary focus was on this interaction analysis.

(3) Interaction between group and text presentation format. The interaction was marginally significant in participant analysis and significant in item analysis for first fixation duration ($F1(2,57)=3.09$, $p1=0.053$, $p^2=0.10$; $F2(2,58)=4.01$, $p2=0.023$, $p^2=0.12$). Simple effects analysis revealed that only the developmental dyslexia group showed a spacing effect, with significantly longer first fixation duration in unspaced than spaced

conditions (F1(1,57)=4.62, p1=0.036, p^2=0.07; F2(1,29)=4.22, p2=0.049, p^2=0.13). Neither chronological age-matched nor reading level-matched groups showed spacing effects (Fs<2.48, ps>0.05).

The interaction was significant for both gaze duration and total fixation time (Fs>3.20, ps<0.048, p^2>0.10). Simple effects analyses revealed: For gaze duration, the developmental dyslexia group showed a spacing effect (F1(1,57)=14.89, p1<0.001, p^2=0.21; F2(1,29)=22.11, p2<0.001, p^2=0.43), while reading level-matched and chronological age-matched groups showed no spacing effects (Fs<3.77, ps>0.05). For total fixation time, all three groups showed spacing effects (Fs>6.13, ps<0.019, p^2>0.10), with no significant difference in effect size between the developmental dyslexia and reading level-matched groups (t1(38)=0.21, p1>0.05; t2(29)=0.61, p2>0.05), but both showed larger effects than the chronological age-matched group (ts>2.40, ps<0.022, ds>0.78).

To further examine the contribution of inter-word spacing to novel word acquisition in children with developmental dyslexia, eye movement data from the dyslexia group in spaced conditions were compared with data from the chronological age-matched group in unspaced conditions. No differences were found in first fixation duration or total fixation time (ts<1.95, ps>0.05), while gaze duration showed a non-significant difference in participant analysis but significant difference in item analysis (t1(38)=1.38, p1>0.05; t2(29)=5.11, p2<0.001, d=1.90), indicating that under word-spaced conditions, novel word acquisition in children with developmental dyslexia reached the level of chronological age-matched children reading unspaced text.

3.3 Discussion

Consistent with previous research (梁菲菲等, 2017; Blythe et al., 2012), Experiment 2 found that inter-word spacing facilitated novel word acquisition in all three groups, with the magnitude and pattern of facilitation varying across groups. Inter-word spacing facilitated all processing stages of novel word acquisition in children with developmental dyslexia, while facilitating only later semantic integration stages in chronological age-matched and reading level-matched groups, with smaller effects for chronological age-matched than reading level-matched groups. These results indicate that inter-word spacing has the greatest facilitative effect on children with developmental dyslexia, followed by reading level-matched children, and the smallest effect on chronological age-matched children. These findings suggest that children with developmental dyslexia depend more heavily on low-level visual segmentation cues during novel word acquisition in reading.

4 General Discussion

Two experiments investigated differences in eye movement patterns during novel word acquisition between children with developmental dyslexia and matched controls, and explored effective approaches for facilitating novel word acquisition. Results revealed: (1) Eye movement patterns during novel word acquisition differed between children with developmental dyslexia and normal children, primarily in early processing stages; (2) Inter-word spacing facilitated novel word acquisition in all three groups, with greater facilitation for children with developmental dyslexia.

These results are discussed below based on processing deficits in developmental dyslexia and cognitive processes of vocabulary acquisition.

4.1 Novel Word Acquisition in Children with Developmental Dyslexia

Learning new words from natural reading represents an important pathway for vocabulary growth in school-age children (Nagy & Scott, 2000). This study found that eye movement pattern changes during novel word acquisition in children with developmental dyslexia differed from both chronological age-matched and reading level-matched groups. As exposure to novel words increased, fixation times on novel words showed a continuous decline pattern in dyslexic children, whereas normal children (both reading level-matched and chronological age-matched) showed a stepwise decline pattern, with particularly large decreases in total fixation time during the second exposure and smaller decreases in subsequent exposures. These results provide new evidence for an atypical developmental pattern in novel word acquisition in developmental dyslexia, as their eye movement fixation patterns during novel word acquisition were dissimilar to both younger reading level-matched and same-age chronological age-matched children. This suggests that abnormal eye movement patterns during novel word acquisition in children with developmental dyslexia result from pathological deficits rather than developmental delays in reading ability.

Correlation analyses between individual test scores and eye movement measures reflecting cognitive processing of novel word acquisition revealed that only alphanumeric rapid naming (including letter and digit rapid naming; see Jones, Branigan, Hatzidaki, & Obregón, 2010; Närhi et al., 2005) and reading fluency tests were significantly correlated with fixation times on novel words. These findings provide new evidence for the relationship between rapid naming, reading fluency, and reading, demonstrating that these tests can not only measure and assess individual word recognition efficiency in reading (Norton & Wolf, 2012) but also evaluate children' s novel word acquisition in natural reading to some extent.

