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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 300 ms, the threshold SOA, adjusted according to response accuracy for reaching 80% 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. Copyright © 2014 John Wiley & Sons, Ltd.

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, 1990; Nicolson & Fawcett, 2007). 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.*, 2003; 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, 1980; Tallal, Merzenich, Miller, & Jenkins, 1998; Walker, Hall, Klein, & Phillips, 2006; Witton *et al.*, 1998) and visual perceptual processing (Goswami *et al.*, 2010; Stefanics *et al.*, 2011; Stein, 1994; Stein & Walsh, 1997; Vidyasagar & Pammer, 2009).

Another important line of research has addressed the dynamic learning process in individuals with developmental dyslexia. This stream of research has found that people suffering from dyslexia have difficulty with paired-association learning (Li *et al.*, 2009; Mayringer & Wimmer, 2000; Messbauer & de Jong, 2003; Vellutino, Steger, DeSetto, & Phillips, 1975) and procedural learning (Nicolson & Fawcett, 2007; Nicolson, Fawcett, Brooks, & Needle, 2010). Researchers have also found strong evidence of an association of dyslexia with difficulties in implicit learning in motor sequence (Gabay, Schiff, & Vakil, 2012a, 2012b; Howard, Howard, Japikse, & Edend, 2006; Menghini *et al.*, 2006; Stoodley, Harrison, & Stein, 2006; Stoodley, Ray, Jack, & Stein, 2008; Vicari *et al.*, 2003, 2005, except for Rüsseler, Gerth, & Münte, 2006, and Kelly, Griffiths, & Frith, 2002) and in linguistic rules (Gabay *et al.*, 2012b; Boada & Pennington, 2006; Pothos & Kirk, 2004; and Folia *et al.*, 2008, for a review, except for Rüsseler *et al.*, 2006), even in cases when their explicit learning is intact (Vicari *et al.*, 2003, 2005). These implicit sequence learning deficits have been commonly attributed to the failure of automaticity in skill learning, which are associated with selective deficits in the fronto-striatal-cerebellar circuits (Howard *et al.*, 2004; Howard *et al.*, 2006; Nicolson, Fawcett, & Dean, 2001; Stoodley *et al.*, 2008).

Notably, the majority of studies on implicit procedural learning in people with dyslexia, including those cited earlier, have focused on dyslexia in terms of an abstract, rule-based, implicit knowledge based on experiences (Folia *et al.*, 2008). The question thus remains as to whether people with dyslexia have a deficit only in abstract, rule-based, implicit knowledge settings (Banai & Yifat, 2012; Oganian & Ahissar, 2012) or a deficit also in basic perceptual learning of concrete skills. Perceptual learning is evidenced by an improvement of perceptual performance as a function of training (Gibson, 1969). This improvement in performance results from an increase in sensory sensitivity, induced by repetitive exposure to various experiences (Karni & Sagi, 1991). A study by Censor, Sagi and Cohen (2012) examined previous evidence supporting the notion that perceptual and motor procedural learning skills in humans exhibit similar properties. The authors proposed that a common general mechanism for learning in humans may exist across several sensory domains. Given that people with dyslexia have a deficit in implicit motor sequence learning, it is plausible that they may also have a deficit in perceptual learning. In support of this assertion, findings from longitudinal studies have revealed that infants' habituation and dishabituation speeds can, to a degree, predict their later intellectual development and academic achievement (Kavšek, 2004; Rose, Feldman, Jankoeski, & Rossem, 2012). 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.*, 2003), 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.*, 2003) 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, 2000). 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.*, 2009; Meng *et al.*, 2011). Previous studies did reveal positive associations between visual skills and Chinese character recognition (Chung *et al.*, 2008; Ho *et al.*, 2004; Huang & Hanley, 1995; Luo *et al.*, 2013; McBride-Chang & Chang, 1995; Meng *et al.*, 2002; Meng *et al.*, 2011; Siok & Fletcher, 2001). Given the relatively important role of visual processing in Chinese reading development, the present study will specifically investigate to what extent Chinese-speaking children with dyslexia would show deficits in visual perceptual learning and whether these deficits are related to their performance in linguistic tasks.

