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Visual statistical learning and orthographic awareness in Chinese children with and without developmental dyslexia

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ABSTRACT

This study examined the role of visual statistical learning in reading and writing and its relationship to orthographic awareness in Hong Kong Chinese children with and without developmental dyslexia. Thirty-five 7- to 8-year-old children with developmental dyslexia and 37 chronologically age-matched controls were tested on visual statistical learning, orthographic awareness, nonverbal cognitive ability, Chinese word reading, and word dictation tasks. Visual statistical learning was assessed using a triplet learning paradigm that required children to detect the temporal order of visual stimuli. Orthographic awareness was measured with a novel character invention task that required children to create pseudocharacters using untaught stroke patterns according to the rules of Chinese character orthography. Children with dyslexia performed significantly worse than their age-matched controls on both the visual statistical learning and orthographic awareness tasks. Furthermore, visual statistical learning was significantly associated with orthographic awareness and word reading. These findings suggest that Chinese children with dyslexia are impaired in visual statistical learning and that such deficits may be related to disrupted orthographic learning abilities, thereby contributing to their reading difficulties.

1. Introduction

Statistical learning refers to the ability to unconsciously extract and integrate various statistical structures of elements of visual or auditory inputs to produce a unitary structure for further learning (e.g., see Erickson & Thiessen, 2015, for a review). A growing body of evidence suggests that visual statistical learning deficits occur in individuals with developmental dyslexia, which is a specific learning difficulty characterized by a failure to acquire reading and writing skills that is not the result of low intelligence, unequal educational or social opportunities, or any sensory damage (see Lyon, Shaywitz, & Shaywitz, 2003, for a review). However, most of these previous studies have focused solely on individuals with dyslexia in English and other alphabetic orthographies (e.g., Gabay, Thiessen, & Holt, 2015; Nicolson et al., 1999; Vicari et al., 2005), with little attention paid to nonalphabetic logographic orthographies, such as Chinese. Moreover, none of these previous studies has investigated directly the relationship between visual statistical learning and orthographic awareness, which is a prerequisite skill for reading and writing development. Thus, the goal of this study is to clarify further the relationship between statistical learning and reading by examining visual statistical learning and orthographic awareness in Hong Kong Chinese children with developmental dyslexia and their typically developing peers.

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Table 1
Profile of Children with Developmental Dyslexia (DD) and Controls.

	DD		Controls		
	Mean	*SD*	*Mean*	*SD*	$F(1, 70)$
Age in month	92.31	6.93	91.46	3.69	0.43
Nonverbal IQ	19.03	3.12	20.05	1.63	3.10[a]
Chinese word reading	46.14	21.48	92.05	24.49	71.16***
Chinese word dictation	19.80	7.76	41.68	15.98	53.61***

Note. ***$p < .001$, [a]$p = .08$.

Statistical learning is regarded as a powerful mechanism that enables infants and young children to acquire various aspects of spoken language, including word segmentation (e.g., Saffran, Aslin, & Newport, 1996), phoneme learning (e.g., Maye, Werker, & Gerken, 2002), word learning (e.g., Yurovsky, Yu, & Smith, 2012), and syntactic development (e.g., Thompson & Newport, 2007). In recent years, a growing number of studies suggest that both child and adult learners are sensitive to statistical structures of orthographic inputs in alphabetic languages and that statistical learning plays a role in reading and writing development (e.g., Frost, Siegelman, Narkiss, & Afek, 2013; Kaefer, 2009; Samara & Caravolas, 2014; Treiman & Kessler, 2006). For example, despite their limited knowledge of how words are composed of letters, English pre-school children were able to differentiate legal words from illegal words that consisted of irregular constituents such as numbers (e.g., mi23se) (Kaefer, 2009). Moreover, even 3-year-old English children were sensitive to common and uncommon letter patterns in English words, and their graphotactic knowledge improved during the prephonological period (Treiman, Kessler, Boland, Clocksin, & Chen, 2018). Additionally, English adults were able to extract embedded artificial orthographic rules (i.e., some consonants would appear only at word beginnings while other consonants would appear only at word endings) and use them to reject illegal words that violated these artificial rules (Samara & Caravolas, 2014).

Although these previous studies showed the positive impact statistical learning has on alphabetic-orthographic learning, a very recent study by Schmalz, Moll, Mulatti, and Schulte-Körne (2018) reported the lack of a significant correlation between statistical learning and orthographic or reading tasks. Specifically, German adult speakers' sensitivity to frequent letter patterns (i.e., bigram sensitivity) was not significantly correlated with their performance on two statistical learning tasks assessed using serial reaction time and artificial grammar learning (AGL) tasks. According to Schmalz et al. (2018), their non-significant findings, which contradict those of previous studies, could be due to task-related factors, including the lack of specific processes of statistical learning associated with reading and variabilities of statistical learning performance (Table 1).

However, one caveat is that the absence of a significant correlation between statistical learning and bigram sensitivity may be the result of other factors, such as the validity of using the bigram legality task to index the learner's orthographic sensitivity. As Schmalz et al. (2018) noticed, all of the adult participants exhibited a high accuracy on bigram sensitivity that was not correlated with reading, which reinforces the notion that the bigram sensitivity task may not be an age-appropriate measure of adult readers' orthographic sensitivity. This, then, suggests the need to clarify further whether an association exists between visual statistical learning and orthographic awareness in a much more visually complex orthography such as Chinese.

In fact, Chinese provides a fascinating opportunity to examine the role of statistical learning in orthographic learning and reading. Because of its nonalphabetic logographic orthography, Chinese comprises various aspects of statistical structures that may call for the use of statistical learning. For example, over 85% of Chinese characters are semantic-phonetic compounds that contain a semantic radical (a clue to meaning) and a phonetic radical (a clue to sound), both of which exhibit certain positional regularities such that semantic radicals usually appear on the left or top while phonetic radicals usually occur on the right or bottom of left-right or top-bottom structured characters.

