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Crossmodal synesthetic congruency improves visual timing in dyslexic children

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ABSTRACT

Consistent with the temporal ventriloquism effect, synesthetic correspondence between the features of visual size and auditory pitch has been shown to modulate the performance of visual temporal order judgment (TOJ) in typical adults. Here in the two main experiments we recruited seventeen dyslexic children and twenty typically developing children to perform a visual TOJ task and measured their ability of synesthetic correspondence between visual size and auditory pitch. In Experiment 1, participants were shown two consecutively presented visual discs that were temporally flanked by two synesthetic congruent or incongruent auditory beeps. In Experiment 2, participants received a crossmodal matching test (visual-size vs. auditory pitch). The results showed that compared to the typically developing group, dyslexic children benefited more from cross-modal synesthetic correspondence to partially compensate for their deficiency in visual TOJ task. The multisensory facilitation for timing performance was correlated with reading ability (Exp.1). Moreover, dyslexic children formed intact "congruent" matching of visually larger shapes to lower auditory pitch, and visually smaller shapes to higher auditory pitch, as did their typically developing peers (Exp 2). The results of our present study suggested general deficits of temporal processing in dyslexic children, However, with relatively intact ability of auditory pitch-visual size matching, dyslexic children could separate visual events using auditory cues. The current study also indicates a feasible way to improve the reading ability by exploiting temporal ventriloquism effect, modulated by appropriate crossmodal synesthetic associations.

1. Introduction

Developmental dyslexia is a specific learning disability of reading and spelling which cannot be attributed to low intellectual ability or inadequate schooling, and affects roughly five to ten percent of school children (Demonet, Taylor, & Chaix, 2004; Shaywitz, Shaywitz, Fletcher, & Escobar, 1990). Many reading disabilities, especially that of developmental dyslexia, are characterized by audiovisual deficits especially in a context of naturalistic speech and word-like stimulation (Shaywitz et al., 1990) and processing deficits in temporally related tasks, such as temporal order judgments (TOJs), sensory-motor synchro-

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nization, and rhythm coordination (Jaskowski & Rusiak, 2005, 2008; Laasonen, Service, & Virsu, 2002; Virsu, Lahti-Nuuttila, & Laasonen, 2003).

In the last decade, studies of temporal processing in dyslexics have changed focus from the unisensory (visual) domain to a multisensory context, mostly by applying the *temporal ventriloquism effect* to the task of TOJ (Hairston, Burdette, Flowers, Wood, & Wallace, 2005; Harrar et al., 2014; Virsu et al., 2003). In temporal ventriloquism, temporal aspects of a visual stimulus such as its onset, interval, or duration, can be shifted by concurrent task-irrelevant but slightly asynchronous auditory stimuli (Bertelson, 1999; Burr, Banks, & Morrone, 2009; Chen & Vroomen, 2013; Fendrich & Corballis, 2001; Freeman & Driver, 2008; Morein-Zamir, Soto-Faraco, & Kingstone, 2003; Scheier, Nijhawan, & Shimojo, 1999; Shi, Chen, & Müller, 2010; Vroomen and de Gelder, 2004). For example, the perceived onset time of a visual stimulus can be biased by the presentation of a task-irrelevant and slightly asynchronous auditory stimulus (Fendrich & Corballis, 2001; Scheier et al., 1999). Hairston et al. (2005) investigated the role of the temporal ventriloquism effect in studying the effects of task-irrelevant auditory information on the performance of a visual TOJ task. They found that dyslexic subjects' performance differed significantly from that of control subjects. This difference occurred because dyslexics integrated auditory and visual information over longer time intervals (i.e., with expanded temporal windows), and showed low sensitivities for discriminating visual temporal order (Hairston et al., 2005). In a similar vein, Laasonen et al. (2002) examined temporal window of integration (TWIN) in dyslexic adults and age and IQ matched controls using audio-tactile temporal order judgment, and found a relative longer stimulus-onset asynchrony (SOA) for the dyslexic group, indicating the multisensory TWIN is generally larger than the one in unisensory conditions.

Stimuli presented in different sensory modalities can share a number of phenomenological attributes. The discrimination of (visual) temporal order, however, is modulated by the processing of concurrent task-irrelevant (and non-temporal) features of the stimuli presented (Droit-Volet & Gil, 2009; Eagleman, 2008; Kanai, Paffen, Hogendoorn, & Verstraten, 2006; Xuan, Zhang, He, & Chen, 2007). For example, people usually associate higher-pitched sounds with smaller/higher/brighter/sharper objects, and lower-pitched sounds with larger/lower/dimmer/rounder objects (Hubbard, 1996). These associations show the synesthetic correspondence between the physical features in different sensory events. Factors such as pitch/loudness in the auditory dimension with size/brightness in the visual dimension could modulate the strength of the crossmodal temporal capture effect including the temporal ventriloquism effect (Evans & Treisman, 2010; Gallace & Spence, 2006; Guzman-Martinez, Ortega, Grabowecky, Mossbridge, & Suzuki, 2012; Makovac & Gerbino, 2010; Parise & Spence, 2008; Parise & Spence, 2009; Parise & Spence, 2012; Spence, 2011; Sweeny, Guzman-Martinez, Ortega, Grabowecky, & Suzuki, 2012). By testing the normal developing adult subjects, Parise and Spence (2008) used the documented synesthetic association between auditory pitch and visual size to show that synesthetic congruency could modulate TOJ performance. They asked adult participants to execute a visual TOJ task, in which two synchronous/consecutively presented visual flashes (one small, one large) were flanked by two auditory beeps (one of low pitch, the other of high pitch), with 150 ms onset asynchronies in each sound/visual pair. In accordance with the typical ventriloquism effect, they found that participants showed enhanced sensitivities for visual TOJ performance in the presence of the flanked beeps. Moreover, participants were better able to discriminate the temporal order of visual stimuli when the visual size was synesthetically congruent with the auditory pitch, due to increased sensitivity.

The correspondence between orthographic tokens and phonemic utterances is quite basic for a beginning reader. However, individuals with developmental dyslexia show impaired ability as well as weak and less automatic integration of letters and speech sounds (Blau, van Atteveldt, Ekkebus, Goebel, & Blomert, 2009; Goswami, 2002; Hahn, Foxe, & Molholm, 2014; Hulme, Goetz, Gooch, Adams, & Snowling, 2007; Jones, Branigan, Parra, & Logie, 2013; Litt & Nation, 2014). Despite of this, dyslexics can achieve typical levels of accuracy in the associations between letters and sounds (Blomert, 2011). To our knowledge, whether synesthetic correspondence, as a form of cross-modal association is preserved in dyslexics remains largely unknown. Moreover, for dyslexic group, the ability of exploiting crossmodal association to modulate visual temporal processing has received relatively little attention in the literature. Therefore, the empirical question for current study is to ask whether/how young dyslexics lean on crossmodal synesthetic correspondence in visual TOJ and if this timing ability has relevance to the reading ability.

