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A Perceptual Learning Deficit in Chinese Developmental Dyslexia as Revealed by Visual Texture Discrimination Training

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Learning to read involves discriminating between different written forms and establishing connections with phonology and semantics. This process may be partially built upon visual perceptual learning, during which the ability to process the attributes of visual stimuli progressively improves with practice. The present study investigated to what extent Chinese children with developmental dyslexia have deficits in perceptual learning by using a texture discrimination task, in which participants were asked to discriminate the orientation of target bars. Experiment 1 demonstrated that, when all of the participants started with the same initial stimulus-to-mask onset asynchrony (SOA) at 3 ms, the threshold SOA, adjusted according to response accuracy for reaching 8 % accuracy, did not show a decrement over 5 days of training for children with dyslexia, whereas this threshold SOA steadily decreased over the training for the control group. Experiment 2 used an adaptive procedure to determine the threshold SOA for each participant during training. Results showed that both the group of dyslexia and the control group attained perceptual learning over the sessions in 5 days, although the threshold SOAs were significantly higher for the group of dyslexia than for the control group; moreover, over individual participants, the threshold SOA negatively correlated with their performance in Chinese character recognition. These findings suggest that deficits in visual perceptual processing and learning might, in part, underpin difficulty in reading Chinese.

Keywords: developmental dyslexia; perceptual learning; texture discrimination; Chinese

INTRODUCTION

Efficient reading involves automatically recognizing printed symbols, and accessing associated phonological and semantic information, after repeated exposure to written materials. However, individuals with developmental dyslexia fail to achieve this

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automaticity in reading, even after extensive reading practice (Nicolson & Fawcett, 199 ; Nicolson & Fawcett, 2 7). Two major frameworks have been presented to account for the origin and mechanisms of developmental dyslexia. The first, the linguistic framework hypothesis, postulates that deficits in accessing and manipulating phonological information account for developmental dyslexia (Ramus *et al*., 2 3; Studdert-Kennedy, 1997; Studdert-Kennedy & Mody, 1995; Wagner & Torgesen, 1987). The second, the nonlinguistic framework hypothesis, proposes that phonological and other deficits at the linguistic level may stem from more fundamental deficits in sensory information processing, including acoustic–auditory, auditory temporal processing (Frith, 1996; Tallal, 198 ; Tallal, Merzenich, Miller, & Jenkins, 1998; Walker, Hall, Klein, & Phillips, 2 6; Witton *et al*., 1998) and visual perceptual processing (Goswami *et al*., 2 1 ; Stefanics *et al*., 2 11; Stein, 1994; Stein & Walsh,-243.2(din)2r achievement (Kavšek, 2 4; Rose, Feldman, Jankoeski, & Rossem, 2 12). The findings of such studies have indicated a relationship between perceptual learning and cognitive learning. Habituation is the process whereby infants decrease their attention to repeatedly presented stimuli (e.g. a circle), whereas dishabituation is the process whereby infants increase their attention to stimuli with a single-feature change (e.g. a circle changing into a triangle). The processes involved in habituation and dishabituation include stimulus encoding, storage and retrieval, which are the basic processes of perceptual learning. If an individual's early perceptual learning abilities are associated with later information processing abilities and academic learning, it is then hypothesized that an association between perceptual learning and higher-order learning may exist.

To the best of our knowledge, except for studies on auditory temporal learning (Merzenich *et al.*, 1996; Tallal *et al.*, 1998; Temple *et al.*, 2 3), no previous study has directly compared the properties and time course of perceptual learning between individuals with dyslexia and typically developing children. Tallal and colleagues (Tallal *et al.*, 1998; Merzenich *et al.*, 1996; Temple *et al.*, 2 3) argued that dyslexic people have a deficit in auditory temporal processing, which can be ameliorated by stretching the auditory stimuli to make them more individually adaptive. Compared with learning English (the alphabetic scripts), learning to read Chinese (the logographic system) may demand more from the reader on visual-orthographic processes in lexical processing (Zhou & Marslen-Wilson, 1999, 2). It is also the case that visual-orthographic processes may play a more important role in learning to read and reading impairment in Chinese than in English (Li *et al.*, 2 9; Meng *et al.*, 2 11). Previous studies did reveal positive associations between visual skills and Chinese character recognition (Chung *et al.*, 2 8; Ho *et al.*, 2 4; Huang & Hanley, 1995; Luo *et al.*, 2 13; McBride-Chang & Chang, 1995; Meng *et al.*, 2 2; Meng *et al.*, 2 11; Siok & Fletcher, 2 1). Given the relatively important role of visual processing in Chinese reading development, the prerl3otng