However, these positional regularities are not exclusively rule-based, but rather much more quasi-regular. According to a corpus analysis of 2570 Chinese characters explicitly taught in Chinese primary schools, Shu, Chen, Anderson, Wu, and Xuan (2003) showed that approximately 72% of these characters are semantic-phonetic compound characters. Of these characters, only 27% have a radical with a fixed position for every character in which it appears, and 43% have a radical that can appear in more than one position. Furthermore, some free-standing radicals, i.e., those that are simple characters themselves, can occur in multiple positions when forming a compound character. For example, the semantic radical 口 can appear either on the left (e.g., 喝 (*to drink*)) or right (e.g., 和 (*harmony*)), or at the top (e.g., 呈 (*to present*)) or bottom (e.g., 吞 (*to swallow*)). Given the quasi-regularities that exist in Chinese character orthography, it seems plausible that Chinese children are utilizing some efficient learning mechanism, such as statistical learning, to acquire a large number of visually unique and complex characters.

Indeed, several studies have suggested the possible role of statistical learning in acquiring Chinese orthographic regularity. For example, Wang, Liu, and Perfetti (2004) found that alphabetic learners who had enrolled in a one-year Chinese course were able to reject illegal characters containing invalid radical positions using untaught Chinese orthographic regularity rules. The authors concluded that these Chinese language learners' implicit orthographic knowledge was acquired through their exposure to a range of Chinese characters. Moreover, using a combination of computational modeling, behavioral naming experiments, and corpus analysis, Yang, McCandliss, Shu, and Zevin (2009) showed that the connectionist model, developed on the basis of probabilistic information of phonetic radicals, predicted the main effect of frequency, consistency, and the interaction of frequency and consistency in learning print-to-sound mapping in Chinese.

Similarly, Tong and McBride (2014) revealed that even kindergarteners were able to learn and apply untaught positional regularities of stroke patterns, which are constituent units in Chinese characters, to form legal pseudocharacters (i.e., non-characters that did not violate any Chinese orthographic rules). Tong and McBride (2014) subsequently attributed the kindergarteners' implicit knowledge of character orthography to statistical learning via their accumulated exposure to character structures. Additionally, He and Tong (2017) demonstrated that Chinese children in Grades 3 and 4 can statistically learn positional, form-sound, and form-meaning regularities of an artificial orthography that are similar to Chinese characters. These findings led us to hypothesize a possible link between visual statistical learning and Chinese orthographic awareness. The first aim of the present study is to examine this link in Chinese children with and without reading difficulties, a fundamental issue that has yet to be explored.

The second aim is to investigate directly the association between statistical learning and Chinese word reading in children with and without developmental dyslexia. This aim is developed on the basis of inconsistent results of previous empirical studies on the relationship between statistical learning and reading in alphabetic languages (e.g., Arciuli & Simpson, 2012; Schmalz et al., 2018). Specifically, two studies (i.e., Arciuli & Simpson, 2012; Frost et al., 2013) reported a significant association between visual statistical learning and reading abilities in English children and adults. For example, using a triplet visual statistical task, Arciuli and Simpson (2012) demonstrated that visual statistical learning and word reading were significantly correlated with each other and that visual statistical learning also uniquely predicted word reading ability in typically developing English children and adults even after controlling for age and attention. Similarly, Frost et al. (2013) found that visual statistical learning was significantly correlated with both pointed nonword reading ability and unpointed word reading ability among adult learners of Hebrew as a second language.

However, a very recent study by Schmalz et al. (2018) showed that statistical learning was not correlated with reading ability in adult German readers. These discrepant results can be partly attributed to the different paradigms used to assess the visual statistical learning process, with Schmalz et al. (2018) using a serial reaction time task (SRT) and an artificial grammar learning (AGL) task, whereas Arciuli and Simpson (2012) employed the triplet paradigm (i.e., Alien Alert task).

Even though all three paradigms have been widely used as an index of statistical learning, these different statistical learning tasks may rely on different cognitive processes of statistical learning, such as extraction and integration (see Erickson & Thiessen, 2015 for a review). Specifically, in the SRT paradigm, individuals become implicitly familiar with a single, long, unidimensional sequence embedded in a continuous stream of stimuli while in the AGL paradigm, individuals implicitly learn the rules (i.e., grammar) of multiple, short and long, bidirectional sequences. For the triple paradigm, individuals implicitly learn multiple, unidirectional sequences (i.e., several target triplets). Furthermore, the SRT, triplet, and AGL paradigms may impose different demands on the four memory-based components of statistical learning, i.e., similarity-based comparison, decay, integration, and abstraction, assumed by Erickson and Thiessen (2015). In particular, given its use of multiple triplets, the triplet paradigm may place a greater emphasis on similarity-based comparison and abstraction compared to the SRT and AGL paradigms, making the triplet paradigm more relevant to reading processes. This may explain why Arciuli and Simpson (2012) found an association between reading and statistical learning using the triplet paradigm, while Schmalz et al. (2018) reported no such association using SRT and AGL.

Another possible factor for the discrepant results concerning the association between statistical learning and reading is orthographic depth, which refers to the correspondence between graphemes and phonemes (GPC). In Schmalz et al. (2018) study, German was deemed less complex than English with its more complicated GPC rules. Thus, the controversy continues as to whether a relationship exists between statistical learning and reading. The present study takes the important first step to address this controversy by investigating the relationships among visual statistical learning, orthographic awareness, and reading in Chinese children with and without developmental dyslexia.

Although a considerable number of studies have examined statistical learning in individuals with dyslexia in alphabetic orthographies, the results are mixed and inconclusive (for reviews, see Schmalz, Altoè, & Mulatti, 2017; van Witteloostuijn, Boersma, Wijnen, & Rispens, 2017). While some studies revealed that individuals with dyslexia exhibited statistical learning deficits (e.g., Sigurdardottir et al., 2017; Vicari et al., 2005; Vicari, Marotta, Menghini, Molinari, & Petrosini, 2003), others did not (e.g., Kelly, Griffiths, & Frith, 2002; Rüsseler, Gerth, & Munte, 2006). For example, using a classic SRT task to assess learning by comparing reaction time change between random blocks and repeated color sequence blocks, Vicari et al. (2003) found that normal readers were able to detect and learn the embedded sequence of colors more efficiently than the group with dyslexia. Similarly, Sigurdardottir et al. (2017) found that adults with dyslexia exhibited poor performance in visual statistical learning of simple nonsense letter-like objects compared to age-matched typical readers. In contrast, Kelly et al. (2002) examined the sequential learning of the spatial order of the visual stimuli by individuals with dyslexia and normal readers and found that both groups exhibited a similar degree of decline in their spatial-ordering response time, indicating an intact statistical learning ability in children with dyslexia.