We conducted two experiments to address the above question. We recruited two groups of participants for the study: developing dyslexic children (DD) and their typically developing (TD) peers. In Experiment 1, all participants took part in the task of visual TOJ, in the presence of synesthetically congruent or incongruent auditory-visual associations. Experiment 2 was a control test. We presented auditory and visual stimuli from Experiment 1 to participants and instructed them to choose appropriate visual sizes to match given auditory pitches. For experiment 2, we aimed to determine whether the performance of TOJs in Experiment 1 is dependent on the potential differential ability for forming auditory-visual synesthetic associations.

2. Method

2.1. Participants

Fourth and fifth grade students were recruited from two local primary schools in Beijing, China to participate in the current study. Seventeen dyslexic children (11 females), with a mean age of 9.96 years old (SE = 0.19) comprised the experimental group. Twenty typically developing children (12 female), with a mean age of 10.16 years old (SE = 0.20) comprised the control group. All participants were native Chinese speakers from families of middle to high socioeconomic status. None of the

Table 1
Demography information and relevant screen tests (raven, reading fluency and character recognition) for typical developing group (TD) and developmental dyslexic group (DD).

Group	Name	Gender	Age	Raven	Reading fluency	Character recognition
TD	lwh	m	9	75th	81	2126
	lyh	f	10.0	75th	49	2834
	why	f	10	75th	54	2909
	ckx	m	10	75th	49	3037
	cxy	f	9.0	75th	57	2079
	txy	f	10	95th	58	2937
	zzy	f	9.0	95th	61	2301
	wds	m	12	75th	43	2855
	zqq	m	12	90th	59	3118
	cyx	m	9.9	90th	40	2450
	cjm	m	10.4	95th	35	2797
	lhy	f	9.8	90th	42	2602
	syy	m	9	90th	56	2197
	wyh	f	10.5	95th	32	2610
	yyf	f	9.7	90th	39	2466
	yzh	m	10.5	95th	46	3034
	zsr	f	10.9	95th	49	3264
	zy	f	9.8	75th	35	2190
	zn	f	10.2	75th	45	3119
DD	czy	m	11.5	50th	43	3101
	tj	f	10	95th	35	2034
	lxj	f	10	50th	33	1820
	llq	f	8.5	95th	34	1538
	swx	f	9	75th	39	1586
	fym	f	10	50th	36	2155
	gjh	m	9	95th	26	1641
	pxl	m	10	75th	24	1585
	qyy	m	10	75th	29	1465
	xb	m	9	50th	27	1554
	wqt	f	10	75th	37	2126
	hdr	f	10	75th	36	1542
	hyt	f	11	75th	32	2204
	hls	m	11.7	75th	32	2447
	lyc	m	10.2	75th	27	1941
	mx	f	8.9	75th	32	1541
	ycl	f	10.5	75th	33	2209
	zzh	m	11	75th	35	2319

participants had a history of neurological disease or psychiatric disorders. All of them were right-handed and had normal hearing and normal or corrected-to-normal vision. The experiment was performed in compliance with all institutional guidelines set by the Academic Affairs Committee of the Department of Psychology, Peking University. Informed consent was obtained from each participant and his or her parents, according to institutional guidelines and the Declaration of Helsinki.

Participants completed the Raven IQ test (Raven, 1941) and two reading tests, the Chinese Reading Fluency Test (Meng, Lin, Wang, Jiang, & Song, 2014) and the Chinese Character Recognition Test (Wang & Tao, 1996), to assess their general intelligence and reading skills. Table 1 shows the relevant information for the participants for whom the data were used for analysis.

2.2. *Behavioral assessment*

The Raven Standard Progressive Matrices (Raven, 1941) were used to measure children's nonverbal IQ. Scoring procedures were based on the Chinese norm (Zhang & Wang, 1989).

The Chinese Reading Fluency Test (CRF) was used to examine ability for rapid retrieval and retention of lexical information as well as the construction and comprehension of sentences (Meng et al., 2014). The testing material was a booklet with ninety sentences and short paragraphs. Each gave a description that required a content-matching answer from one of five pictures. The pictures illustrated typical life events. For example, one of the images could be described as "A little girl is playing with a ball in the yard." Another could be described as "Those children are sitting in the horse carriage." Though the task is time-demanding, children were encouraged to complete as many questions as possible within ten minutes.

The Chinese Character Recognition Measure and Assessment Scale (Wang & Tao, 1996) for Primary School Children incorporates 210 single Chinese characters, divided into ten parallel character lists based on their level of difficulty. The order of the characters in each list was arranged according to order of word frequency-from high (easy) to low (difficult). Participants were asked to compose a written word with the target character, that is to say, a constituent morpheme, (for example, 伟 , /wei2/, 伟大 -great; 田 /tian2/, 种田 -farm) within forty minutes. Performance was measured by the total number of correct answers.

The dyslexic children had to meet the following three criteria for inclusion in the study. *First*, their score on the Raven Test had to no less than the 50th percentile. *Second*, their score on the fluency test had to be below the mean score of the group from the same school year. The score from the fluency test was less critical and adopted for reference only. *Third*, the critical criterion was their score on the Character Recognition Test (Wang et al., 2014; Zhao, Qian, Bi, & Coltheart, 2014). For the dyslexic group, scores on the CRT were below one and a half standard deviations of the mean score for the test group. The age- and grade-matched typically developing readers were selected from the reading-impaired children's peers. Children defined as typical Chinese readers, in addition to having an average IQ as measured by the Raven test, needed to meet the requirement that their scores were above the grade average in reading fluency and on the CRT.

The mean scores of reading fluency were 49.2 ± 2.5 for TD group and 33.1 ± 1.8 for DD group. The mean standard Raven scores were 84.5 ± 2.7 and 74.1 ± 3.4 for TD group and dyslexic group. The mean numbers of character recognition were 2701.1 ± 84.7, and 1876.6 ± 90.2 for control group and dyslexic group. Two- sample Kolmogorov–Smirnov analysis showed that the two groups were equivalent in the IQs, $p > 0.05$. However, the TD (control) group had better performance in word recognition and reading fluency, $ps < 0.001$.