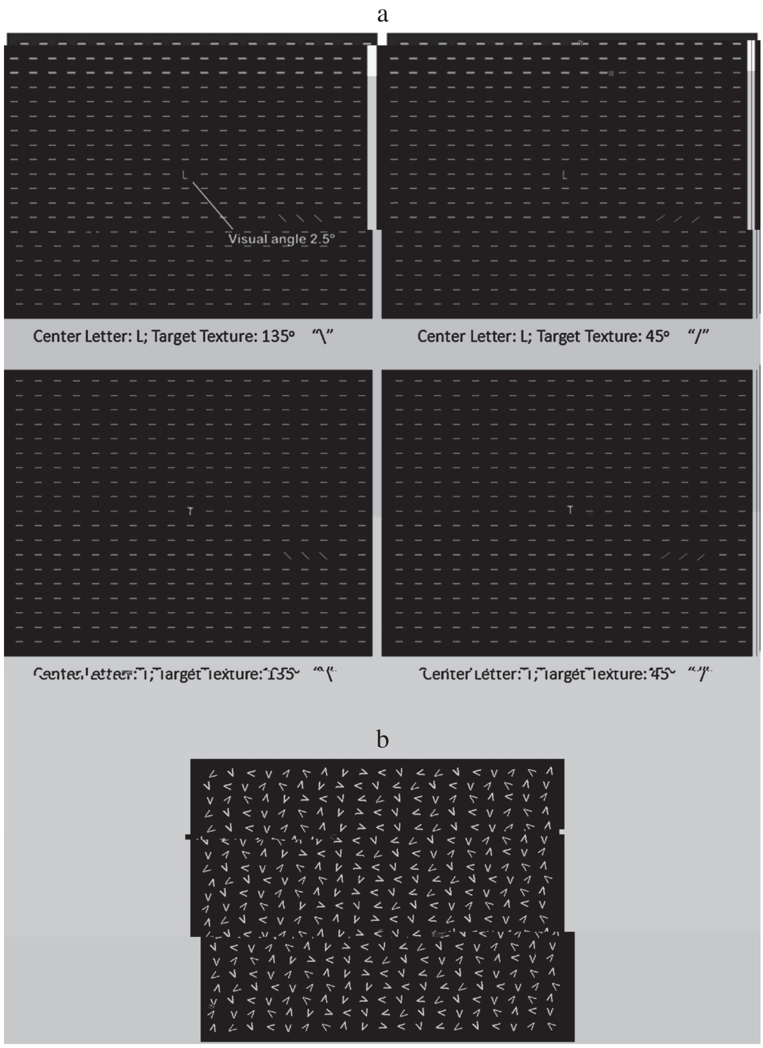

Figure 1. Experimental stimuli displays. [a] TDT stimuli frame and [b] mask frame.

METHODS

Participants

In this study, 38 Chinese-speaking children, 19 with dyslexia and 19 typical readers, in grades four, five and six, were selected according to the procedures described in the following text. None of the participants had a history of neurological disease or psychiatric disorders. In particular, the DSM-IV ADHD Scale (American Psychiatric Association, 1994) was used to exclude children with ADHD. All of the participants were right-handed and had normal or corrected-to-normal vision. Informed consent was obtained from each participant and his or her parents. This study was approved by the Ethics Committee of the Department of Psychology, Peking University.

Within each group, 1 were assigned to Experiment 1 and nine to Experiment 2. Participant screening was based on a Chinese written vocabulary test and reading fluency test (see in the following text and in Table 1).

Pretests

The Standardized Chinese Character Recognition Test (Wang & Tao, 1996) involved 21 characters, divided into 1 groups on the basis of reading difficulty level. Participants were asked to write down a compound word on the basis of a constituent morpheme provided on the sheet. Performance was measured by the total number of correct characters (morphemes) that the participants could utilize in word compositions. Participants had to know morpheme combination rules to form a compound word. The scores from this test formed the index of the participants' Chinese character recognition performance.

The Reading Fluency Test was composed of 95 sentences. Each sentence was paired with five multiple-choice pictures. Participants were asked to read each sentence and select, from five pictures, the one that best illustrated the meaning of the sentence. Children were encouraged to complete as many paragraphs as possible within a 1 -min period. The total number of sentences that the participants could understand determined the performance score. This task required rapid retrieval and retention of lexical information and construction of sentential representation.

Additionally, *Raven's Standard Progressive Matrices* were used to measure the children's nonverbal IQ. Scoring procedures were based on the Chinese norm (Zhang & Wang, 1985).

Children were placed in the group of dyslexia if their scores on the character recognition test were at least 1.5 grades below the norm and if reading fluency test scores were lower than the mean scores of their grades. Additionally, they had typically developed IQ. The chronological age-matched and grade-matched control children were selected from among their peers. Similar procedures for recruiting children with dyslexia or with reading impairment were implemented by previous studies (Meng, Tian, Jian, & Zhou, 2 7; Shu, Chang, Wu, & Liu, 2 6; Siok, Perfetti, Jin, & Tan, 2 4; Siok *et al.*, 2 8).

Materials

The stimuli in the current study in the texture discrimination task (Karni & Sagi, 1991) were white on a uniform black background and appeared on a 17-in. coloured monitor at a 57 cm viewing distance (Figure 1). The resolution of the monitor was set at 1 24 × 768 pixels, and the frame rate was 85 Hz.

The stimulus was a texture display made of 19 × 19 high-contrast horizontal line segments, covering an area with a 17.53° × 13.32° visual angle. The lines were .44° × . 8° and spaced .55 d spa° apart. The targets consisted of three adjacent diagonal bars (135°, '\' or 45°, '/'; Figure 1), which were presented in the lower-left visual quadrant (the fourth quadrant), at 2.5° of the visual angle from fixation. A rotated letter 'T' or 'L' (tilted 2.5°–5°) appeared as a fixation in the centre of the whole screen. A mask was made of 19 × 19 randomly oriented V-shaped patterns, and the display size was the same as the stimulus display.

Table 1. Characteristics of the participants, with standard deviation in parentheses

	Two groups of participants				Subgroup of Experiment 1				Subgroup of Experiment 2			
	Dyslexia group (n = 19, 11 men)	Control group (n = 19, seven men)	F	P	Dyslexia group (n = 1 , eight men)	Control group (n = 1 , five men)	F	P	Dyslexia group (n = 9, three men)	Control group (n = 9, two men)	F	P
Age	116.74 (1 .99)	116.91 (11.6)	. 6	> .1	117.84 (9.12)	117.6 (12.61)	. 1	> .1	115.64 (7.51)	116.21 (4.44)	. 4	> .1
Raven	7 . (18.93)	8 .52 (14.33)	3.73	> .1	67 (22.14)	78 (17.51)	1.52	> .1	73.33 (15.21)	83.33 (1 .)	2.72	> .1
Reading fluency	32.21 (7. 9)	43.47 (7.14)	24. 6	< . 1	34.3 (6.83)	46.6 (8.12)	13.42	< . 1	3 .11 (7. 8)	4 .33 (4.12)	14. 1	< . 1
Chinese character recognition	1455.33 (47 .31)	2393.82 (665.71)	25.13	< . 1	1472.92 (43 .42)	2846.74 (5 1.61)	26.39	< . 1	11 2.41 (151.85)	1888.32 (412.74)	28.74	< . 1

Age is depicted by mean months for the dyslexic and control groups. The Raven scores are mean percentiles for the dyslexic and control groups. For reading fluency, the numbers represent means of items that the dyslexic and control groups answered correctly. For Chinese character recognition, the numbers are the numbers of characters that children could use correctly in word composition.