Given the controversy surrounding statistical learning among individuals with dyslexia, it is critically important to clarify further the relationship between visual statistical learning and reading and writing difficulties. Moreover, as most previous studies have focused largely on individuals with dyslexia in alphabetic orthographies, with little attention paid to children with dyslexia in non-alphabetic orthographies, especially Chinese, the present study examined whether Chinese children with developmental dyslexia showed visual statistical learning and orthographic learning deficits relative to their typically developing peers.

To summarize, the present study had two goals. First, we examined the existence of a potential link between visual statistical learning and orthographic awareness and, conditionally, the possible contributions of visual statistical learning to Chinese word reading and dictation. We hypothesized that if a significant association does exist, performance on statistical learning would be significantly associated with Chinese orthographic awareness and would uniquely account for the variance of Chinese word reading and dictation. Also, if visual statistical learning capacities do indeed underlie orthographic awareness and reading, we would expect that poor visual statistical learning capacities would result in impaired orthographic awareness and reading. Thus, it seems plausible that children with reading difficulties (e.g., developmental dyslexia) would more likely exhibit visual statistical learning deficits as compared with their typically developing peers who have no reading difficulties. Thus, the second goal of our study is to examine this hypothesis by comparing visual statistical learning performance between Chinese children with dyslexia and their typically developing peers.

2. Method

2.1. Participants

Participants consisted of 35 children with dyslexia (20 boys, 15 girls; Mean age = 7 years, 8 months, *SD* = 6.93 months) and 37 age-matched controls (23 boys, 14 girls; Mean age = 7 years 7 months; *SD* = 3.69 months) in Grade 2. All were native Cantonese speakers recruited from Hong Kong mainstream schools where Cantonese was the primary medium of instruction. None of them had any cognitive or uncorrected sensory impairments. Based on the observed probability level, the number of predictors, the effect size and the sample size, our post hoc power analysis indicated that the observed power was above 95% with an effect size of .35 at the level of significance of $\alpha = 0.05$ (Faul, Erdfelder, Lang, & Buchner, 2007). Ethical approval for this study was obtained from the University of Hong Kong Ethics Committee.

The participants with dyslexia were formally diagnosed by a clinical psychologist or an educational psychologist using the Hong Kong Test of Specific Learning Difficulties in Reading for Primary School Students–Second Edition (HKT-P II, Ho, Chan, Chung, Tsang et al., 2007). HKT-P II consists of three literacy subtests (i.e., Chinese word reading, one-minute word reading, and word dictation) and cognitive and linguistic subtests (i.e., digit rapid naming, phonological awareness, phonological memory, and orthographic awareness). In Hong Kong, Chinese children are diagnosed with dyslexia if they have normal intelligence (i.e., an IQ of 85 or above), but their literacy composite score and one cognitive composite score are at least one standard deviation below the age-appropriate means (Chung, Ho, Chan, Tsang, & Lee, 2011; Ho, Chan, Lee, Tsang, & Luan, 2004; Ho, Chan, Chung, Lee et al., 2007; Ho, Chan, Chung, Tsang et al., 2007). Since our participants ranged in age from 7 years; 7 months to 8 years; 0 months, the cutoff scores for Chinese word reading and Chinese word dictation were 62 and 35, respectively, while the cutoff scores for the cognitive and linguistic tasks were: digit rapid naming = 25.76, rhyme detection = 9, onset detection = 5, word repetition I = 71, non-word repetition = 63, word repetition II = 55, left-right reversal = 61, lexical decision = 45, and radical position = 13.

The age-matched controls had Chinese word reading and word dictation scores at or above the age-appropriate levels. The children with dyslexia and the age-matched control groups were matched on age, $t\,(70) = .66, p = .51$, and gender, $t\,(70) = .43, p = .67$. In order to verify the reading profile of these two groups of children, the HKT-P II subtests of Chinese word reading and word dictation were administered (see the description of these two tests below). For our participants with dyslexia, mean scores for word reading ($M = 46.14$, $SD = 21.48$) and word dictation ($M = 19.80$, $SD = 7.76$) were far below the corresponding cutoff scores (i.e., word reading = 62; word dictation = 32) for Chinese children with dyslexia between the ages of 7 years; 8 months and 8 years; 0 months. In contrast, the mean scores of our age-matched controls for word reading ($M = 92.05$, $SD = 24.49$) and word dictation ($M = 41.68$, $SD = 15.98$) were much higher than the corresponding cutoff scores. Furthermore, children with dyslexia performed significantly worse than the age-matched controls on word reading, $F\,(1, 70) = 71.16, p < .001, \eta_p^2 = .50$, and word dictation, $F\,(1, 70) = 53.61, p < .001, \eta_p^2 = .43$; but their nonverbal IQ scores were not significantly different from the age-matched controls, $F\,(1, 70) = 3.10, p = .08$. This further confirmed the diagnosis or classification of children with dyslexia and children without dyslexia.

2.2. Measures

2.2.1. Nonverbal ability

Sets A and B of Raven's Standard Progressive Matrices (1998) were used to assess nonverbal intelligence. Each set consisted of 12 questions. A target matrix with one missing element was presented along with six possible options. The participants were asked to select the option that would best complete each matrix pattern. The Cronbach's alpha was .61 for this test.

2.2.2. Chinese word reading

A 150 two-character word list, adopted from HKT-SpLD (II) (Ho, Chan, Chung, Lee et al., 2007; Ho, Chan, Chung, Tsang et al., 2007), assessed participants' ability to read. Children were instructed to read the list of words aloud as accurately and quickly as possible. There was no time limit for the completion of this test. Testing stopped if the child made 15 consecutive errors. One point was given for each correctly read word. The maximum score for this test was 150. The Cronbach's alpha was .99 for this test.

2.2.3. Chinese word dictation

Adopted from the HKT-SpLD (II) (Ho, Chan, Chung, Lee et al., 2007, Ho, Chan, Chung, Tsang et al., 2007), this test consisted of 46 two-character words arranged in ascending order of difficulty and assessed participants' word writing ability. As the experimenter read aloud the target words, the participants responded by writing the words on a provided sheet of paper. No time limit was included for this task, but children were asked to write the words as accurately and quickly as possible. Testing stopped if the child scored zero on eight consecutive words. One point was given for each correctly written character. The maximum score for this test was 96. The Cronbach's alpha was .96 for this test.