2.3. Stimuli

For the TOJ task, the visual stimuli consisted of two black circles, one subtending 5 cm and the other subtending 2 cm (5.2° vs. 2.1° of visual angle, respectively). The black circles were presented 5 cm (5.2°) to the left or right of a central red fixation point against a gray background. The auditory stimuli consisted of two sine wave tones (with frequencies of 300 and 4300 Hz) presented for 40 ms each (65 dB, with a 5 ms rising/falling ramp). The stimuli were presented approximately 60 cm from the participant's view. Stimulus presentation and data collection were implemented with computer programs developed with Matlab 7.1 (MathWorks Inc., Natick, MA) and Psychophysics Toolbox (Brainard, 1997; Pelli, 1997).

For the crossmodal matching task, three types of auditory stimuli and three types of visual stimuli were used. The auditory beep (30 ms in duration) was of either low pitch (300 Hz), medium pitch (2300 Hz), or high pitch (4300 Hz). The visual disc was picked from one of the following three sizes: small (2.1° of visual angle, coded as '1'), medium (3.6°, coded as '2'), and large (5.2°, coded as '3'). We inserted the medium pitch (2300 Hz) and medium visual size (3.6°) and mixed them randomly with the other two cohorts (low vs. high pitch, small vs. large size), to reduce the potential response strategies that participants could use when fewer stimulus conditions were given.

2.4. Design and procedure

2.4.1. Experiment 1: visual TOJ task

In the visual TOJ task, an 11 (inter-stimuli intervals) × 3 (2 audiovisual and 1 visual-only conditions) factorial between-participants design was used. The inter-stimuli interval (ISI) between the two visual stimuli in each condition was varied using the method of constant stimuli. ISIs of ±233, ±166 ±100, ±66, ±33, and 0 ms were used. Negative values indicate that the smaller of the two visual stimuli was presented second, while positive values indicate that the larger of the two visual stimuli was presented second. Three experimental conditions were manipulated: congruent audiovisual correspondence, incongruent audiovisual correspondence, and visual-only.

Two types of congruent trials (Low pitch – Big size/High pitch – Small size) and two types of incongruent trials (Low pitch – Small size/High pitch – Big size) were presented. For the visual-only condition, a pair of circles appeared in the absence of sound. In the audiovisual condition, the time intervals between the onset of the first (second) auditory stimulus and the onset of the first (second) visual stimulus were 150 ms, as shown in Fig. 1. In half of the trials, the first auditory stimulus was high pitched and the second was low pitched. In the other half, the order was inverted. The orders of congruent and incongruent trials were presented randomly and counterbalanced. There were 396 trials in total. All the trials were separated into nine blocks (with 44 trials in a block). In between each block, participants could take a rest.

The participants sat in front of a liquid crystal display (LCD) screen (Model: TongFang, TGJ-21E81B, 21.5 in., 60 Hz refresh rate) and wore headphones. Each trial began with the presentation of the central fixation point, which lasted for 500 ms. In the audiovisual condition, the first auditory stimulus was presented after a random blank interval between 500 ms and 700 ms. The first visual stimulus was presented to the left or right of the fixation point 150 ms after the first auditory stimuli, and remained on the screen until the end of the trial. The second visual stimulus was subsequently presented on the other side of the fixation point (after the corresponding ISI to the first visual stimulus) and also remained visible until the end of the trial. The second auditory stimulus followed, 150 ms after the second visual stimulus. This temporal configuration between auditory and visual stimuli was consistent with that used by Parise and Spence (2008), in which the two flank beeps would "pull" away the visual disc, giving rise to enhanced sensitivities for discriminating visual temporal order. In the visual-only condition, the timing parameters remained the same as in the sound condition, but only two visual discs appeared with the given ISIs. The participants had to indicate which visual disc (the one to the left or right of the fixation point) came first by pressing the left or right arrow key on a computer keyboard, while trying to ignore the task-irrelevant auditory stimuli, as shown in Fig. 1a and b.

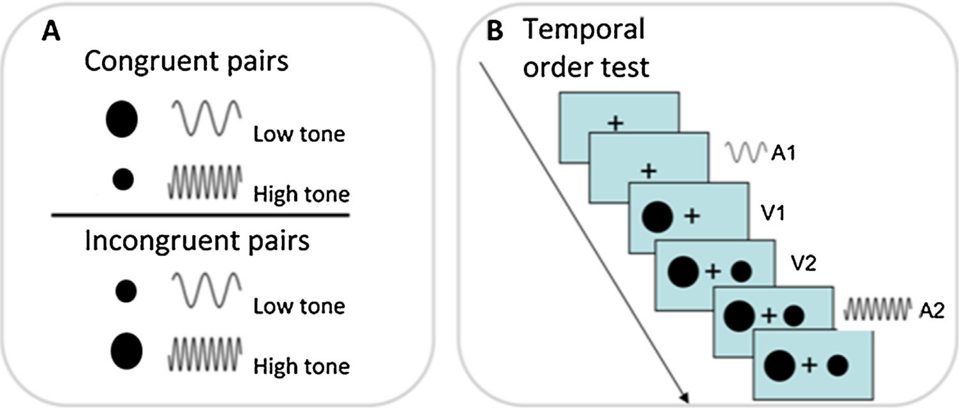

Fig. 1. Stimuli and sample trial for Experiment 1. (A) Large or small flashes were combined with high- or low-pitched tones in a synesthetically congruent (low-large, high-small) or incongruent (low-small, high-large) fashion. (B) Stimuli sequence for the visual temporal order test. Participants judged which side of a visual stimulus came first.Two visual stimuli (V1 and V2, synchronous or with intervals of 33, 66, 100, 166, or 233 ms) were accompanied by two auditory beeps (A1 and A2). The stimulus onset asynchronies (SOAs) between A1 and V1, and between A2 and V2, were fixed at 150 ms.

2.4.2. Experiment 2: visual size-auditory pitch matching

After completing the TOJ task (Experiment 1), all participants attended a crossmodal matching task in which they determined how different auditory pitches matched given visual sizes (Experiment 2). In Experiment 2, we did not systematically manipulate the ISI between the visual disc and auditory beep, since the task was matching the visual size to auditory pitch, instead of the typical TOJ task (which is indeed dependent on the ISI between sensory events). However, we randomized the time interval between auditory signal and visual disc to rule out potential response bias, in which participants might perform the matching based on the fixed temporal interval between auditory and visual events. Each trial used the following procedure. Firstly, the auditory beep was presented. Then, after a random blank interval of 700 ms to 1000 ms, three black discs appeared. These three discs (always in a combination of small, medium, and large sizes) were placed horizontally with a center-to-center distance of 8°. However, the order of each disc was randomized. Participants were required to press the left, down, or right arrow key (corresponding to the left, middle, and right stimulus on the screen) to match the visual size to the pitch of the given auditory beep. There were 36 trials in total.