Procedures

The procedure of each trial is as follows. First, a white cross was presented at the centre of the black background screen for 25 ms, followed by a 3 ms blank screen, and then the stimuli were displayed for 12 ms. After an interval of stimulus-to-mask onset asynchrony (SOA, which may vary according to experimental design), the masking was shown for 1 ms, and then the participants judged the central letter and target texture. That is, the participants first determined whether the central letter was T or L (to determine whether or not the participants were able to see the centre) and then judged the orientation of target texture (45° '/' or 135° '\'; Figure 1). The response was deemed correct when judgments on both the letter and the target texture were correct. There was no feedback, and the reaction time was not limited.

EXPERIMENT 1

To the best of our knowledge, there has been no systematic study on the perceptual learning of developmental dyslexia in the texture discrimination task; hence, there are no agreed-upon conclusions regarding whether or not adults and children use the same initial threshold SOA in TDT. The first experiment set the initial value of threshold SOA, the same as in the classic TDT studies at 3 ms (Karni & Sagi, 1991; Schwartz *et al.*, 2 2; Yotsumoto *et al.*, 2 8).

Before the experiment, all participants went through eight practice sessions. The SOA of practice sessions started from 1 ms, so that the participants could have enough time to see the stimuli clearly and learn how to respond.

In the formal experiment, participants were administered five sessions of training over five successive days. Each session included five blocks with 4 trials each. After each block, participants took a short break. If the response accuracy was beyond 8 % in a block, the SOA of the next block was reduced by 23 ms; otherwise, the SOA was increased by 23 ms in the next block.

Results

During the training sessions, all of the participants evidenced stable and high-level accuracy on the central letter (T/L) discrimination task (group of dyslexia, 91.83%; control group, 92.88%), suggesting that the participants viewed the fixation well during the experiment.

The threshold SOAs for the two groups of children in five sessions were averaged separately. Learning curves depicted the learning progress of the two groups of children (Figure 2). The curves showed that threshold SOA in the control group decreased from the initial 3 to 55 ms at the final session. In contrast, the mean threshold SOA in the group of dyslexia was 293 ms at the final session. The mean threshold SOA of the two groups in the five sessions was submitted to a mixed-design ANOVA with group as a between-subjects factor and learning sessions as a within-subjects factor. The main effect of group was significant [$F(1, 18) = 32.42$, $p <$. 1], indicating that the group of dyslexia ($m = 328$ ms) had significantly higher threshold SOA than the control group ($M = 154$ ms). The main effect of training sessions was also significant [$F(4, 72) = 28.58$, $p <$. 1]. The interaction between group of

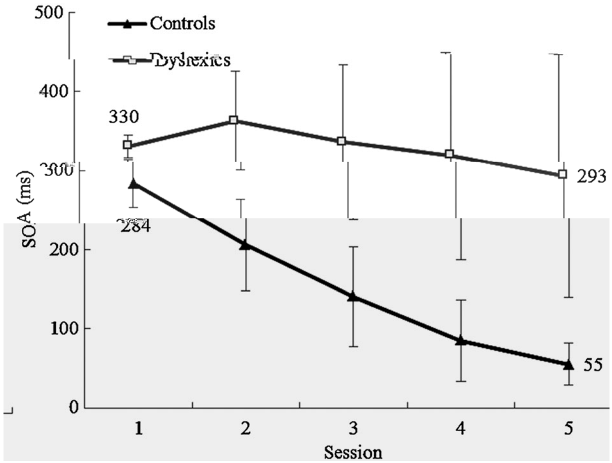

Figure 2. Learning curves for two groups of children at initial SOA of 3   ms in Experiment 1. The error bars represent standard deviation.

participants and training session was also significant [$F(4, 72) = 14.33$, $p < .\ \ 1$]. Further intra-group pairwise comparisons observed significant learning effects in the first four sessions of training (ps $< .\ \ 1$) for the control group, whereas the comparison between the fourth and the fifth sessions did not reach significance ($p > .1$). In contrast, the pairwise comparisons of threshold SOA within the group of dyslexia did not obtain any significant effect (ps $> .1$, Bonferroni adjustments for multiple comparisons).

It is clear that the control group benefited from repetitive practice, as shown by the continually shortened SOAs. Contrary to the control group, children with dyslexia had difficulty in reaching 8 % response accuracy at the initial 3   ms threshold SOA. Hence, their threshold SOA increased at first and then decreased very slowly. They did not attain significant perceptual learning in five sessions of training.

EXPERIMENT 2

The results of Experiment 1 seemed to suggest that children with dyslexia have deficits in perceptual learning. But do children with dyslexia really lack abilities in perceptual learning? Careful observation of the perceptual learning curve of the group of dyslexia revealed that the SOA increased in the first session and then decreased gradually. These data suggest that the initial 3   ms SOA may not be optimal for the children with dyslexia; therefore, they found the task too difficult to learn. If a starting SOA suitable for dyslexic people is set, children with dyslexia might also attain perceptual learning level similar to the control children. The purpose of Experiment 2 was to investigate whether children with dyslexia can achieve perceptual learning with adaptive initial SOAs of each individual.

Procedures

In order to determine the initial SOA value for each participant, a probe/detecting experiment composed of 4 trials was designed; the starting value of SOA was set at 6 ms. If the response for one trial was correct, then SOA of the next trial was decreased by 58 ms; otherwise, it was increased by 58 ms. For each participant, the average SOA of the last 2 trials was set as his or her initial threshold SOA.

Then, each participant underwent five sessions of training on five consecutive days, with one session per day. Each session included five blocks with 4 trials each. In each block, there were five kinds of SOA (initial threshold SOA, initial threshold SOA ± 58 ms, initial threshold SOA ± 116 ms), which were repeated eight times. A Weibull function was fitted to the percent of correct responses for each session. The threshold SOA of each session was defined as the SOA corresponding to 8 % correct responses.

