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Temporal Processing Development in Chinese Primary School–Aged Children With Dyslexia

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Abstract

This study aimed to investigate the development of visual and auditory temporal processing among children with and without dyslexia and to examine the roles of temporal processing in reading and reading-related abilities. A total of 362 Chinese children in Grades 1–6 were recruited from Taiwan. Half of the children had dyslexia, and the other half were typically developing children who matched the dyslexic group on age, intelligence, and gender. Our results indicate that for typically developing children, the visual and auditory modalities follow the same developmental trend: The children in first and second grades performed significantly worse than the older children. Among the children with dyslexia, however, significant improvements in the visual modality were observed with increasing age. Furthermore, although both modalities were important for all reading-related abilities and for Chinese character reading in first and second grades, the visual modality significantly predicted only orthographic knowledge and Chinese character reading in third and fourth grades. In contrast, the auditory modality affected only phonological awareness. In fifth and sixth grades, only visual temporal processing slightly contributed to the orthographic knowledge and Chinese character reading of the dyslexic group. Also, the relationship between temporal processing and Chinese character reading is strongly influenced by age.

Keywords

dyslexia, Chinese, temporal processing

Dyslexia is a learning disability that is characterized primarily by difficulties with spelling and decoding, and approximately 5% to 17% of children suffer from reading difficulties or dyslexia (Lyon, Shaywitz, & Shaywitz, 2003). In general, children with dyslexia are recognized as having difficulty with phonological processing, such as phonological awareness (PA) and rapid automatized naming (RAN) in alphabetic languages (Wolf & Bowers, 2000).

However, other researchers argued that these reading problems may be caused by a basic deficit in processing rapidly sequenced components and information—namely, a temporal processing deficit (for a review, see Farmer & Klein, 1995). Temporal processing is thought to involve a hierarchy of information extraction presented over time or the production of a sequence of behaviors. Individuals who fail to detect, identify, individualize, and perceive multiple stimuli in the correct sequence are considered to have a temporal processing deficit (Klein, 2002).

The temporal processing hypothesis of dyslexia was firstly discussed by Tallal and colleagues, and their temporal order judgment (TOJ) research revealed that examinees are able to respond to two auditory stimuli with different interstimulus intervals (ISIs) in the correct order of presentation. Tallal (1980) found that around half of children with dyslexia demonstrated obvious difficulties with TOJ tasks and that the correlation between the TOJ task and nonword reading was significant. Subsequent studies supported that those with dyslexia performed worse on TOJ tasks than those without dyslexia and also found similar findings from stimulus in the both auditory and visual modalities (for a review, see Farmer & Klein, 1995; Ramus, 2001).

Relationships of Reading, Literacy Abilities, and Temporal Processing

As the clear pattern in the relationship between auditory temporal processing and phonological processing (e.g., PA and RAN) has been well investigated, the contribution of auditory temporal processing was also found as significant to word reading, reading comprehension, and dictation by

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controlling PA and/or RAN in recent years (Catts, Gillispie, Leonard, Kail, & Miller, 2002). On the contrary, the role of visual temporal processing has not been widely demonstrated. Inconsistent views were raised regarding the associations among visual temporal processing, orthographic knowledge (OK), and word reading (Olson & Datta, 2002). Even the direct evidence is still lacking, a reasonable inference that visual temporal processing is an important factor in OK was made (e.g., Burt, 2006).

Therefore, the evidence to date suggests that temporal processing's contributions to literacy abilities may be modality specific. That is, auditory temporal processing is important to PA and RAN, and visual temporal processing is important to OK. This view, especially with respect to PA and OK, is consistent with the evidence found by previous studies (e.g., Booth, Perfetti, MacWhinney, & Hunt, 2000). Those findings aside, temporal processing seems to relate closer with RAN than with the other two literacy abilities, and the association between temporal processing and RAN might be more than modal specific. However, there is a lack of evidence to show the association of reading, literacy abilities, and temporal processing in its entirety.

Development of Literacy Abilities and Temporal Processing

Although an increasing number of researchers have accepted this hypothesis, debates on it are incessant (e.g., Denenberg, 1999; Mody, Studdert-Kennedy, & Brady, 1997). Regarding the possible reason for the equivocal support for this hypothesis—that is, some studies have reported that age affects children's performance on illusions or persistence (considered to be a result of temporal processing) in auditory (Davis & McCroskey, 1980; Irwin, Ball, Kay, Stillman, & Rosser, 1985) and visual (Lovegrove & Heddle, 1980) modalities—some researchers have recently targeted the relationship between developmental and temporal processing deficits in children with dyslexia, especially as it relates to their developmental lag. The relevant studies have mainly focused on comparing the temporal processing performance of children with and without dyslexia at different ages.