When learning new words during reading, readers need to concentrate attentional resources on lexical and contextual cues to identify novel words (Fukkink, 2005). On one hand, readers lack top-down lexical representations for novel words in memory; on the other hand, the novel words used in this study were all opaque, meaning readers could not infer whole-word meanings from constituent morphemes, forcing them to search contextual cues for meaning inference (Blythe et al., 2012; Liang et al., 2015, 2017). However, children with developmental dyslexia in this study exhibited deficits in automatic form-sound conversion and reading fluency reflecting multiple low-level cognitive processes, meaning they must allocate more attentional resources to low-level processing of novel words, including orthographic, phonological, and morphological processing and establishing form-sound connections, leaving fewer resources for searching effective contextual cues for semantic inference and integration, thereby affecting reading comprehension efficiency (Fukkink, 2005; Li et al., 2015). Additionally, the selected dyslexic children showed phonological and orthographic awareness deficits, which would hinder processing of orthographic and phonological information in novel words. In summary, due to limited cognitive resources allocated to novel words and difficulties in effectively obtaining low-level information, children with developmental dyslexia exhibit different eye movement patterns during novel word acquisition, resulting in slower learning.

It should be noted that novel word acquisition in natural reading is an extremely complex cognitive activity influenced by both learner factors (e.g., language proficiency, vocabulary size, emotional state) and reading factors (e.g., reading task, reading purpose) (Pulido, 2004). Therefore, multiple factors may contribute to slow novel word acquisition in developmental dyslexia, and future research should focus on one or several processing stages in the "novel word acquisition model in natural reading" using more targeted experimental designs to provide more evidence for the cognitive mechanisms underlying novel word acquisition deficits in developmental dyslexia.

4.2 Spacing Effect on Novel Word Acquisition in Children with Developmental Dyslexia

Previous research has found that inter-word spacing as a visual word segmentation cue highlights continuous words visually, facilitating Chinese readers' reading to some extent, a phenomenon termed the spacing effect (梁菲菲, 2013). This effect occurs not only in Chinese word identification but also in vocabulary acquisition contexts, with its magnitude modulated by readers' reading skill level (Blythe et al., 2012). This is because high-skill readers (e.g., adults) can utilize not only low-level visual information but also high-level linguistic information from words themselves for segmentation, such as morpheme familiarity (梁菲菲, 王永胜, 张慢慢, 闫国利, 白学军, 2016) and morpheme position probability (Liang et al., 2017). In contrast, low-skill readers (e.g., children), whose ability to utilize various linguistic cues is still developing (Reichle et al., 2013), depend more on low-level visual cues for word segmentation. This study found that compared to chronological age-matched children (fifth graders), the facilitative effect of inter-word spacing was more pronounced in reading level-matched children (third graders), further confirming that the spacing effect in vocabulary acquisition gradually decreases as children age and reading skill improves.

This study also found that inter-word spacing had a significantly greater facilitative effect on children with developmental dyslexia than normal children, facilitating both early and late processing stages of novel word acquisition in dyslexic children while affecting only late stages in matched groups. This indicates that the spacing effect is influenced not only by reading skill level but also by the presence of developmental dyslexia. Two possible mechanisms may explain how inter-word spacing facilitates vocabulary acquisition in children with developmental dyslexia.

First, inter-word spacing may reduce visual crowding effects. Previous research has found that children with developmental dyslexia exhibit greater visual crowding effects than normal children, meaning they are more susceptible to interference from adjacent stimuli when processing target stimuli (Zorzi et al., 2012). In alphabetic scripts, increasing inter-letter spacing (distance between letters) alleviated visual crowding effects in children with developmental dyslexia and effectively improved their reading speed (Perea, Panadero, Moret-Tatay, & Gómez, 2012). Chinese research has also found that increasing distance between distractor and target characters alleviated visual crowding effects to some extent and facilitated target character identification in children with developmental dyslexia (郭志英, 2016). Due to the special nature of Chinese text, both character spacing and word spacing exist. Compared to single characters, words have greater psychological reality in Chinese reading (Bai, Yan, Liversedge, Zang, & Rayner, 2008; Shen et al., 2012). Therefore, increasing visual distance between word units may be more effective than increasing character spacing in Chinese reading. This study confirmed at the sentence reading level that inter-word spacing effectively reduces crowding between adjacent word units and facilitates novel word acquisition in children with developmental dyslexia.

Second, inter-word spacing helps children with developmental dyslexia successfully segment words. Chinese text lacks explicit visual word boundary information, making word segmentation the primary step in novel word acquisition during natural reading (白学军等, 2014; Liang et al., 2017). Inserting inter-word spacing in Chinese text can strengthen connections between the two morphemes of a novel word in terms of form, sound, and meaning at the visual level, while helping readers quickly establish lexical representations at the whole-word level. This effectively compensates for processing deficiencies in word segmentation and identification caused by word recognition deficits in developmental dyslexia, helping them complete word segmentation accurately and rapidly, thereby facilitating novel word acquisition.

This study also found that inserting inter-word spacing in Chinese text enabled children with developmental dyslexia to achieve normal levels of novel word acquisition. Since vocabulary acquisition in natural reading directly affects children' s vocabulary size, which effectively predicts reading ability (周雪莲, 程亚华, 李宜逊, 韩春翔, 李虹, 2016), these findings provide a practical intervention approach for improving novel word acquisition in children with developmental dyslexia.

Under the conditions of this study, the following conclusions were drawn: (1) Compared to normal children, children with developmental dyslexia acquire novel words more slowly, primarily manifesting as delayed early processing and inefficient late processing in novel word acquisition, likely due to deficits in automatic form-sound conversion and reading fluency reflecting multiple low-level cognitive processes, resulting in an atypical developmental pattern of novel word acquisition. (2) Inter-word spacing as visual word segmentation information helps children with developmental dyslexia successfully segment words and may reduce text crowding effects to some extent, thereby facilitating novel word acquisition.

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