Results

During the training sessions, accuracy on the central letter discrimination task (T/L) was stable and at a high level (group of dyslexia, 88.13%; control group, 93.53%) in all subjects, suggesting that the participants viewed the fixation well during the experiment.

An ANOVA on 2 (groups) × 5 (training sessions) showed that SOAs in training differed significantly across the two groups of children (Figure 3). The main effect of group was significant [$F(1, 16) = 4\ .22$, $p < \ .\ \ 1$], suggesting that the group of dyslexia (M = 627 ms) had a significantly higher threshold SOA than the control children (M = 169 ms). Further pairwise comparisons showed that the threshold SOA in the first session of group with dyslexia (M = 783 ms, SD = 168) was significantly higher than that of the control group [M = 317 ms, SD = 135; $F(1, 16) = 42.2$, $p < \ .\ \ 1$]. After long-term training, the threshold SOA in the last session of group with dyslexia (M = 46 ms, SD = 251) was still significantly higher than that of the control group [M = 8 ms, SD = 35; $F(1, 16) = 2\ .28$, $p < \ .\ \ 1$].

The main effect of training sessions was also significant [$F(4, 64) = 35.538$, $p < \ .\ \ 1$], but the interaction between group and training session did not reach significance [$F(4, 64) = 1.558$, $p = \ .2$], showing that the two groups of children

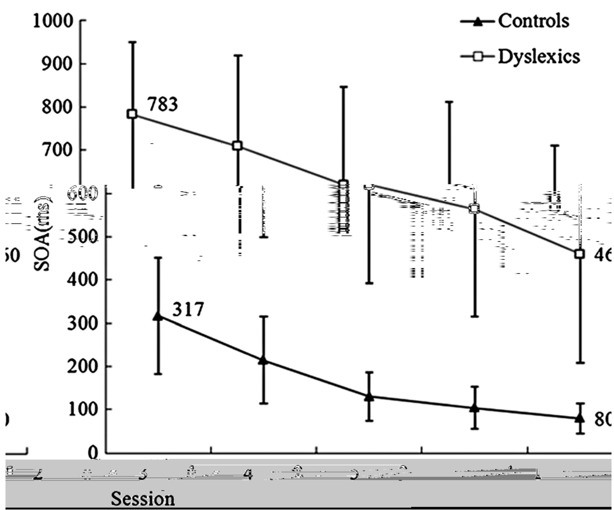

Figure 3. The perceptual learning curves for two groups of children at adaptive initial stimulus-to-mask onset asynchrony (SOA) in Experiment 2. The error bars represent standard deviation.

had similar learning patterns across five sessions of perceptual learning. Further intra-group *post hoc* analysis, by comparing the SOA of the first session with the SOA of the last session, showed that both groups of children achieved significant improvement ($p <$. 1, Bonferroni adjustments for multiple comparisons). These data suggest that, when started with an initial SOA in line with their processing abilities, children with dyslexia can also attain perceptual learning during day-to-day practice. Compared with normal readers, children with dyslexia need longer threshold SOA across all of the training sessions, indicating that children with dyslexia might have deficits in visual perceptual processing and learning.

In order to evaluate the perceptual learning rates of the two groups of children, the comparative learning rate (CR) was calculated by subtracting the last SOA (B) from the first SOA (A) and dividing it by the first SOA (A); therefore, CR is represented as CR = (A − B) / A. The results showed that CR of the dyslexia group (M = . 41, SD = .17) was significantly lower than that of the control group [M = .74, SD = .94; F(1, 16) = 1 .773, $p <$. 1].

We then investigated whether the threshold SOA in TDT correlated significantly with the children's performance in Chinese character recognition. Significant negative correlations on performance of Chinese character recognition were revealed for the initial and the final threshold SOA (r = − .723 and r = − .746, respectively, ps < . 25, Bonferroni correction for multiple comparisons). Threshold SOA in other sessions showed similar correlations. Moreover, the perceptual learning rate (CR, mentioned previously) was positively associated with Chinese character recognition (r = .53, $p <$. 5). Figure 4a and b are Scatter-plots depicting the relationships between threshold SOA (e.g. SOA1) and CR (perceptual learning rate) with Chinese character recognition in Experiment 2.

DISCUSSION

The focus of the present study was to examine the characteristics and time course of perceptual learning in TDT by Chinese children suffering from developmental dyslexia. Experiment 1 showed that, when accompanied with a fixed starting SOA

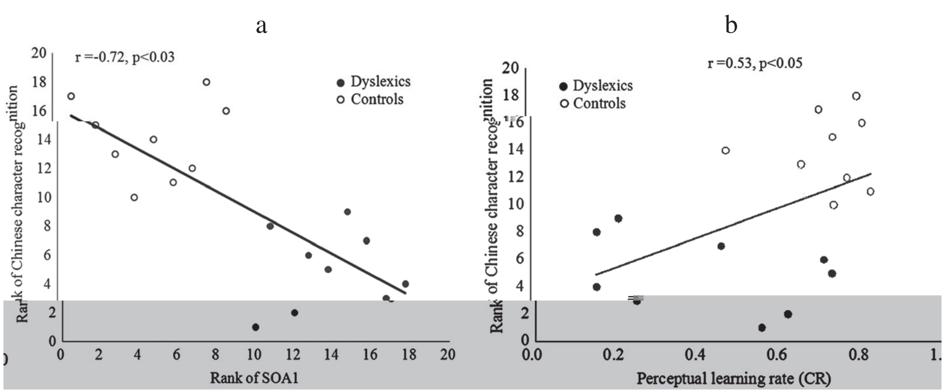

Figure 4. Correlations between perceptual learning and Chinese character recognition. [a] Scatter-plot of Chinese character recognition and stimulus-to-mask onset asynchrony 1 (SOA1) in Experiment 2 and [b] Scatter-plot of Chinese character recognition and perceptual learning rate in Experiment 2.