3. Results

We obtained the JNDs from fitted psychometric curves and then implemented repeated measures analysis of variance (ANOVA), with JNDs as the independent factor and stimuli conditions as within-participant dependent-factors, and experimental groups as between-participant dependent-factors. Psychometric logistic functions were calculated for each participant for each condition to the percentage of “Larger second (Small first)” (i.e., large visual stimulus first or small visual stimulus first) responses across all the given ISIs (Treutwein & Strasburger, 1999). The JNDs were obtained from the psychometric curve by estimating the half of ISI difference between 25% and 75% of the “Larger second” responses. Fig. 2 depicts the average psychometric functions for both the typically developing and dyslexic groups.

3.1. Cross-modal synesthetic correspondence and TOJ

In the control group, the JNDs for congruent, incongruent, and visual-only conditions were 37.6 ± 5.0 ms, 44.8 ± 5.8 ms, and 52.7 ± 8.8 ms. In the dyslexic group, they were 66.2 ± 5.5 ms, 72.3 ± 6.3 ms, and 102.3 ± 9.5 ms. The mean JNDs for each condition for both group are shown in Fig. 3.

Repeated measures ANOVAs with the experimental conditions (congruent, incongruent, visual control) as the within-participants factor and experimental group (control vs. dyslexic) as the between-participants factor showed a main effect of group. For the control group, the mean JND was 45.0 ± 6.0 ms, which was lower than that of the dyslexic group, which was 80.3 ± 6.5 ms, $F(1,35) = 15.63$, $p < 0.001$, $\eta_p^2 = 0.309$. The main effect of experimental condition was significant. The mean JNDs for the congruent, incongruent, and visual control conditions were 51.9 ± 3.7 ms, 58.5 ± 4.3 ms, and 77.5 ± 6.4 ms, $F(2,70) = 22.56$, $p < 0.001, \eta_p^2 = 0.402$. Bonferroni-corrected comparisons showed significant differences among the above three conditions (p’s < 0.01).The interaction between experimental condition and group was significant, $F(2,74) = 4.93$, $p < 0.05$, $\eta_p^2 = 0.117$.

Further simple effect analysis showed that for typical developing group (TD), the main effect of experimental conditions (’congruent’, ‘incongruent’ and ‘visual-only’) was significant, $F(2,70) = 4.11$, $p < 0.05$. Also, the main effect of experimental conditions within DD group was also significant, $F(2,70) = 23.10$, $p < 0.001$. On the other hand, we made comparisons of each experimental condition across the two groups. For ‘congruent’ condition, the mean JND in TD was smaller than the one

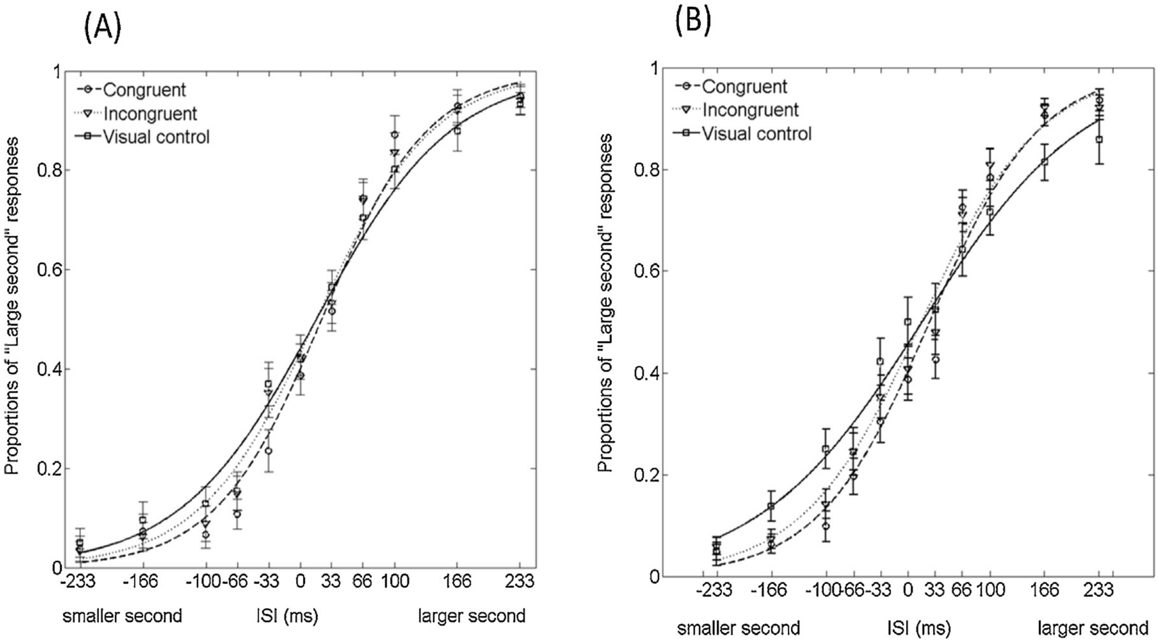

Fig. 2. Psychometric fitting curves for the typically developing group (A) and dyslexic group (B) for the visual temporal order judgment (TOJ) in both visual-only and audiovisual conditions. The dashed line with circles shows the percentage of correct responses (with the larger visual stimulus appearing second) as a function of ISI between two flashes, in the condition of congruent auditory-visual synesthetic correspondence (low pitch-large size; high pitch-low size). The dotted line with triangles shows the result of incongruent synesthetic correspondence (low pitch-small size and high pitch-large size). The solid line with squares shows the result of the control condition-visual TOJ without sounds.

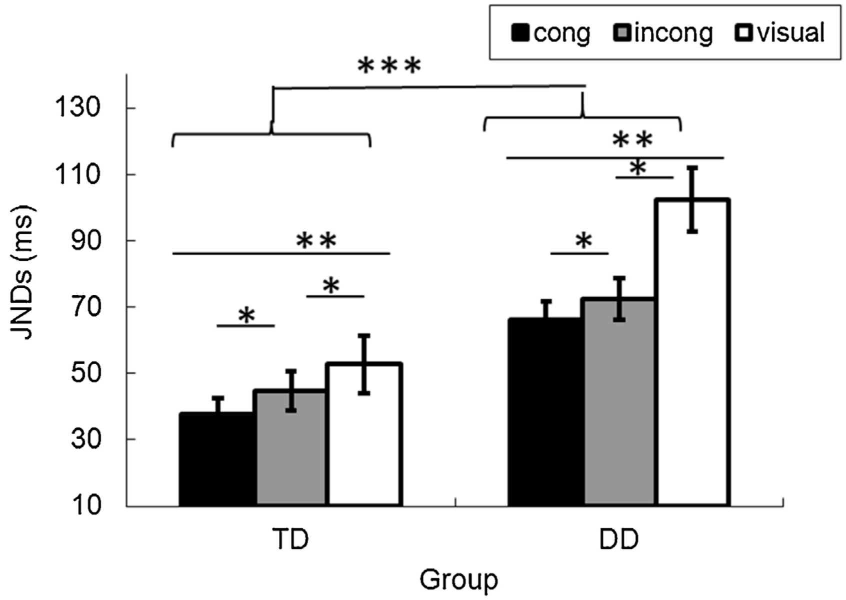

Fig. 3. The just noticeable differences (JNDs) for the TOJ. Black bars depict the JNDs for the congruent condition, gray bars for the incongruent condition, and white bars for the visual condition (*denotes $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$).

in DD group, $F(1,35) = 14.68$, $p < 0.01$; The trends were the same for the other two conditions- 'incongruent' and 'visual', $F(1,35) = 10.21$, $p < 0.01$ and $F(1,35) = 14.61$, $p < 0.01$.