For instance, Hautus, Setchell, Waldie, and Kirk (2003) found that only the dyslexic children aged 6–7 and 8–9 years showed significant worse auditory temporal processing than their peers without dyslexia, but this significant problem was not found for elder children or adults with dyslexia. This result might explain the nonsignificant differences between children with typical development and dyslexic children from some studies (e.g., Walker et al., 2002).

Given that the well-investigated contributions of literacy abilities to reading have also been shown to change with age in children with and without dyslexia (e.g., de Jong & van der Leij, 2003; Protopapas, Altani, & Georgiou, 2013), "age" should be a key element to the examinations of temporal processing deficits and its roles in reading.

Temporal Processing Deficit Hypothesis of Dyslexia in Chinese

The temporal processing deficit hypothesis in dyslexia has been examined, and it has provided strong evidence that temporal processing is related to reading performance among readers of alphabetic languages, as reviewed here. However, the application of this hypothesis to nonalphabetic languages, such as Chinese, remains rare. An examination of nonalphabetic languages could demonstrate the universal use of this hypothesis.

The basic unit of a Chinese character—which is associated with a morpheme and represents a syllable in Chinese language—is a stroke, and approximately 620 stroke patterns can be constructed to represent the radical of Chinese characters (Chung et al., 2008). Both stroke- and radical-level information requires processing items with high visual complexity, so visual-related abilities and skills have been found to be an important factor in learning Chinese characters (Liu, Chen, & Chung, 2015). Additionally, Chinese children with dyslexia have been found to have a primary deficit in visual processing (Ho, Chan, Chung, Lee, & Tsang, 2007). Therefore, it is reasonable to infer that Chinese dyslexic children have specific deficits in the visual modality of temporal processing.

To date, several studies have examined the temporal processing deficits of Chinese-speaking children with dyslexia. For example, Meng et al. (2005) investigated the temporal processing deficit hypothesis among Chinese children with dyslexia. Their results indicated that auditory TOJ was the most important predictor of reading fluency and character naming speed but did not predict vocabulary size. On the contrary, even though Chung et al. (2008) indicated that children with dyslexia performed worse than typically developing children on visual and auditory TOJ, they found that the visual TOJ remained a significant predictor of Chinese character recognition when auditory TOJ and literacy abilities were introduced, although the same result was not found for the auditory TOJ.

One possible reason for the conflicting results is the fundamental assumption that modality affects the temporal processing deficit of children with dyslexia. Since the temporal processing deficits of readers with dyslexia may occur in the auditory and visual modalities (for a review, see Farmer & Klein, 1995), the involvement of only one modality, such as Meng and colleagues' (2005) design, may not show the whole picture, especially for languages such as Chinese that require extensive reliance on the visual modality during reading (Liu et al., 2015).

Another reason for these controversial results may be the relationship between the developmental lag and temporal processing deficits in children with dyslexia. There is a 2-year discrepancy in mean age between two studies (Chung et al., 2008: 8.9; Meng et al., 2005: 10.9), and it may lead to the significantly different results, as discussed above (Hautus et al., 2003). Furthermore, although this age difference could enhance our understanding of temporal processing development in Chinese and its effect on the deficit among Chinese children with dyslexia, few, if any, previous studies have examined the differences in primary school–aged Chinese children.

Finally, the other possible reason for the discrepant results in these two studies is their focus on different reading performance outcomes. Chung et al. (2008) focused on character reading, whereas Meng et al. (2005) examined reading fluency, vocabulary size, and character naming. Considering the relatively complicated levels of reading in Chinese (Ku & Anderson, 2003) in which most single Chinese characters join with other characters to form different words, it is difficult to examine levels of reading performance while controlling the possible factors for each level. Therefore, this study focused on the character level, only PA, OK, and RAN were examined but not morphological awareness, because the role of morphological awareness in Chinese reading is relatively complicated and has greater contributions at higher levels of reading (e.g., McBride-Chang et al., 2008).

Research Aims

In sum, given the salient linguistic differences between Chinese and alphabetic languages, the present study aimed to investigate the visual and auditory temporal processing performance of Chinese children with and without dyslexia and their associated mechanisms relative to several literacy abilities and character reading in different primary school age groups. This study was designed with two major aims in mind.