2.2.4. Orthographic awareness

A pseudo-character invention task, adopted from a study by Tong and McBride (2014), was used to assess participants' orthographic knowledge of Chinese characters by testing their sensitivity to legal positions of non-radical stroke patterns. The non-radical stroke patterns used were components of real characters, in this case fixed visual-graphic patterns that could not be physically separated. These stroke patterns conveyed neither semantic nor phonological information so as to avoid the application of radical positional constraints that may have been learned in school. Unlike the orthographic knowledge measures that assessed explicit knowledge or the combination of explicit and implicit orthographic knowledge used in previous studies (e.g., Liu, Chen, & Chung, 2015; Wang & Yang, 2018), our novel character invention task purely assessed children's implicit learning of untaught orthographic knowledge of Chinese character orthography.

Two types of stroke patterns were used: fixed-position and free-position. Fixed-position stroke patterns only appear in specific positions within characters (e.g., 𡗗 only appears at the top position, as in 春 (*spring*)). Conversely, free-position stroke patterns appear in different locations in different characters (e.g., 𦰩 can appear in the left position, as in 難 (*difficult*), or in the right position, as in 嘆 (*to sigh*)). Each stroke pattern was printed in black on a white 10 cm × 10 cm card. Two 30 cm × 15 cm character structure cards were also used. Each card consisted of two square boxes. The boxes on one card were horizontally linked (i.e., □□), signifying a left-right character structure, while boxes on the other card were vertically linked (i.e., 日), signifying a top-bottom character structure.

The pseudo-character invention task consisted of two practice trials and 29 test trials. For each trial, participants were asked to form the most "real-character-like" pseudo-character using a given pair of stroke patterns by placing each one on the appropriate character structure card. There were four possible combinations for each pair, but only one was orthographically legal. Immediate feedback was given for the practice trials but not for the test trials. The scoring method consisted of one point credited for each correctly invented pseudo-character. The maximum score for this test was 29. The Cronbach's alpha was .55 for this test.

2.2.5. Statistical learning

A visual statistical learning task was designed on the basis of a triplet learning task used in a study by Arciuli and Simpson (2011). The stimuli consisted of 12 newly invented abstract figures that were created by combining two or more common shapes (i.e., circle, star, triangle, rectangle, arrow, cross, ellipse, hexagon, and diamond). For example,  was formed by combining elements of a star and a rectangle. These novel figures were used instead of familiar shapes to avoid any participant's preference towards specific shapes that might attract additional attention and provide clues for segmentation. These 12 figures were grouped into four triplets named ABC, DEF, GHI, and JKL (i.e., ABC was the first triplet group, and A, B, and C were the figures within this triplet).

This task consisted of a familiarization and a testing phase. The familiarization phase consisted of four triplets (i.e., ABC, DEF, GHI, and JKL), with each triplet repeated 24 times. Figures within a triplet always appeared in sequence, but the order of triplet presentation was counterbalanced within the familiarization stream, during which a continuous stream of novel figures was presented. Figures appeared individually with a vision time of 1 s. A blank white screen with a vision time of 0.2 s was presented to separate each successive novel figure. The long vision time was set to avoid the effect of "attentional blink" (Shapiro & Raymond, 1997).

A cover task was adopted to ensure participants paid adequate attention to the stream of figures. For six of the 24 presentations of each triplet, one of the figures was presented twice in a row. These repetitions were distributed equally among the three figures within each triplet to prevent any boundary cues. Participants were instructed to respond whenever they saw two identical figures in a row.

After the familiarization phase, participants were informed about the triplet pattern in the stream and that figures were arranged in groups of three. In the testing phase, four new triplets were created and referred to as unusual triplets since they had yet to appear in the familiarization stream. Each unusual triplet was formed by combining the figures from each of the three different normal triplets that appeared in the familiarization stream. In each testing trial, participants were presented with a normal triplet and an unusual triplet and required to indicate verbally which group of triplets they thought had appeared in the familiarization stream. No time limit was imposed. One point was given for each successfully identified normal triplet. The maximum score for this test was 32. The Cronbach's alpha was .56 for this test. An example of the familiarization and testing phases is presented in Fig. 1.

2.3. Procedures

Consent was obtained from both the participants and their parents. Participants were tested individually either in a quiet space at home or at their school campus. All participants were administered five tasks in the following order: Raven's standard progressive matrices, Chinese word reading, Chinese word dictation, pseudo-character invention, and visual statistical learning. Participants were given a 5-minute break between tasks.

2.4. Data analysis

Prior to our analyses, an examination of the distributions of all variables was conducted. The results showed that the skewness values for all variables were between -2 and +2, which are within the acceptable range (George & Mallery, 2010). Thus, all data were included, and raw scores were used in the following analysis.

We conducted the first set of analyses using partial correlation and hierarchical multiple regression to examine our first research question regarding the relationship among statistical learning, orthographic awareness, and reading and writing. Specifically, the partial correlation analysis was conducted on the basis of the whole sample (i.e., N = 72) by controlling for nonverbal IQ. The hierarchical regression analyses were conducted to further evaluate the relationship between visual statistical learning and orthographic awareness and the contributions of visual statistical learning to Chinese word reading and dictation.