The auditory beeps (in both the congruent and incongruent correspondence conditions) that accompanied the two visual events imposed a typical ventriloquism effect (pulling the two visual events away in time), making the visual temporal order judgment easier (with decreased JNDs), compared with the condition of pure visual TOJ (i.e., without tones). Interestingly, for the sound conditions, synesthetically congruent correspondence invoked a larger effect in facilitating the performance of temporal order judgment than it did in the audio-visually incongruent condition.

To quantify the cross-modal benefits of the visual TOJ as well as the interaction effect between factors of experiment and audiovisual conditions, we calculated delta values as the average differences of: (1) Differential JNDs for the congruent condition and the visual-only condition; and (2) Differential JNDs for the incongruent condition and the visual-only condition. The formula is as follows:

$$\text{delta} = [(\text{cong.-visual}) + (\text{incong.-visual})]/2$$

The mean improvement for the typically developing group was -11.5 (3.3) and -28.1(8.2) for the dyslexic group. The benefit was larger for the dyslexic group than the control group, $F(1,36) = 3.948$, $p < 0.05$, $\eta^2 = 0.133$.

In general, these results indicate that the dyslexic group demonstrated lower sensitivity than their control peers in judging visual temporal order (with elevated JNDs). However, in comparison with the normal reading group, dyslexic children benefitted more while utilizing crossmodal cues in audiovisual situations, but were still less efficient as their control peers, given that the disparity in (general) crossmodal processing remained.

3.3. Correlation between JNDs and reading skills

In the reading fluency test, the control group (mean score: 49.2 ± 2.5) performed better than the dyslexic group (mean score: 33.1 ± 1.8), $F(1,36) = 25.19$, $p < 0.001$, $\eta^2 = 0.438$. In the character recognition test, the control group (2701.1 ± 84.7) also performed better than the dyslexic group (1876.6 ± 90.2), $F(1,36)$=47.72, $p < 0.001$, $\eta^2 = 0.445$.

Next, we calculated Pearson correlations to examine the association between sensitivities of visual timing (JNDs) and reading ability (scores of character recognition test and reading fluency). Since the distributions of reading ability scores from the two groups, especially the typically developing group, were more centralized, we collapsed the data from both groups and performed the correlation analysis, as done in some previous studies (Bruni et al., 2009; Demb, Boynton, Best, & Heeger, 1998; Kronbichler et al., 2008). There was a moderate correlation (with coefficients ranging from -0.3 to -0.4) among the JND values and reading abilities (measured by the character recognition test and reading fluency), $ps < 0.05$. The coefficients of each correlation are shown in Fig. 4. From the pattern of the scatter plots, we found that the typically developing group had generally high sensitivities of TOJ and fewer individual differences. In contrast, the dyslexic group showed decreased sensitivities and larger individual differences. Generally, the JNDs were correlated with scores of character recognition and reading fluency, indicating that literacy skills could be reflected by basic perceptual abilities, including temporal processing deficit in visual time order judgment (Lorusso, Cantiani, & Molteni, 2014; Ortiz, Estevez, Muneton, & Dominguez, 2014; Romani, Tsouknida, & Olson, 2015).

3.4. Reaction time in TOJ task

We calculated the reaction times (RTs) when the two groups performed the TOJ task. The mean RTs for dyslexics and typically developing group were 599 ± 30 ms, 591 ± 28 ms, $F(1,72) = 0.043$, $p = 0.836$, $\eta^2 = 0.001$. The main effect of experimental conditions was significant, $F(2,144) = 4.444$, $p < 0.05$, $\eta^2 = 0.058$. RTs for ‘congruent’, ‘incongruent’ and ‘visual-only’ were 584 ± 21 ms, 592 ± 20 ms, and 608 ± 22 ms. Bonferroni corrected comparison showed the RT in ‘congruent’ condition was faster than the one in ‘visual’ condition, $p < 0.01$. However, the interaction between factors of experimental conditions and groups was not significant, $F(2,144) = 0.489$, $p = 0.614$.

3.5. Auditory pitch-visual size matching test

We adopted repeated measures ANOVAs for this analysis. The main effect of experimental conditions was significant. The mean matching scores for low pitch, medium pitch, and high pitch to corresponding visual sizes were 2.242 ± 0.071, 1.659 ± 0.061 and 1.353 ± 0.065, $F(2,70) = 47.995$, $p < 0.001$, $\eta_p^2 = 0.578$. Bonferroni corrected comparisons showed significant differences between all three conditions, p’s < 0.001. However, no group mean difference was found, $F(1,35) = 0.035$, $p = 0.852$, $\eta_p^2 = 0.001$. The mean matching scores were 1.744 ± 0.052 for the control group and 1.759 ± 0.057 for the dyslexic group.

In the control group, the scores of matching/rating sizes were 2.294 ± 0.096 (standard error), 1.661 ± 0.082 and 1.279 ± 0.089 for low pitch (300 Hz), medium pitch (2300 Hz), and high pitch (4300 Hz). In the dyslexic group, the scores were 2.192 ± 0.104, 1.657 ± 0.089, and 1.427 ± 0.096 for low, medium, and high pitches. The mean scores for each condition of the control and dyslexic group are shown in Fig. 5. The interaction between experimental condition and group was not significant, $F(2,70) = 0.923$, $p = 0.402$, $\eta_p^2 = 0.026$.

These results indicate that both the TD group and the DD group showed equivalent synesthetic correspondence between auditory pitch and visual size. Participants in both groups typically associated high-pitch sounds with small visual objects and low-pitch sounds with big objects.

Therefore, the auditory pitch-visual size matching test showed that dyslexic children remain the intact ability of associating the high pitch to small visual-size object, as did in their control peer.