The first aim was to ascertain whether temporal processing deficits would be found among Chinese children with developmental dyslexia at various primary school ages. According to Hautus and colleagues' (2003) study on alphabetic languages, ages of 10 to 11 years could be very important cutoff points, given that the auditory TOJ of children with dyslexia could catch up with that of children without dyslexia. Based on the nature and effect of the Chinese language (Chung et al., 2008), different developmental trends of auditory and visual TOJs might be found. Therefore, we expected to find significant developments in temporal processing until 10 to 11 years of age; however, this ceiling might differ for the two modalities.

The second aim was to examine visual and auditory temporal processing to explain variances in the literacy abilities, including PA, OK, and RAN, and character reading of Chinese children with and without dyslexia at different primary school ages. Specifically, we aimed to address whether these relations are similar or different for children with dyslexia versus typically developing children. Within this aim, two topics were targeted. First, visual and auditory TOJ's contributions to PA, OK, and RAN in different primary school age groups were examined. We expected to find modality-specific results indicating that auditory TOJ is particularly important for PA and that visual TOJ is important for OK, consistent with the works of Meng et al. (2005) and Chung et al. (2008). Furthermore, auditory and visual TOJs might significantly contribute to RAN (Catts et al., 2002). Second, visual and auditory temporal processing's contributions to character reading were also addressed, while controlling for literacy abilities. Based on the work of Chung et al., visual TOJ was expected to make a substantial contribution to character reading. For both these topics, children with dyslexia were expected to display a delayed pattern of TOJ, especially in the visual modality.

Methods

Participants

A total of 362 Chinese children from first to sixth grade were recruited from Taiwan and separated into three primary school age groups according to their current grades (i.e., first and second graders, third and fourth graders, and fifth and sixth graders). Half of the participants had dyslexia, and there were two steps for recruiting the students in this group. First, special educators at the primary schools selected students who were officially identified as having or were suspected of having learning disabilities by Taiwan local authorities and who scored in the lowest 25th percentile on the regular Chinese examinations in their classes. Furthermore, the primary definition of dyslexia was a standard score below −1.5 standard deviations on the *Chinese Character Recognition Test* (Huang, 2001) and normal intelligence (IQ score >80). This study's criteria for dyslexia also included normal or corrected-to-normal vision and hearing and the absence of attention-deficit/hyperactivity disorder. Finally, 57 first and second graders, 63 third and fourth graders, and 61 fifth and sixth graders with dyslexia were included in the study. The combination of two grades into one group reflected the methods used in previous studies that investigated temporal processing development among participants with and without dyslexia (e.g., Hautus et al., 2003).

The other half of the participants had standard development, with standard scores above −1.5 standard deviations on the *Chinese Character Recognition Test* (Huang, 2001), grade-appropriate reading achievement levels (and above the last 25th percentile of achievement in the subject of Chinese), normal intelligence, normal or corrected-to-normal visual acuity, and normal hearing. These participants

Table 1. Descriptive Statistics for Six Groups.

Grades (students per group)	Dyslexic	Typically developing	t	Cohen's d
First and second (n = 57)				
Age	7.76 (1.44)	7.91 (2.01)		
IQ	89.97 (13.09)	96.59 (17.42)	1.75	−0.43
Character reading	38.07 (17.22)	70.95 (13.36)	8.66**	−2.13
Third and fourth (n = 63)				
Age	9.70 (1.62)	9.85 (1.50)		
IQ	94.75 (16.59)	98.65 (16.57)	1.01	−0.24
Character reading	44.73 (15.77)	76.07 (12.23)	9.54**	−2.22
Fifth and sixth (n = 61)				
Age	11.37 (1.11)	11.68 (1.97)		
IQ	98.76 (17.06)	99.75 (12.48)	0.26	−0.07
Character reading	37.85 (12.69)	74.54 (10.85)	12.24**	−3.11

Note. Mean scores are presented with standard deviations in parentheses.
**p < .01.

were treated as controls and were carefully selected to match the dyslexia group in terms of age, IQ, and gender. In other words, the number of control subjects in each primary school age group corresponded to the number of children in the dyslexic group. The characteristics of these participants are presented in Table 1.

Measurements

The participants were tested with a number of cognitive and literacy abilities tests, including standardized tests and researcher-designed tasks. Within each session, the tasks were counterbalanced across participants. Specially, after completing the nonverbal intelligence and character reading tests used to screen participants, all eligible participants underwent random sequences of tests for the four abilities (i.e., OK tests, PA test, RAN test, and TOJ tasks). Detailed descriptions of these measures follow.