Perceptual learning has been found in various visual tasks involving basic visual features, such as motion direction (Ball & Sekuler, 1987), spatial phase (Fahle, 1994), hyperacuity (Schoups, Vogels, & Orban, 1995), orientation discrimination (Vogels & Orban, 1985) and texture discrimination (Karni & Sagi, 1991). Among these psychophysical paradigms, the texture discrimination task (TDT) is one of the most intensively studied. In this task, a frame of texture stimuli is presented, followed by a mask frame. Participants are typically asked to search for singleton stimuli in the texture and perform a particular task (e.g. orientation discrimination) towards these imperative stimuli (Figure 1). Recent neuroimaging studies utilizing TDT have shown that changes in the primary visual cortex (V1) might underpin perceptual learning in adults (Karni & Sagi, 1991; Schwartz, Maquet, & Frith, 2002; Yotsumoto, Watanabe, & Sasaki, 2008). On the other hand, top-down influences exerted on V1 from later visual processing stages (Hupe *et al.*, 1998; Mehta, Ulbert, & Schroeder, 2000) or from fronto-parietal attention networks (Schwartz *et al.*, 2004; Song *et al.*, 2007) have also been detected with perceptual learning. In the present study, we applied TDT to Chinese school children with dyslexia and a matched control group.

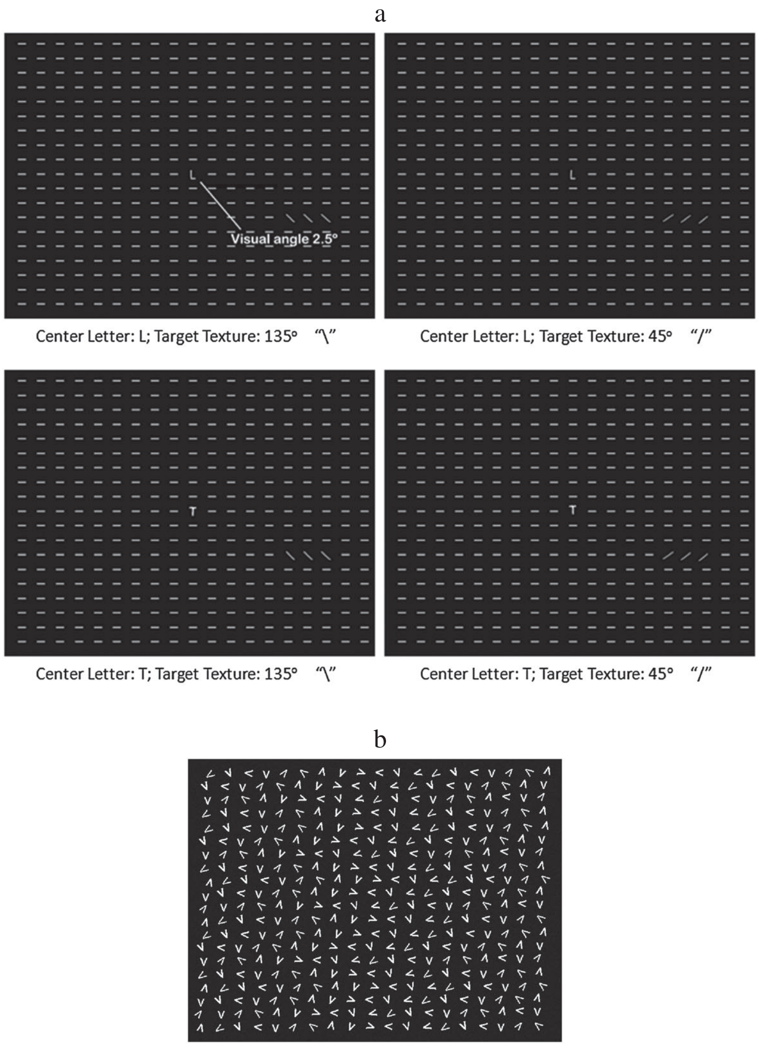

Figure 1. Experimental stimuli displays. [a] TDT stimuli frame and [b] mask frame.

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, 10 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 210 characters, divided into 10 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 10-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, 2007; Shu, Chang, Wu, & Liu, 2006; Siok, Perfetti, Jin, & Tan, 2004; Siok *et al.*, 2008).

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 1024 × 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 0.44° × 0.08° and spaced 0.55 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 ($n = 10$, eight men)	Control group ($n = 10$, five men)	F	P	Dyslexia group ($n = 9$, three men)	Control group ($n = 9$, two men)	F	P
Age	116.74 (10.99)	116.91 (11.60)	0.006	>0.1	117.84 (9.12)	117.60 (12.61)	0.001	>0.1	115.64 (7.51)	116.21 (4.44)	0.04	>0.1
Raven	70.00 (18.93)	80.52 (14.33)	3.73	>0.1	67 (22.14)	78 (17.51)	1.52	>0.1	73.33 (15.21)	83.33 (10.0)	2.72	>0.1
Reading fluency	32.21 (7.09)	43.47 (7.14)	24.06	<0.001	34.3 (6.83)	46.6 (8.12)	13.42	<0.01	30.11 (7.08)	40.33 (4.12)	14.01	<0.001
Chinese character recognition	1455.33 (470.31)	2393.82 (665.71)	25.13	<0.001	1472.92 (430.42)	2846.74 (501.61)	26.39	<0.001	1102.41 (151.85)	1888.32 (412.74)	28.74	<0.001

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 250 ms, followed by a 300 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 100 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 300 ms (Karni & Sagi, 1991; Schwartz *et al*., 2002; Yotsumoto *et al*., 2008).