As suggested by one of the reviewers, we continued to analyse and show percentages of how often was each of the pitches connected to each of the circles. The percentages of how often each pitch category (high, medium, low) corresponds to the synesthetically congruent circle (small, medium, large) were 74.0 %, 41.0 % and 60.4 %. Among each given 12

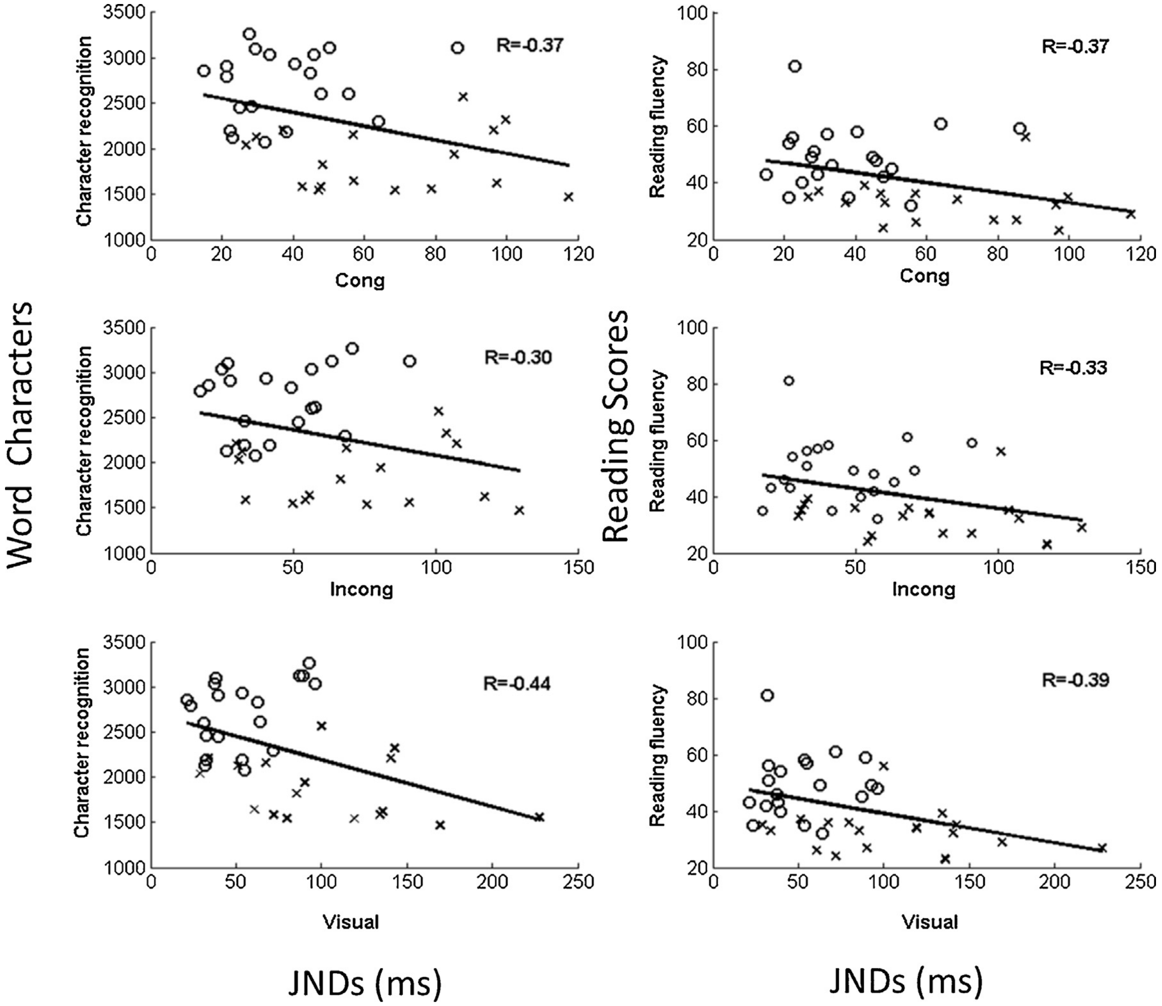

Fig. 4. Scatter plots of reading fluency and character recognition as a function of JND indifferent audiovisual conditions. The circles indicate the samples from typically developing children and the crosses indicate those from the dyslexic group. "Cong" shows the condition for synesthetic congruent matching of auditory pitch and visual size. "Incong" indicates the synesthetic incongruent matching of auditory pitch and visual size. The "Visual' condition shows the visual-only stimuli in the absence of sounds.

trials, the mean 'congruent' mapping numbers were 8.874 ± 0.501 for high pitch vs small size, 4.914 ± 0.533 for medium pitch vs medium size, and 7.251 ± 0.606 for low pitch vs. large size. There are significant main effect of the three mappings, $F(2,74) = 22.795$, $p < 0.001$, and significant differences between high pitch-small size and low pitch-large size, $p < 0.05$. The dyslexia group had relatively lower 'congruent' mapping rate (mean = 51.6%) than the typical developing group had (mean = 65.3 %), $F(1,37) = 3.632$, $p = 0.064$.

3.6. Reaction time analysis for matching task

Since we did not record the *Reaction Time (RT)* in Experiment 2, in an additional separate test, we recruited another 22 participants, 11 TD group (mean age: 10.9, 4 female) and 11 DD group (mean age: 11.0, 3 female) to complete the same task as in Experiment 2 but recorded the RT for each participant.

The mean matching scores for low pitch, medium pitch, and high pitch to corresponding visual sizes were 2.383 ± 0.102 (standard error) (corresponding to 67.4 % of trials), 1.750 ± 0.106 (corresponding to 44.7 % of trials) and 1.398 ± 0.103 (corresponding to 61.0 % of trials) for low pitch (300 Hz), medium pitch (2300 Hz), and high pitch (4300 Hz), $F(2,40) = 23.901$, $p < 0.001$, $\eta_p^2 = 0.544$. Bonferroni corrected comparison showed significant differences between all three conditions, *p*s < 0.01. However, no group mean difference was found, $F(1, 20) = 0.015$, $p = 0.904$, $\eta_p^2 = 0.001$. The mean matching scores were 1.836 ± 0.088 for the control group and 1.851 ± 0.088 for the dyslexic group. In the control group, the scores of matching/rating sizes were 2.462 ± 0.145 (standard error), 1.712 ± 0.150 and 1.333 ± 0.146 for low pitch (300 Hz), medium pitch (2300 Hz), and high pitch (4300 Hz). In the dyslexic group, the scores were 2.303 ± 0.145, 1.788 ± 0.150, and 1.462 ± 0.146