(3   ms), Chinese children with dyslexia did not achieve as high of a perceptual learning level as those in the control group. Further investigation with an adaptive threshold SOA for each individual in Experiment 2 revealed that the group of dyslexia could achieve a certain degree of improvement in perceptual learning. However, as predicted, their threshold SOAs throughout all of the learning sessions were much higher than those of the control children, and their perceptual learning rates were lower than those of the controls. Additionally, over all of the participants in the experiments, the threshold SOA in TDT was negatively correlated with performance in Chinese character recognition. These results demonstrate that Chinese school children with developmental dyslexia have deficits in visual perceptual processing and learning.

The finding that children with dyslexia have deficits in very basic visual perceptual learning supported our prediction that individuals with dyslexia have basic visual perceptual learning difficulty, apart from previously reported difficulties in procedural learning (Nicolson & Fawcett, 199 ; Nicolson & Fawcett, 2   7), in implicit learning (Howard *et al.*, 2   6; Vicari *et al.*, 2   5) and in paired-association learning (Li *et al.*, 2   9). This result showed that learning difficulty in children with dyslexia was not confined to abstract rule-based knowledge learning (Folia *et al.*, 2   8) and association learning (Li *et al.*, 2   9) but also occurred in learning to discriminate very basic visual features; this extended the understanding of learning deficits in individuals with dyslexia to basic perceptual learning. Further experimentation needs to clarify whether it is a separate type of learning difficulty or if it is a deficit associated with implicit motor sequence learning rooted in a common mechanism (Conso

Consistently, research on the neural basis of visual perceptual learning has supported the aforementioned observation. Gibson (1963, p. 29) defined perceptual learning as '[any] relatively permanent and consistent change in the perception of a stimulus array, following practice or experience with this array'. The mainstream view suggests that cortical changes occurring in the early visual cortex, such as the primary visual cortex, (V1) underlie behavioural changes in visual perceptual learning (Karni & Sagi, 1991; Pourtois, Rauss, Vuilleumier, & Schwartz, 2 8; Schoups, Vogels, Qian, & Orban, 2 1; Schwartz *et al*., 2 2; Walker, Stickgold, Jolesz, & Yoo, 2 5; Yotsumoto *et al*., 2 8). However, recent psychophysical studies have also suggested that perceptual improvements might be related to changes outside of the visual cortices (Zhang & Li, 2 1 ; Zhang, Xiao, *et al*., 2 1 ; Zhang, Zhang, *et al*., 2 1): Perceptual learning could be a result of refinement of processing in the decision-making and attentional systems. This idea is supported by neuroimaging studies showing that only the activity pattern in the anterior cingulate cortex tracks changes during perceptual learning (Kahnt, Grueschow, Speck, & Haynes, 2 11).

For developmental dyslexia, it has been proposed that defects may exist anywhere along the dorsal visual stream (Vidyasagar & Pammer, 2 9), and the deficits at different levels of the magnocellular pathway are associated with impaired performance in different aspects of reading (Kevan & Pammer, 2 8). The higher threshold SOAs for children with reading impairment observed in the present study might, in fact, be indicative of deficiency in higher-level visual cortex or in the neural network responsible for top-down control, including attention and decision-making. Although such deficiency can be compensated, to some extent, by extensive training, the results of Experiment 2 suggested that deficits in basic perceptual processing may not be completely reversed.

Of particular importance are the implications of the present findings for educational curriculum design and reading remediation for developmental dyslexia. A comparison of the results from Experiment 1 (fixed SOA) and Experiment 2 (adaptive SOA) clearly shows that it is difficult to produce a learning effect if the training or learning programme does not fit the learners' current level of processing. The 'resister', who cannot benefit from traditional intervention reported in previous literature (Fuchs & Fuchs, 2 6; Troia & Whitney, 2 3) may benefit from a training programme and a procedure that individuate and adapt in terms of temporal and/or finely grained processing (Merzenich *et al*., 1996; Temple *et al*., 2 3). Moreover, the present findings also suggested an important role of perceptual learning in early diagnosis and training for developmental dyslexia. Recently, studies have indeed shown that perceptual manipulation and training could improve reading performance in dyslexia (Zorzi *et al*., 2 12) and cognitive function in middle-aged and older adults (Wolinsky *et al*., 2 13).

Additionally, the present study observed large heterogeneity within the group of dyslexia in perceptual learning. In order to examine whether long-term training can ameliorate the deficiency of children with dyslexia in perceptual learning, two cases with dyslexia (starting with the SOA at 1 ms) were followed-up after 17 and 14 sessions of training (one session each day), respectively, until their threshold SOA did not reduce obviously for three consecutive days. Case 1 (final threshold SOA was 129 ms) achieved a great deal of perceptual learning during 17 consecutive sessions, although the subjects did not achieve the same threshold SOA as the mean threshold SOA of the control children (8 ms ± 35) on the fifth training day in Experiment 2. However, Case 2 (final threshold SOA of 596 ms on the 14th day of training) learned very slowly and did not reach the initial threshold SOA (3 ms) of the control children in

Experiment 2. These findings revealed that children with dyslexia can benefit from long-term repetitive training, even though they may not catch up with controls. Meanwhile, the dissociation between the courses of perceptual learning in the aforementioned two cases, and the much-wider standard deviation in the group of dyslexia than in the control group (Figure 3), implies inter-group variability among dyslexia-affected children.

Taken together, the present study observed a link between visual perceptual learning and Chinese reading and suggested that deficits in visual perceptual processing and learning might, in part, underpin difficulty in reading Chinese. However, the following additional questions are raised from this preliminary observation. First, because we know that visual perceptual learning involves various visual features, the generalization of the present findings needs to be verified with more participants and varieties of visual perceptual learning tasks (Lin, Wang, & Meng, 2 13). Second, the nature, correlation or causality, of the relationship between visual perceptual learning and Chinese reading has also yet to be clarified with longitudinal design and training study. Third, the underlying mechanisms between visual perceptual learning and reading also need to be explored in depth.