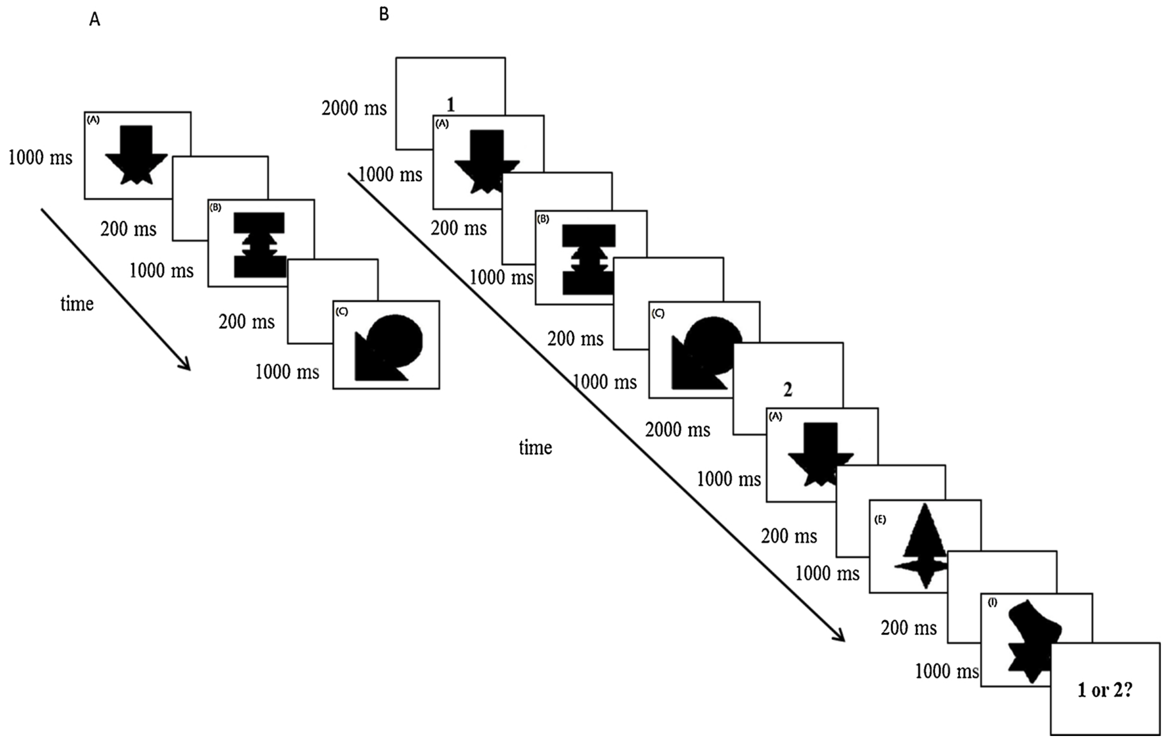

Fig. 1. An example for the procedure of statistical learning task in familiarization phase (A) and testing phase (B).

We conducted the second set of analyses using a MANOVA, ANOVA, and predictive discriminant analysis to address our second research question concerning whether Chinese children with dyslexia exhibit impaired statistical learning and orthographic awareness. The MANOVA was conducted first to examine whether the children with dyslexia differed from their typically developing peers on visual statistical learning and orthographic awareness tasks after controlling for nonverbal IQ. The follow-up ANOVA analysis examined the difference in visual statistical learning and orthographic awareness between children with dyslexia and their age-matched controls. Finally, the predictive discriminant analysis was conducted to determine to what extent statistical learning and orthographic awareness could distinguish children with dyslexia from their typically developing controls.

3. Results

3.1. The partial correlation analysis

As shown in Table 2, the orthographic awareness task and the visual statistical learning task were significantly correlated with each other (r = .50, p < .001). Moreover, the visual statistical learning task was significantly correlated with Chinese word reading (r = .46, p < .001) and word dictation (r = .39, p < .001). Likewise, orthographic awareness was also significantly correlated with Chinese word reading (r = .53, p < .001) and word dictation (r = .55, p < .001). This indicates a positive relationship between visual statistical learning ability and orthographic awareness, both of which significantly correlated with Chinese word reading and word dictation. The relationships among visual statistical learning, orthographic learning, Chinese word reading, and word dictation in both groups are shown in Fig. 2.

Table 2
Partial Correlations among All Variables after Controlling for the Effect of Nonverbal IQ for All participants (N =72).

	1	2	3	4
1. Statistical learning	–			
2. Orthographic awareness	.50***	–		
3. Chinese word reading	.46***	.53***	–	
4. Chinese word dictation	.39***	.55***	.81***	–

Note. ***p < .001.

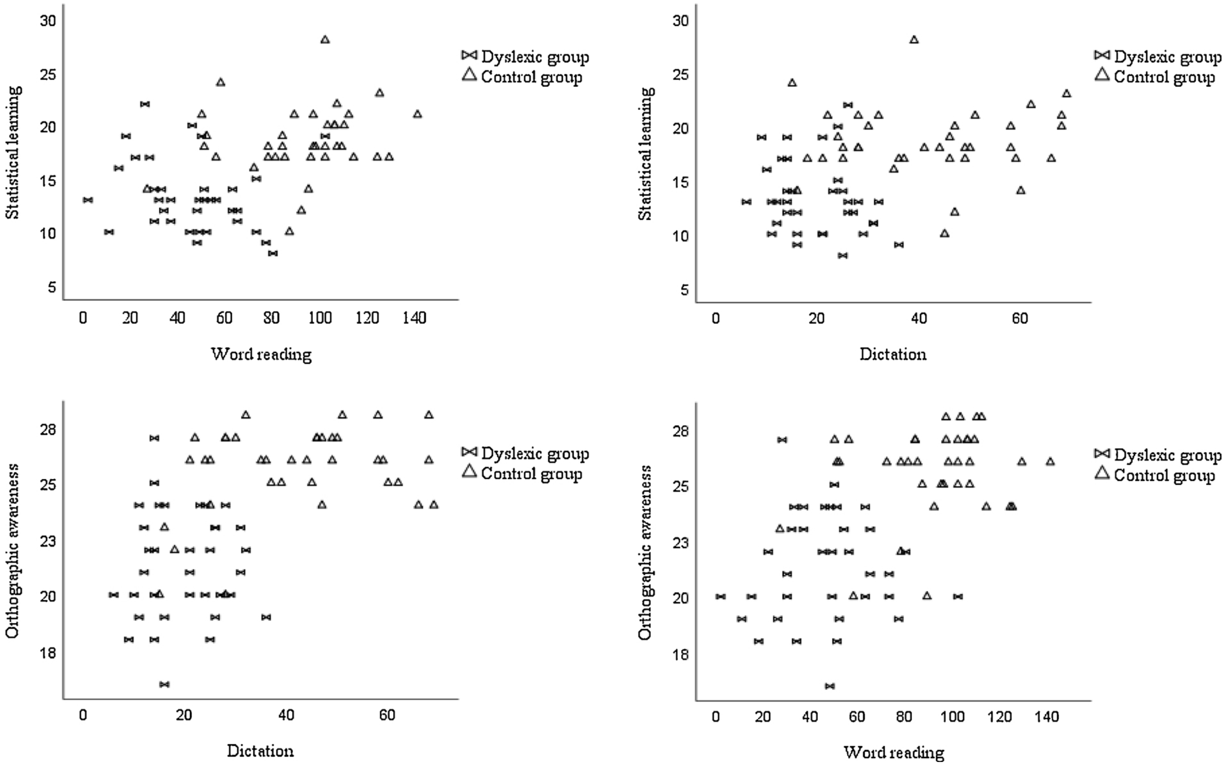

Fig. 2. Scatter plots for dyslexic and control groups showing the relationship among visual statistical learning, orthographic awareness, Chinese word reading and dictation.