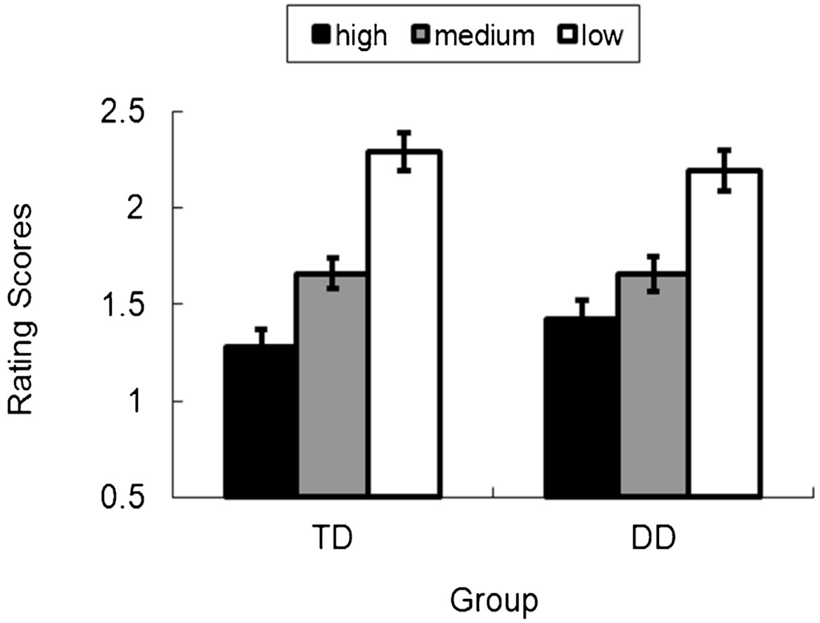

Fig. 5. Auditory pitch-visual size matching task. Value 1 denotes the selection of the smaller circle, Value 2 selection of the medium circle, and Value 3 selection of the large circle. The black bars depict the average matching score of visual size corresponding to the high-pitch tone.The gray bars depict the average matching score of visual size corresponding to the medium-pitch tone, and the white bars depict the average matching score of visual size corresponding to the low-pitch tone.

for low, medium, and high pitches. The interaction between experimental condition and group was not significant, $F(2,40) = 0.563$, $p = 0.574 \eta_p^2 = 0.027$.

We also analyzed the reaction time (RT). Generally, RT in the TD group (1310 ± 66 ms) was slower than the one in DD group (1259 ± 66 ms), $F(1, 20) = 5.182$, $p < 0.05$. The mean RTs for low pitch, medium pitch, and high pitch to corresponding visual sizes were 1062 ± 52 ms (standard error), 1310 ± 69 ms and 1086 ± 67 ms for low pitch (300 Hz), medium pitch (2300 Hz), and high pitch (4300 Hz), $F(2,40) = 6.828$, $p < 0.01$, $\eta_p^2 = 0.255$. Bonferroni corrected comparisons showed the RT in medium pitch condition was slower than the RTs in other two conditions, $ps < 0.05$. $p < 0.05$, $\eta_p^2 = 0.206$. In the TD group, the mean RTs were 953 ± 74 ms (standard error), 1213 ± 98 ms and 973 ± 95 ms for low pitch (300 Hz), medium pitch (2300 Hz), and high pitch (4300 Hz). In the DD group, the mean RTs were 1171 ± 74 ms, 1408 ± 98 ms, and 1199 ± 95 ms for low, medium, and high pitches. The interaction between experimental condition and group was not significant, $F(2,40) = 0.023$, $p = 0.977$, $\eta_p^2 = 0.001$.

Therefore, the reaction times of cross-modal matching were slower in DD group than the ones in the TD peer group, suggesting that dyslexics have difficulty in shifting their attention between modalities when carrying out the cross-modal matching task (Hari & Renvall, 2001; Harrar et al., 2014). For both groups, the medium pitch condition led to increased reaction times, indicating condition of medium pitch is not distinct enough to be discerned (compared with the low and high pitches).

4. General discussion

The current findings are in agreement with previous studies that tapped into the temporal aspects of visual processing in dyslexia (Laasonen, Service, & Virsu, 2001; Tallal, Miller, & Fitch, 1993), in which the dyslexic groups had difficulties in performing the TOJ task as compared to the participants in the control groups. However, dyslexics gained more benefits in judging the order of visual stimuli that were flanked by temporally close beeps, although the DD group still had larger JNDs in audiovisual condition than TD group (de Boer-Schellekens & Vroomen, 2012; Hairston et al., 2005). Our data replicated the findings of Parise and Spence (2008). The congruent auditory pitch-visual size pair indeed improved the performance of visual TOJ beyond that of the incongruent pair. For the congruent conditions, the visual disc was more readily attracted by the temporal proximate auditory stimulus, leading to a stronger ventriloquism effect and with decreased JNDs, as shown in the typical developing adult subjects (Burr et al., 2009; Shi et al., 2010). In contrast, for the incongruent condition, the feature association between auditory pitch and visual size was not closely correlated, which lead to a shadowed auditory capture effect on visual events, and hence a weaker temporal ventriloquism effect (higher JNDs than those in the congruent condition). This finding suggests that the facilitation effect of auditory events upon visual events (mainly via the mechanism of temporal ventriloquism) is a wide-spread multisensory illusion occurring in both typically and atypically developing individuals. The result pattern also suggests that dyslexics may be able to partially compensate for their visual timing difficulties by using more efficiently the temporal information conveyed through auditory inputs.

Indeed, the dyslexic group have been revealed to show the deficits in visual related perceptual processing, including the temporal order judgment. Recent theoretical survey of the underlying neuro-cognitive mechanisms for developmental dyslexia has shown three potential leading theories: (1) the phonological theory (Paulesu et al., 2001; Shaywitz et al., 2002; Shaywitz et al., 1998); (2) the cerebellar theory (Nicolson, Fawcett, & Dean, 1995) and 23) the magnocellular theory (auditory and visual) theory (Livingstone, Rosen, Drislane, & Galaburda, 1991; Stein, 2001; Stein & Walsh, 1997) and 3) the cerebellar theory (Nicolson et al., 1995). Ramus et al. (2003) summarized with large volume of data to support the phonological theory (with specific impairment in the representation, storage and/or retrieval of speech sounds). The cerebellar theory, on the other hand, argued that the presence of additional sensory and motor disorders in certain dyslexia individuals. The present study shows that dyslexia group have demonstrated common deficits in perceptual sensory processing (with relatively large JNDs even in visual both uni- and multi-sensory TOJ performance), suggesting the magnocellular theory plays a role in accounting for the general perceptual deficits in visual temporal order judgments for dyslexic children.