Before the experiment, all participants went through eight practice sessions. The SOA of practice sessions started from 1000 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 40 trials each. After each block, participants took a short break. If the response accuracy was beyond 80% 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 300 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 [$F(1, 18) = 32.42$, $p < 0.0001$], 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 [$F(4, 72) = 28.58$, $p < 0.0001$]. The interaction between group of

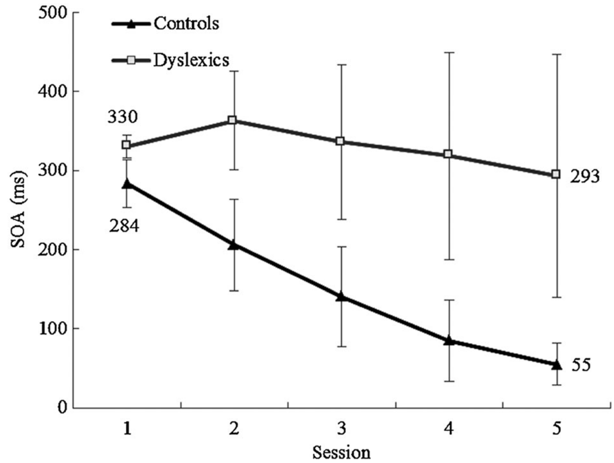

Figure 2. Learning curves for two groups of children at initial SOA of 300 ms in Experiment 1. The error bars represent standard deviation.

participants and training session was also significant [$F(4, 72) = 14.33$, $p < 0.0001$]. Further intra-group pairwise comparisons observed significant learning effects in the first four sessions of training (ps < 0.001) for the control group, whereas the comparison between the fourth and the fifth sessions did not reach significance ($p > 0.1$). In contrast, the pairwise comparisons of threshold SOA within the group of dyslexia did not obtain any significant effect (ps > 0.1, 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 80% response accuracy at the initial 300 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 300 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 40 trials was designed; the starting value of SOA was set at 600 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 20 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 40 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 80% 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 [$F(1, 16) = 40.22$, $p < 0.001$], 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, $SD = 135$; $F(1, 16) = 42.20$, $p < 0.001$]. After long-term training, the threshold SOA in the last session of group with dyslexia ($M = 460$ ms, $SD = 251$) was still significantly higher than that of the control group [$M = 80$ ms, $SD = 35$; $F(1, 16) = 20.28$, $p < 0.001$].

The main effect of training sessions was also significant [$F(4, 64) = 35.538$, $p < 0.001$], but the interaction between group and training session did not reach significance [$F(4, 64) = 1.558$, $p = 0.20$], showing that the two groups of children

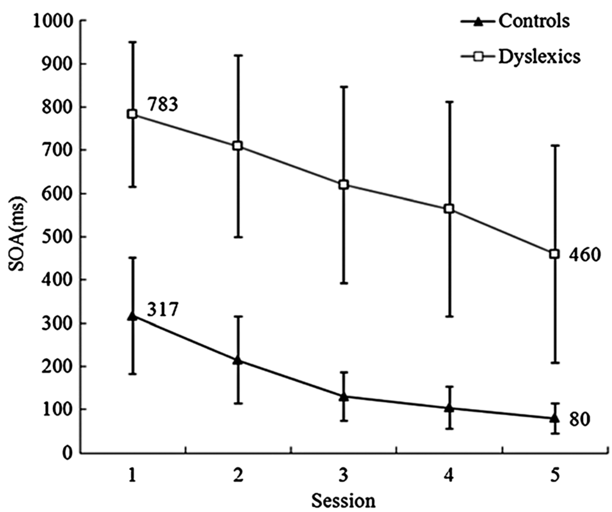

Figure 3. The perceptual learning curves for two groups of children at adaptive initial stimulus-to-mask onset asynchrony (SOA) in Experiment 2. The error bars represent standard deviation.

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 ($p < 0.01$, 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 ($M = 0.41$, $SD = 0.17$) was significantly lower than that of the control group [$M = 0.74$, $SD = 0.94$; $F(1, 16) = 10.773$, $p < 0.01$].