CONFLICT OF INTEREST

None.

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Fahle, M. (1994). Human pattern recognition: Parallel processing and perceptual learning. *Perception*, *23*, 411–427.

Folia, V., Uddén, J., Forkstam, C., Ingvar, M., Hagoort, P., & Petersson, K. M. (2 8). Implicit learning and dyslexia. *Annals of the New York Academy of Science*, *1145*, 132–15 .

Frith, C. (1996). A biological marker for dyslexia. *Nature*, *382*, 19–2 .

Fuchs, D., & Fuchs, L. S. (2 6). Introduction to response to intervention: What, why, and how valid is it? *Reading Research Quarterly*, *41*(1), 93–99.

Gabay, Y., Schiff, R., & Vakil, E. (2 12a). Dissociation between online and offline learning in developmental dyslexia. *Journal of Clinical and Experimental Neuropsychology*, *34*, 279–288.

Gabay, Y., Schiff, R., & Vakil, E. (2 12b). Dissociation between the procedural learning of letter names and motor sequences in developmental dyslexia. *Neuropsychologia*, *50*, 2435–2441.

Gibson, E. J. (1963). Perceptual learning. *Annual Review of Psychology*, *14*, 29–56.

Gibson, E. J. (1969). Principles of perceptual learning. New York: Appleton–Century–Crofts.

Goswami, U., Wang, H.-L. S., Cruz, A., Fosker, T., Mead, N., & Huss, M. (2 1). Language-universal sensory deficits in developmental dyslexia: English, Spanish, and Chinese. *Journal of Cognitive Neuroscience*, *23*, 325–337.

Ho, C., Chan, D., Lee, S., Tsang, S., & Luan, V. (2 4). Cognitive profiling and preliminary subtyping in Chinese developmental dyslexia. *Cognition*, *91*, 43–75.

Howard, J. H., Howard, D. V., Dennis, N. A., Yankovich, H., & Vaidya, C. J. (2 4). Implicit spatial contextual learning in healthy aging. *Neuropsychology*, *18*(1), 124–134.

Howard, J. H., Howard, D. V., Japikse, K. C., & Edend, G. F. (2 6). Dyslexics are impaired on implicit higher-order sequence learning, but not on implicit spatial context learning. *Neuropsychologia*, *44*, 1131–1144.

Huang, H. S., & Hanley, J. R. (1995). Phonological awareness and visual skills in learning to read Chinese and English. *Cognition*, *54*, 73–98.

Hupe, J. M., James, A. C., Payne, B. R., Lomber, S. G., Girard, P., & Bullier, J. (1998). Cortical feedback improves discrimination between figure and background by V1, V2 and V3 neurons. *Nature*, *394* (6695), 784–787.

Kahnt, T., Grueschow, M., Speck, O., & Haynes, J. D. (2 11). Perceptual learning and decision-making in human medial frontal cortex. *Neuron*, *70*(3), 549–559.

Karni, A., & Sagi, D. (1991). Where practice makes perfect in texture discrimination: Evidence for primary visual cortex plasticity. *Proceedings of the National Academy of Sciences of the United States of America*, *88*, 4966–497 .

Kavšek, M. (2 4). Predicting later IQ from infant visual habituation and dishabituation: A meta-analysis. *Journal of Applied Developmental Psychology*, *25*, 369–393.

Kelly, S. W., Griffiths, S., & Frith, U. (2 2). Evidence for implicit sequence learning in dyslexia. *Dyslexia*, *8*(1), 43–52.

Kevan, A., & Pammer, K. (2 8). Visual processing deficits in preliterate children at familial risk for dyslexia. *Vision Research*, *48*, 2835–2839.

Legge, G. E., Cheung, S.-H., Yu, D., Chung, S. T. L., Lee, H.-W., & Owens, D. P. (2 7). The case for the visual span as a sensory bottleneck in reading. *Journal of Vision*, 7(2), 9, 1–15.

Li, X. H., Jing, J., Zou, X. B., Huang, X., Jin, Y., Wang, Q. X., … Yang, S. Y. (2 9). Picture perception in Chinese dyslexic children: An eye-movement study. *Chinese Medical Journal*, *122*, 267–271.

Lin, O. (2 13). Texture discrimination training and reading development in Chinese-speaking school children. Peking University thesis, Beijing, June.

Lin, O., Wang, Z. K., & Meng, X. (2 13). Visual perceptual learning in Chinese-speaking developmental dyslexia revealed by visual search. *Acta Psychologica Sinica*, *45*, 762–772.

Luo, Y. C., Chen, X., Deacon, S. H., Zhang, J., & Yin, L. (2 13). The role of visual processing in learning to read Chinese characters. *Scientific Studies of Reading*, *17*, 22–4 .

Mayringer, H., & Wimmer, H. (2   ). Pseudoname learning by German-speaking children with dyslexia: Evidence for a phonological learning deficit. *Journal of Experimental Child Psychology*, *75*, 116–133.

McBride-Chang, C., & Chang, L. (1995). Memory, print exposure, and metacognition: Components of reading in Chinese children. *International Journal of Psychology*, *30*, 6 7–616.

Mehta, A. D., Ulbert, I., & Schroeder, C. E. (2). Intermodal selective attention in monkeys II: Physiological mechanisms of modulation. *Cerebral Cortex*, *10*, 359–37 .

Meng, X., Cheng-Lai, A., Zeng, B., Stein, J. F., & Zhou, X. (2 11). Dynamic visual perception and reading development in Chinese school children. *Annals of Dyslexia*, *61*, 161–176.

Meng, X., Tian, X., Jian, J., & Zhou, X. (2 7). Orthographic and phonological processing in Chinese dyslexic children: An ERP study on sentence reading. *Brain Research*, *1179*, 119–13 .