3.2. Regression analyses

Three regression analyses were conducted to further examine the relationship between visual statistical learning and orthographic awareness, as well as their contributions to word reading and word dictation. The results of the three regression analyses are summarized in Tables 3 and 4.

The first regression analysis was performed to examine whether a significant association exists between visual statistical learning and orthographic awareness. Nonverbal IQ was entered into the first block as a control variable, and Chinese word reading and word dictation were entered into the second block as control variables because both orthographic awareness and visual statistical tasks were moderately correlated with Chinese word reading and dictation. Visual statistical learning was then entered in the final step. As shown in Table 3, visual statistical learning still accounted for 8% of the total variance of orthographic awareness after taking into account the contributions of nonverbal IQ, Chinese word reading, and dictation abilities.

The second regression analysis was performed to evaluate the contribution of visual statistical learning to Chinese word reading. As shown in Table 4, visual statistical learning uniquely accounted for 2.4% of the variance of Chinese word reading after controlling for nonverbal IQ and word dictation but not orthographic awareness. Importantly, visual statistical learning still accounted for 1.6% of the total variance in Chinese word reading even after controlling for orthographic awareness, nonverbal IQ, and word dictation.

As shown in Table 4, the third regression analysis on the associations among Chinese word dictation, statistical learning, and orthographic awareness revealed that the contribution of visual statistical learning was not significant after taking into account the variance of nonverbal reasoning and word reading whether orthographic awareness was controlled or not.

Table 3
Hierarchical Multiple Regression Analyses Predicting Chinese Orthographic Awareness from Visual Statistical Learning among All Children After Controlling for Nonverbal IQ, Chinese Word Reading and Chinese Word Dictation.

Steps	Variables	β	*t*	R^2	ΔR^2	ΔF
Step 1	Nonverbal IQ	.106	1.05	.03	.03	2.83
Step 2	Chinese word reading	.109	.62	.32	.31	16.24***
	Chinese word dictation	.34	2.11*			
Step 3	Visual statistical learning	.31	3.00**	.39	.08	8.97**

Note. $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$.

Table 4
Hierarchical Multiple Regression Analyses Predicting Chinese Word Reading and Word Dictation from Visual Statistical Learning.

Step	Variables	Chinese word reading β	t	R^2	ΔR^2	ΔF	Chinese word dictation β	t	R^2	ΔR^2	ΔF
without controlling for orthographic awareness											
Step 1	Nonverbal IQ	.20	3.12**	.10	.10	8.06**	−.11	−1.43	.03	.03	1.95
Step 2	Dictation/Word reading	.72	10.16***	.70	.59	135.00***	.84	10.16***	.67	64	135.00***
Step 2	Visual statistical learning	.17	2.41*	.72	.024	5.79*	.01	.13	.67	.00	.02
with controlling for orthographic awareness											
Step 1	Nonverbal IQ	.20	2.97*	.10	.10	8.06**	−.12	−1.63	.03	.03	1.95
Step 2	Dictation/Word reading	.69	8.77***	.688	.59	135.00***	.77	8.77***	67	64	135.00***
Step 3	Orthographic awareness	.05	.62**	.693	.01	2.07	.18	2.12*	.690	.02	4.15*
Step 4	Visual statistical learning	.15	2.00*	.71	.016	3.96*	−.05	−.56	.691	.002	.35

Note. *$p < .05$, **$p < .01$, ***$p < .001$.

3.3. MANOVA and ANOVA analyses

Fig. 3 shows the performance of statistical learning and orthographic awareness in children with dyslexia and their age-matched controls. Given the significant correlation between visual statistical learning and orthographic awareness, a MANOVA was conducted to examine whether children with dyslexia differed from their typically developing controls while controlling for nonverbal IQ. There was a significant overall group effect (Wilks $\lambda = .41$, F (2, 69) = 49.11, $p < .001$, $\eta_p^2 = .59$). The univariate F test revealed a significant difference between the two groups on the visual statistical learning task (F (1, 70) = 41.93, $p < .001$, $\eta_p^2 = .38$), and on orthographic awareness (F (1, 70) = 67.98, $p < .001$, $\eta_p^2 = .49$), with children with dyslexia having lower scores than the age-matched controls.

Furthermore, an ANOVA analysis showed a significant difference between children with dyslexia and their age-matched controls on orthographic awareness (F (1, 69) = 35.58, $p < .001$, $\eta_p^2 = .34$) after controlling for visual statistical learning. Similarly, children with dyslexia performed significantly worse than the controls on visual statistical learning even after controlling for orthographic awareness (F (1, 69) = 15.84, $p < .001$, $\eta_p^2 = .19$). These results clearly indicate that the children with dyslexia performed worse than the normal readers on both statistical learning and orthographic awareness tasks.

3.4. Predictive discriminant analysis

To determine the extent to which statistical learning and orthographic awareness could distinguish children with dyslexia from their typically developing controls, a predictive discriminant analysis was conducted. The Chi-square test was significant (Wilks$\lambda = .41$, Chi-square = 61.08, $df = 2$, Canonical correlation = .77, $p < .001$). Overall, 91.4% of the original grouped cases and 91.4% of the cross-validated grouped cases were correctly classified. The standardized canonical discriminant function coefficients showed that the magnitude of orthographic awareness (i.e., .77) was greater than the coefficients for statistical learning (i.e., .57), suggesting that orthographic awareness appears to be the stronger correlate of the two variables on the discriminant score.