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 ($r = -0.723$ and $r = -0.746$, respectively, ps < 0.025, 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 ($r = 0.53$, $p < 0.05$). 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

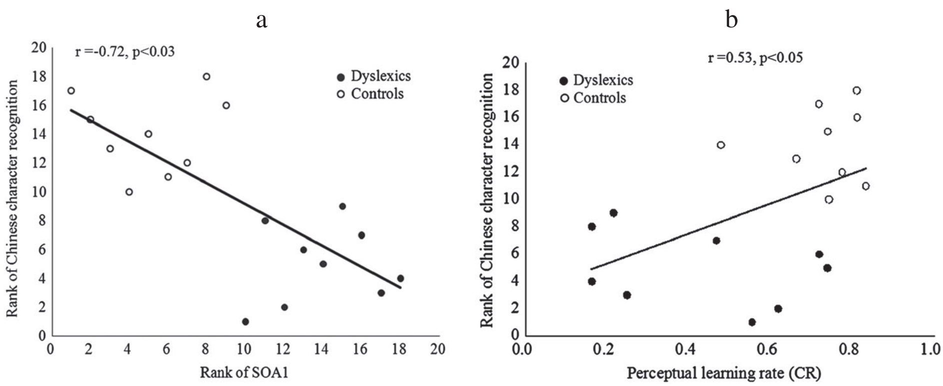

Figure 4. Correlations between perceptual learning and Chinese character recognition. [a] Scatter-plot of Chinese character recognition and stimulus-to-mask onset asynchrony 1 (SOA1) in Experiment 2 and [b] Scatter-plot of Chinese character recognition and perceptual learning rate in Experiment 2.

(300 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, 1990; Nicolson & Fawcett, 2007), in implicit learning (Howard *et al*., 2006; Vicari *et al*., 2005) and in paired-association learning (Li *et al*., 2009). This result showed that learning difficulty in children with dyslexia was not confined to abstract rule-based knowledge learning (Folia *et al*., 2008) and association learning (Li *et al*., 2009) 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 (Censor *et al*., 2012).

Given that the SOA values in TDT are considered as time thresholds within which observers are able to capture features of objects and form object representation (Bergen & Julesz, 1983; Sagi & Julesz, 1985), the significantly higher SOAs for readers with dyslexia therefore demonstrated that they were unable to extract the visual features of the presented stimuli as efficiently as the controls. Moreover, given that the threshold SOA for each session here was negatively correlated with children's Chinese character recognition ability, reading fluency, phonological awareness and rapid naming (Lin, 2013), we may argue that deficits in basic visual perceptual processing in children with dyslexia play an important role in learning to read logographic Chinese (see also Meng *et al*., 2011). In fact, visual perceptual learning has been shown to enlarge visual span size and produce corresponding improvement in reading speed in young children (Chung, Legge, & Cheung, 2004) and older adults (Yu, Cheung, Legge, & Chung, 2010); this revealed the role of visual perceptual learning in reading and supported the claim that the visual span acts as a sensory bottleneck in reading (Legge *et al*., 2007).

However, alternate processes, other than visual span, might also exist that underlie perceptual learning and Chinese reading. Regression analyses with TDT, temporal processing and Chinese character recognition found that temporal processing could mediate the relationship of TDT and Chinese character recognition (Lin, 2013). In particular, the variance in performance of Chinese character recognition, accounted for by threshold SOAs of TDT, dropped from 25.8% to 5.3% when temporal interval judgment was entered into the regression equation first. This result was in accordance with the finding of another study reporting that TDT perceptual learning was mostly temporal learning (Wang, Cong, & Yu, 2013). These findings suggested that the mechanisms that underlie visual perceptual learning and Chinese reading might be not confined to localized visual processes.

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, 2008; Schoups, Vogels, Qian, & Orban, 2001; Schwartz *et al.*, 2002; Walker, Stickgold, Jolesz, & Yoo, 2005; Yotsumoto *et al.*, 2008). However, recent psychophysical studies have also suggested that perceptual improvements might be related to changes outside of the visual cortices (Zhang & Li, 2010; Zhang, Xiao, *et al.*, 2010; Zhang, Zhang, *et al.*, 2010): 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, 2011).

For developmental dyslexia, it has been proposed that defects may exist anywhere along the dorsal visual stream (Vidyasagar & Pammer, 2009), and the deficits at different levels of the magnocellular pathway are associated with impaired performance in different aspects of reading (Kevan & Pammer, 2008). 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, 2006; Troia & Whitney, 2003) 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.*, 2003). 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.*, 2012) and cognitive function in middle-aged and older adults (Wolinsky *et al.*, 2013).

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 1000 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 (80 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 (300 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, 2013). 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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