Meng, X., Zhou, X., Zeng, B., Kong, R., & Zhuang, J. (2 2). Visual perceptual skills and reading abilities in Chinese-speaking children (in Chinese). *Acta Psychologica Sinica*, *34*(1), 16–22.

Menghini, D., Hagberg, G. E., Caltagirone, C., Petrosini, L., & Vicari, S. (2 6). Implicit learning deficits in dyslexic adults: An fMRI study. *NeuroImage*, *33*, 1218–1226.

Merzenich, M. M., Jenkins, W. M., Johnston, P., Schreiner, C., Miller, S., & Tallal, P. (1996). Temporal processing deficits of language-learning impaired children ameliorated by training. *Science*, *271*, 77–81.

Messbauer, V., & de Jong, P. F. (2 3). Word, nonword, and visual paired associate learning in Dutch dyslexic children. *Journal of Experimental Child Psychology*, *84*, 77–96.

Nicolson, R. I., & Fawcett, A. J. (199). Automaticity: A new framework for dyslexia research. *Cognition*, *35*, 159–182.

Nicolson, R. I., & Fawcett, A. J. (2 7). Procedural learning difficulties: Reuniting the developmental disorders? *Trends in Neurosciences*, *30*(4), 135–141.

Nicolson, R. I., Fawcett, A. J., Brooks, R. L., & Needle, J. (2 1). Procedural learning and dyslexia. *Dyslexia*, *16*(3), 194–212.

Nicolson, R. I., Fawcett, A. J., & Dean, P. (2 1). Developmental dyslexia: The cerebellar deficit hypothesis. *Trends in Neurosciences*, *24*(9), 5 8–511.

Oganian, Y., & Ahissar, M. (2 12). Poor anchoring limits dyslexics' perceptual, memory, and reading skills. *Neuropsychologia*, *50*, 1895–19 5.

Pothos, E. M., & Kirk, J. (2 4). Investigating learning deficits associated with dyslexia. *Dyslexia*, *10*, 61–76.

Pourtois, G., Rauss, K. S., Vuilleumier, P., & Schwartz, S. (2 8). Effects of perceptual learning on primary visual cortex activity in humans. *Vision Research*, *48*, 55–62.

Ramus, F., Rosen, S., Dakin, S. C., Day, B. L., Castellote, J. M., White, S., & Frith, U. (2 3). Theories of developmental dyslexia: Insights from a multiple case study of dyslexic adults. *Brain*, *126*, 841–865.

Rose, S. A., Feldman, J. F., Jankoeski, J. J., & Rossem, R. V. (2 12). Information processing from infancy to 11 years: Continuities and prediction of IQ. *Intelligence*, *40*, 445–457.

Rüsseler, J., Gerth, I., & Münte, T. F. (2 6). Implicit learning is intact in adult developmental dyslexic readers: Evidence from the serial reaction time task and artificial grammar learning. *Journal of Clinical and Experimental Neuropsy-chology*, *28*, 8 8–827.

Sagi, D., & Julesz, B. (1985). 'Where' and 'what' in vision. *Science*, *228*, 1217–1219.

Schoups, A. A., Vogels, R., & Orban, G. A. (1995). Human perceptual learning in identifying the oblique orientation: Retinotopy, orientation specificity and monocularity. *The Journal of physiology*, *483*(Pt 3), 797–81 .

Schoups, A., Vogels, R., Qian, N., & Orban, G. (2 1). Practicing orientation identification improves orientation coding in V1 neurons. *Nature*, *412*(6846), 549–553.

Schwartz, S., Maquet, P., & Frith, C. (2 2). Neural correlates of perceptual learning: A functional MRI study of visual texture discrimination. *Proceedings of the National Academy of Sciences*, *99*, 17137–17142.

Schwartz, S., Vuilleumier, P., Hutton, C., Maravita, A., Dolan, R. J., & Driver, J. (2 4). Attentional load and sensory competition in human vision: Modulation of fMRI responses by load at fixation during task irrelevant stimulation in the peripheral visual field. *Cerebral Cortex*, *15*(6), 77 –786.

Shu, H., Chang, C. W., Wu, S., & Liu, H. (2 6). Understanding Chinese developmental dyslexia: Morphological awareness as a core cognitive construct. *Journal of Educational Psychology*, *98*(1), 122–133.

Siok, W. T., & Fletcher, P. (2 1). The role of phonological awareness and visual-orthographic skills in Chinese reading acquisition. *Developmental Psychology*, *37*, 886–899.

Siok, W. T., Niu, Z. D., Jin, Z., Perfetti, C. A., & Tan, L. H. (2 8). A structural-functional basis for dyslexia in the cortex of Chinese readers. *Proceedings of the National Academy of Sciences*, *105*, 5561–5566.

Siok, W. T., Perfetti, C. A., Jin, Z., & Tan, L. H. (2 4). Biological abnormality of impaired reading is constrained by culture. *Nature*, *43*, 71–76.

Song, Y., Peng, D. L., Lu, C. M., Liu, C. H., Li, X. L., Liu, P. P., … Ding, Y. L. (2 7). An event-related potential study on perceptual learning in grating orientation discrimination. *Neuroreport*, *18*(9), 945–948.

Stefanics, G., Fosker, T., Huss, M., Mead, N., Szucs, D., & Goswami, U. (2 11). Auditory sensory deficits in developmental dyslexia: A longitudinal ERP study. *NeuroImage*, *57*, 723–732.

Stein, J. F. (1994). A visual defect in dyslexics? In A. Fawcett & R. Nicolson (Eds.), Dyslexia in children: Multidisciplinary perspectives (pp. 137–156). Hemel Hempstead: Harvester Wheatsheaf.

Stein, J. F., & Walsh, V. (1997). To see but not to read: The magnocellular theory of dyslexia. *Trend in Neurosciences*, *20*, 147–152.

Stoodley, C. J., Harrison, E. P. D., & Stein, J. F. (2 6). Implicit motor learning deficits in dyslexic adults. *Neuropsychologia*, *44*, 795–798.