It is of note that the crossmodal benefits for visual timing were larger for the dyslexic group than for the typically developing group. This finding was consistent with the inverse-effectiveness principle revealed in recent literature (Stein and Stanford, 2008), in which initial temporal window size serves as a strong predictor of the outcomes for temporal training and multisensory integration effects (Powers, Hillock, & Wallace, 2009; Stevenson, Wilson, Powers, & Wallace, 2013). In our case (as observed in Fig. 3), for the dyslexia group, the initial larger JNDs (i.e., which larger temporal window size) for visual TOJs, predict a large improvements of sensitivities of TOJ in the presence of auditory beeps (with large decrease of the absolute values of JNDs). To put in another way, the larger JNDs (corresponding to the 'weak' condition) in visual-only condition for the dyslexia group provide a good stand point for the larger effect by audiovisual condition to be easily observable, while for the typical developing group, those trends are relatively less obvious. This finding suggests that although the dyslexic group showed a general deficiency in processing time information (Farmer and Klein, 1995; Hairston et al., 2005; Laasonen et al., 2001; Laasonen et al., 2002), they were capable of exploiting crossmodal cues (auditory signals) to facilitate their visual TOJs. Nonetheless, it would not have been definitive to eliminate the gap between two groups with such a strategy, for the dyslexic children were still less sensitive to the temporal discrepancies between two visual events enclosed by sounds, as compared with their control peers.

The present study, however, revealed a more complex picture for the crossmodal processing in dyslexia group. With the main task of TOJ, what we found was that the reaction times of both dyslexia group and typical developing group were comparable to those of typically developing group, but the former were with larger JNDs, in performing the TOJ (Experiment 1). In Experiment 2, both groups were equivalent in the ability of associating high (low) pitch to small (large) visual-size, although the reaction times of this matching was slower for the dyslexic group. Dyslexia group seemed to have counterbalance deficits between sensitivity and speed in crossmodal synaesthetic integration. On one hand, they preserved the faculty to match crossmodal stimuli and use their combination to guide perception. On the other hand, they were hardly skilled to perform well in limited time. Due to the lack of proficiency in crossmodal integration, there would be much more difficulties in letter-speech sound mapping, which presumably leads to deficits in orthographic-phonological binding (with less automatic binding) among those poor readers. This argument backs up the potential general deficits in audiovisual integration for most existent studies (for a review, see Hahn et al., 2014).

Moreover, as recent studies elucidated the crossmodal binding of letter and speech sound turned out to show cross-linguistic differences. There was a variable and unreliable relationship between the orthography and phonological representations, due to varied features across languages (Holloway, van Atteveldt, Blomert, & Ansari, 2015). English (dyslexic) learners had low automatic letter-speech binding, given its opaque nature of orthographies in English. We speculate that for Chinese readers, the building of the letter-speech association might impose a greater cognitive challenge for dyslexic readers, as the Chinese characters might be visual-spatially more complex and non-transparent than the characters in other languages (since the correspondence between phonology and orthography is relatively arbitrary). The characteristic features of dyslexia lie in the reduced automaticity and deficits in robust multisensory representation of the association between letter-speech sound (Hahn et al., 2014). Therefore, for most dyslexic children as well as dyslexic adults, as long as letter-speech sound pairs have not developed into automatically integrated audiovisual objects, the speed of reading (reading fluency) will remain constrained (Blomert & Willems, 2010; Froyen, Willems, & Blomert, 2011).

With the connection through orthographic-phonological binding, the sensitivity for TOJs was closely linked with individuals' linguistic reading scores. These findings echo previous studies that have shown that extracting phonological information during both text reading and character naming depends on the temporal organization of the information available (Talcott et al., 2000; Witton et al., 1998). Previous studies indicated that dyslexic children showed reduced letter-sound integration, and the degree of severity of the reading impairment seems directly related to the ability to identify and process letter-speech sound pairs as unique audiovisual objects (Blau et al., 2010; Blomert, 2011; Foxe et al., 2015; Hahn et al., 2014; de Gelder and Vroomen, 1998). Together with the evidence from literature, the present results indicate that dyslexia group had low efficiency in crossmodal synaesthetic binding, which thus impaired their ability to associate letter form and speech sound, and eventually hindered the development of literacy

The relatively intact audiovisual synesthetic correspondence (in terms of accuracy) suggests a feasible way to launch a remediation training program to improve the reading skills. As we have shown, the dyslexia group leave room for improvement of the auditory pitch-visual size matching task, by reducing the reaction time (i.e., elevated automaticity) and improved rates of 'congruent' mapping (such as low auditory pitch with large visual size). The current study therefore suggests, it is likely that young dyslexics can improve their timing ability via a sufficient training protocol/optimized intervention that uses cross-modal correspondence, including that of synesthetic correspondence between auditory pitch and visual size (Franceschini et al., 2013; Powers et al., 2009). Indeed, recent efforts have been reported to intervene the reading difficulties in dyslexia (Serniclaes, Collet, & Sprenger-Charolles, 2015; Zaric et al., 2015). Recent evidence has shown that reading improvement following nonlinguistic training programs suggests a role for a more general multisensory processing deficit in dyslexia, at least when it comes to the acquisition of multisensory correspondence (Lorusso et al., 2014). Although, the present results did not clearly expound the relation between crossmodal temporal processing and reading acquisition, the training of reducing reaction times and improving 'congruency' percentages in associating auditory-pitch and visual-size could help to improve the reading skills for dyslexic children. Recent endeavors in this regard have turned out to be successful. For instance, a computer-based sound-symbol paradigm (SSP) has been adopted for kindergarten children, their reading performance has been measured before formal reading instruction and has been revealed to associate with later reading development after SSP (Foxe et al., 2015).

The present study still leaves some questions unaddressed. In current study, we are not informed whether there is some certain relationship between the processing of synaesthetic correspondence and the association of orthographic-phonological representations.

As we understood, there remained an unknown bridge to address the function of crossmodal integration to orthographic-phonological representations for the participants in this study. Likewise, the underlying mechanism of how the ascendancy in temporal judgment contributed to better performance on reading is still open to further discussion. Additionally, in the present study we were not able to pinpoint the time course of the association between auditory pitch and visual size (Maurer et al., 2007; Schneider & Chein, 2003). At current stage we are not able to reveal how attention and crossmodal binding play a role in reaching this association. Thus we cannot disentangle the correspondence based on detection-level versus decision-level (Harrar et al., 2014). Those limitations could be addressed with further studies.

In conclusion, we found that dyslexic children have shown a general deficit in multisensory integration, but gained cross-modal benefits for visual TOJ performance by crossmodal synesthetic congruency. The current findings also suggest that it is possible to exploit the potentially intact audiovisual synesthetic correspondence in the dyslexic children, to improve their reading ability through basic timing training (such as by improving the reaction times during audiovisual synesthetic mapping and narrow the time integration window for audiovisual events), modulated by appropriate cross-modal synesthetic associations.

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