4. Discussion

The present study demonstrated a strong association between visual statistical learning and implicit orthographic awareness in Chinese, and that visual statistical learning appeared to be a significant predictor of Chinese word reading even after taking into

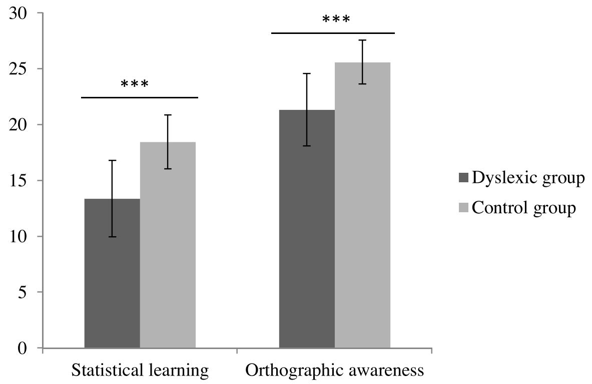

Fig. 3. Comparisons between children with dyslexia and the typically developing children on statistical learning and orthographic awareness. *Note.* The error bars and stars indicate standard deviation and the significance level, respectively.

account the effects of nonverbal IQ, word dictation, and orthographic awareness. Furthermore, Chinese children with dyslexia exhibited deficits in both visual statistical learning and orthographic awareness as compared to their typically developing peers. Additionally, apart from orthographic awareness, statistical learning was a critical factor distinguishing Chinese children with dyslexia from their typically developing peers. These findings and their relation to existing theories and educational practice on Chinese developmental dyslexia are discussed below.

Consistent with previous research (e.g., He & Tong, 2017; Tong & McBride, 2014), the strong association between visual statistical learning and orthographic awareness indicates that statistical learning may help Chinese children acquire orthographic regularities of characters. This finding can be explained in terms of the processes necessary for learning a large number of visually complex characters during the primary school period. Specifically, as a logographic script, Chinese has no grapheme-phoneme correspondence. Instead, the mapping between sound, meaning and form is arbitrary. Also, despite the existence of semantic and phonetic radicals, the relationships between radicals and the sound or meaning of their compound characters are much more quasi-regular. Thus, in addition to explicit instruction, a robust and efficient learning tool is necessary to help Chinese children acquire at least 2500 visually complex characters during their primary school years.

Our results demonstrate that visual statistical learning is that potential tool that children can use to extract statistical structures of character inputs and form unitary chunks to store in memory for further learning. For example, the stroke-pattern 厤 has never been explicitly taught in school, but it always appears as a unitary component on the top position of a top-bottom structured character, such as 曆 (*calendar*), 歷 (*to pass*), and 磿 (*mill*). Similarly, the stroke pattern 皀 consistently appears on the left in left-right structured characters, such as 既 (*since*) and 即 (*promptly*). However, most stroke patterns or radicals can appear in different positions. For example, according to a corpus analysis of Chinese characters, the stroke pattern 彡 appears in 19 characters and is localized on the left side in three (e.g., 須 (*beard*)) and on the right side in 16 (e.g., 彤 (*red*), 衫 (*shirt*), 杉 (*fir*), and 彩 (*colored*)) (Lui, Leung, Law, & Fung, 2010). Since these stroke patterns and their positional features have never been explicitly taught in schools, children discover them only if they are able to extract these frequently occurring units and integrate their positional features across different examplars to induce a unitary representation or structure that supports further learning.

Another related novel finding is that Chinese children with dyslexia exhibited impairment in visual statistical learning, which further suggests that visual statistical learning may be a potential source of reading difficulties in Chinese children with dyslexia. In fact, this finding fits well with prior studies showing visual statistical learning deficit in readers with dyslexia in alphabetic languages (e.g., Sigurdardottir et al., 2017; Vicari et al., 2005, 2003). Several potential factors may be related to the presence of visual statistical learning impairments in Chinese children with dyslexia. One is the visual complexity of Chinese characters, especially traditional Chinese characters learned by Hong Kong Chinese children. It is widely known that Chinese characters have unique and complex square configurations: strokes packed into stroke patterns or radicals; and stroke patterns or radicals stacked horizontally or vertically to form left-right or top-bottom structured characters. It is estimated that some characters consist of 32 strokes (Lü & Ding, 1996) and that the average number of strokes is 12.7 (Yang, 2000). As discussed above, Chinese characters exhibit quasi-regularity and variability in the mappings of radicals with sounds or meanings. Many characters may contain the same radical components but represent different sounds and meanings. For example, the semantic radical 舟(a *boat*-related concept) can appear in the characters 船(a boat), 艦(a warship), 艇(a long, narrow boat), and 舶(an ocean-going ship), indicating different types of ships; it can also appear in the characters 航(to navigate), 舵(a rudder), and 舷(bulwarks) to indicate *ship-related* concept. The same radical can also appear in the character 般 (same as), whose meaning has nothing to do with boats or ship-related concepts. Given their visual similarities, simply recognizing each of these characters doesn't suffice for Chinese children's acquisition of them. However, acquiring them can be accomplished through a statistical learning process, which involves similarity-based comparison, integration, decay, and abstraction of multiple exemplars from print input (Erickson & Thiessen, 2015). Thus, it is not surprising to observe disrupted statistical learning in Chinese children with dyslexia.

Additionally, the impaired visual statistical learning exhibited by Chinese children with dyslexia may be partly related to the ineffective capacity of the procedural learning system that "subserves the learning and control of established sensorimotor and cognitive habits, skills and procedures" (Gabay et al., 2015, p. 935). Specifically, in our study, the established triplet paradigm visually presented the children with a sequence of figures in the familiarization phase, with each sequence repeated multiple times. In the testing phase, the participants were asked to distinguish the predefined sequence of visual figures with a fixed order from the sequence of visual figures with a random order. To successfully complete this task, the participants had to detect an embedded temporal order (i.e., ABC, DEF, GHI, and JKL) that they were not explicitly informed about during the learning phase. Thus, the nature of the visual statistical learning task used in the present study is, to some extent, an implicit procedural learning task. In fact, according to Gabay et al. (2015), impairment in procedural learning may influence automatization of skill and knowledge and lead to mild motor and articulatory problems that can possibly affect print-sound conversion, word recognition, verbal working memory, and orthographic learning; this may result in impoverished phonological representations and concomitant difficulties in print-sound conversion, thereby contributing to reading difficulty in children with dyslexia.