Stoodley, C. J., Ray, N. J., Jack, A., & Stein, J. F. (2 8). Implicit learning in control, dyslexic, and garden-variety poor readers. *Annals of the New York Academy of Science*, *1145*, 173–183.

Studdert-Kennedy, M. (1997). Deficits in phoneme awareness do not arise from failures in rapid auditory processing. Paper presented at the international symposium on basic neural mechanisms in cognition and language with special reference to phonological problems in dyslexia, Stockholm, Sweden.

Studdert-Kennedy, M., & Mody, M. (1995). Auditory temporal perception deficits in the reading impaired: A critical review of the evidence. *Psychonomic Bulletin & Review*, 2, 5 8–514.

Tallal, P. (198). Auditory temporal perception, phonics, and reading disabilities in children. *Brain and Language*, *9*, 182–198.

Tallal, P., Merzenich, M. M., Miller, S., & Jenkins, W. (1998). Language learning impairments: Integrating basic science, technology, and remediation. *Experimental Brain Research*, *123*, 21 –219.

Temple, E., Deutsch, G. K., Poldrack, R. A., Miller, S. L., Tallal, P., Merzenich, M. M., & Gabrieli, J. D. E. (2 3). Neural deficits in children with dyslexia ameliorated by behavioral remediation: Evidence from functional MRI. *Proceedings of the National Academy of Sciences*, *100*, 286 –2865.

Troia, G. A., & Whitney, S. D. (2 3). A close look at the efficacy of Fast ForWord Language for children with academic weaknesses. *Contemporary Educational Psychology*, *28*, 465–494.

Vellutino, F. R., Steger, J. A., DeSetto, L., & Phillips, F. (1975). Immediate and delayed recognition of visual stimuli in poor and normal readers. *Journal of Experimental Child Psychology*, *19*, 223–232.

Vicari, S., Finzi, A., Menghini, D., Marotta, L., Baldi, S., & Petrosini, L. (2 5). Do children with developmental dyslexia have an implicit learning deficit? *Journal of Neurology Psychiatry*, *76*, 1392–1397.

Vicari, S., Marotta, L., Menghini, D., Molinari, M., & Petrosini, L. (2 3). Implicit learning deficit in children with developmental dyslexia. *Neuropsychologia*, *41*, 1 8–114.

Vidyasagar, T. R., & Pammer, K. (2 9). Dyslexia: A deficit in visual-spatial attention, not in phonological processing. *Trends in Cognitive Sciences*, *14*, 57–63.

Vogels, R., & Orban, G. A. (1985). The effect of practice on the oblique effect in line orientation judgments. *Vision Research*, *25*, 1679–1687.

Wagner, R. K., & Torgesen, J. K. (1987). The nature of phonological processing and its causal role in the acquisition of reading skills. *Psychological Bulletin*, *101*, 192–212.

Walker, K., Hall, S., Klein, R., & Phillips, D. (2 6). Development of perceptual correlates of reading performance. *Brain Research*, *1124*, 126–141.

Walker, M. P., Stickgold, R., Jolesz, F. A., & Yoo, S. S. (2 5). The functional anatomy of sleep-dependent visual skill learning. *Cerebral Cortex*, *15*, 1666–1675.

Wang, R., Cong, L. J., & Yu, C. (2 13). The classical TDT perceptual learning is mostly temporal learning. *Journal of Vision*, *13*(5): 9, 1–9.

Wang, X. L., & Tao, B. P. (1996). Chinese character recognition test battery and assessment scale for primary school children. Shanghai: Shanghai Education Press.

Witton, C., Talcott, J. B., Hansen, P. C., Richardson, A. J., Griffiths, T. D., Rees, A., … Green, G. G. R. (1998). Sensitivity to dynamic auditory and visual stimuli predicts nonword reading ability in both dyslexic and normal readers. *Current Biology*, *8*, 791–797.

Wolinsky, F. D., Vander Weg, M. W., Howren, M. B., Jones, M. P., & Dotson, M. M. (2 13). A randomized controlled trial of cognitive training using a visual speed of processing intervention in middle aged and older adults. *PloS ONE*, *8*(5): e61624. DOI: 1 .1371/journal.pone. 61624

Yotsumoto, Y., Watanabe, T., & Sasaki, Y. (2 8). Different dynamics of performance and brain activation in the time course of perceptual learning. *Neuron*, *57*, 827–833.

Yu, D., Cheung, S. H., Legge, G. E., & Chung, S. T. L. (2 1). Reading speed in the peripheral visual field of older adults: Does it benefit from perceptual learning? *Vision Research*, *50*, 86 –869.

Zhang, E., & Li, W. (2 1). Perceptual learning beyond retinotopic reference frame. *Proceedings of the National Academy of Sciences*, *107*, 15969–15974.

Zhang, H. C., & Wang, X. P. (1985). Raven standard progressive matrices: Chinese city revision. Beijing: The National Revision Collaborative Group.

Zhang, T., Xiao, L. Q., Klein, S. A., Levi, D. M., & Yu, C. (2 1). Decoupling location specificity from perceptual learning of orientation discrimination. *Vision Research*, *50*, 368–374.

Zhang, J. Y., Zhang, G. L., Xiao, L. Q., Klein, S. A., Levi, D. M., & Yu, C. (2 1). Rule-based learning explains visual perceptual learning and its specificity and transfer. *The Journal of Neuroscience*, *30*, 12323–12328.

Zhou, X. L., & Marslen-Wilson, W. (1999). Phonology, orthography, and lexical semantic activation in reading Chinese. *Journal of Memory and Language*, *41*, 579–6 6.

Zhou, X. L., & Marslen-Wilson, W. (2). The relative time course of semantic and phonological activation in reading Chinese. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *26*, 1245–1265.

Zorzi, M., Barbiero, C., Facoetti, A., Lonciari, I., Carrozzi, M., Montico, M., … Ziegler, J. C. (2 12). Extra-large letter spacing improves reading in dyslexia. *Proceedings of the National Academy of Sciences*, *109*, 11455–11459.