Moreover, in view of both the current results, in which visual statistical learning uniquely associated with orthographic awareness, and the unique contribution of visual statistical learning to Chinese orthographic awareness, it seems reasonable to propose that visual statistical learning may be one of the underlying factors associated with the impairment of orthographic knowledge in Chinese children with dyslexia. Relative to normal readers, Chinese children with dyslexia may be deficient in extracting frequently coherent orthographic units, such as stroke patterns or radicals, and fail to integrate the positional features of these orthographic units to induce a unitary representation for further learning. Thus, they exhibit difficulties in discovering the positional constraints or radical information embedded in characters, which is a necessary component of word reading in Chinese. This explanation is consistent with the visual statistical learning account explaining alphabetic orthographic knowledge deficit in children with dyslexia in alphabetic orthographies (e.g., Arciuli & Cupples, 2006; Deacon, Conrad, & Pacton, 2008).

Additionally, the impaired visual statistical learning exhibited by children with dyslexia may be due to their visual attention deficit, which refers to the inability to allocate attentional resources efficiently among stimuli. This deficit was commonly found in children with dyslexia in previous studies (e.g., Badcock, Hogben, & Fletcher, 2011; Visser, Boden, & Giaschi, 2004). In the study by Badcock et al. (2011), for example, children with dyslexia were shown to require a much longer processing time than normal readers to identify sequential stimuli. On the visual statistical learning task used in the present study, the processing of the continuous stream of figures presented proved demanding for children with dyslexia as they needed to employ greater attentional resources than normal readers. Thus, children with dyslexia apparently concentrated more than normal readers on the identification of the figures, resulting in less available attentional resources to process the central aspect of the task, which was to extract the embedded temporal sequence from the stream of stimuli (Vicari et al., 2003). In turn, they failed to detect the presence of triplet groups within the familiarization stream. This explanation aligns with a previous study by Baker, Olson, and Behrmann (2004)) in which visual statistical learning was found to be constrained by a lack of visual attention.

Finally, the visual statistical learning deficits exhibited in children with dyslexia may be linked to a temporal processing deficit, which is broadly defined as the cognitive process required when dealing with two or more stimuli. Farmer and Klein (1995) subdivided this ability into three stages: determination of the stimuli, temporal order judgment, and sequence matching or discrimination. In our statistical learning test, all children with dyslexia achieved 100% accuracy in identifying repeated figures during the cover task. This implied that they were able to recognize different figures and did not fail at the determination stage. However, they were more likely to fail at the temporal order judgment and sequence discrimination stages, which is consistent with other studies showing the impairment at these stages in individuals with dyslexia (e.g., Ben-Artzi, Fostick, & Babkoff, 2005; Martino, Espesser, Rey, & Habib, 2001). Relevant to our study, the long stream of stimuli presented in the familiarization phase posed a great challenge for participants with dyslexia. They expended greater effort than normal readers in accurately distinguishing the temporal order of presented figures, or even failed to do so (Ben-Artzi et al., 2005). Consequently, they were not able to perceive the sequence of figures properly, let alone detect the embedded triplet patterns.

Our study is the first to show that Chinese children with dyslexia exhibit impaired visual statistical learning. This extends the current theoretical understanding of the role of statistical learning in reading and writing development, which was mainly based on studies of alphabetic orthographies, by suggesting that visual statistical learning deficit is also an indicator for children with dyslexia in Chinese. Furthermore, the strong association between visual statistical learning and orthographic awareness indicates that impaired visual statistical learning not only relates to orthographic learning, but may also contribute to the overall ability of those with dyslexia to read (Vicari et al., 2005). As indicated in our results, even after controlling for nonverbal reasoning, word dictation, and orthographic awareness, visual statistical learning still explained unique variance of reading. This finding fits well with some previous studies on alphabetic languages that report a positive association between statistical learning and reading (e.g., Arciuli & Simpson, 2012; Frost et al., 2013). However, as we are clearly aware of the correlational nature of this finding, it is necessary for future research to establish an intervention study that examines whether visual statistical learning training can improve orthographic awareness and, ultimately, word reading in Chinese children with dyslexia.

Although the present findings support the importance of visual statistical learning in Chinese orthographic and reading acquisition, it should be noted that this study is a cross-sectional design that focused on 7- to 8-year-old children only. This age range of participants may restrict any causal interpretation of the relationship between development of visual statistical learning ability and development of Chinese orthographic knowledge. Furthermore, the present study assessed only visual statistical learning ability. Several previous studies reported that individuals with dyslexia showed deficits in other forms of statistical learning, such as motor sequencing learning (e.g., Vicari et al., 2003) and auditory statistical learning (e.g., Gabay et al., 2015).

Additionally, the reliability of the visual statistical learning task was relatively low in this study, but it is comparable to a recent study that reported that Cronbach's alpha was .68 and .72 for the first and second sessions, respectively (Arnon, 2019). The low reliability of our statistical learning task could be due to an insufficient number of trials in the test phase. Also, according to Siegelman, Bogaerts, and Frost (2017)), the limitation of the triplet paradigm may be a potential confounding variable influencing the relationship between statistical learning and reading. According to Siegelman et al. (2017), the relatively small number of trials in the familiarization phase (i.e., 4 triplets with each triplet repeated 24 items) may create measurement error when examining individual differences in visual statistical learning. Additionally, psychometric problems may occur since all test items are of the same type and their level of difficulty does not change (see Siegelman et al., 2017, for a review). Thus, an important avenue for future research is to conduct comprehensive longitudinal studies using various statistical learning measures to investigate how statistical learning capacities across visual and auditory domains in young children are related to their reading skills and difficulties over the course of subsequent years.

In conclusion, the present study demonstrates that visual statistical learning and orthographic awareness are directly associated with each other, and that visual statistical learning still uniquely explains a significant but small amount of variance of word reading even after controlling for orthographic awareness and word dictation. Furthermore, Chinese children with dyslexia exhibit difficulties in both visual statistical learning and orthographic awareness, suggesting that, in addition to orthographic awareness, visual statistical learning may be another key factor for distinguishing children with dyslexia from their typically developing peers. Our findings point to the relationships among visual statistical learning, orthographic awareness, and reading acquisition. Future research needs to examine further these connections by unraveling the statistical learning mechanism in reading acquisition.

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