Nonverbal IQ test. *Raven's Standard Progressive Matrices–Parallel* is a standardized test of nonverbal IQ that consists of 60 items with increasing difficulty. Each item has a visual target matrix with one missing part. The children were provided with six- to eight-response options and were asked to select the response that completes the missing piece in the visual matrix. Nonverbal IQ was calculated per the Taiwanese norm established by the Chinese Behavioral Science Corporation in 2006 (Chen & Chen, 2006). Test-retest reliability was measured as .81 and was tested over a 35-day period.

Temporal order judgment tasks. Two temporal order judgment tasks were constructed according to tests devised by Bretherton and Holmes (2003) and Chung et al. (2008). The visual stimulus (visual temporal processing task) was a pair of white circles (O) and crosses (×) that measured 25 × 25 mm, and the auditory stimulus was a pair of sine wave tones (auditory temporal processing task; i.e., a low tone [250 Hz] and a high tone [500 Hz]). In both tasks, stimuli had a 75-ms duration and appeared consecutively, separated by an ISI of 8, 15, 30, 60, 150, or 305 ms. The stimuli were presented with four possible pair sequences: ×O, O×, ××, and OO for the visual modality and high-high, low-low, high-low, and low-high for the auditory modality. The order of the presentation of the conditions was counterbalanced.

For the visual and auditory temporal processing tasks, there were eight practice trials with visual feedback for the correct and incorrect responses, followed by 72 experimental trials consisting of 12 trials per ISI with random assignments. No visual feedback was provided in the experimental trials. The dependent measure was the number of trials conducted across the ISIs for which the response was correct (accuracy). Thirty fourth graders with standard development were tested prior to this measurement to check the test-retest reliability (the interval was 4 weeks); the results were .88 (visual temporal processing task) and .81 (auditory temporal processing task).

Character-reading measure. The *Chinese Character Recognition Scale*, developed by Huang (2001), is a standardized test in which the participants are asked to respond as quickly as possible by pronouncing characters aloud or writing their Zhuyin Fuhao, which is a widely used system in Taiwan that contains consonants, medial sounds, and rhymes that represent the sounds of Chinese characters. During the test, the teachers were not allowed to give the participants clues or hints. The test arrangement included 20 lines of 10 Chinese characters each, for a total of 200 Chinese characters. The test was designed for use with children in first through ninth grade. Test-retest reliability was measured as .94 with a 4-week interval.

Literacy ability measures

Phonological Awareness Test Battery. Tzeng, Chen, and Hsieh (2006) developed the *Phonological Awareness Test Battery* (screening) to test the PA of students in primary and secondary school. This test involves five tasks—vowel identification, consonant identification, lexical tone identification, phoneme deletion (onset), and phoneme blending—with 10 items in each task. In the three identification tasks, the participants listened to auditory stimuli and were asked to choose the correct answer from four options. In the phoneme deletion task, the participants listened to a compound sound with multiple phonemes and were then asked to delete the first sound (e.g., a stimulus /bei2/ with the answer /ei2/). In the phoneme blending task, two single sounds were presented, and the participants were asked to put them together and read the blended sound aloud (e.g., two stimuli /yi/ and /ang/ with the answer /yang/). All Cronbach's α coefficients should range from .60 to .73. The relationships between this task and other reading comprehension measurements and academic achievement in Mandarin Chinese are expected to be significant.

Orthographic knowledge tests. Three standardized measurements were used to measure OK in this study: the *Chinese-Radical Recognition Task*, the *Semantic Radical Task*, and the *Phonetic Radical Task*, which were taken from Hung and Fang (2006a, 2006b). For the *Radical Recognition Task*, 20 multiple-choice items were constructed with pseudo-characters or exceptional characters (Hung, 2006). In this test, four real characters or pseudo-characters were presented visually at the same time, and the participants were asked to choose a specific stimulus that did not contain a component that was common to the other three (i.e., the targeted radical). In this case, the targeted radical for each item was not highlighted or otherwise indicated. For instance, for the four stimuli 協, 捎, 賀, and [illegible], the correct answer is 捎 because all of the other stimuli include the radical 力. The *Semantic Radical Task* includes 17 multiple-choice items constructed with low-frequency characters containing semantic radicals with "different frequencies of the constructing character," "different positions of the semantic radical," and "deformations of the semantic radical" (Hung & Fang, 2006b). In this test, four real but low-frequency characters were presented visually, and the participants were asked to choose the character that did not have a relevant meaning. Low-frequency characters were selected as stimuli to discourage the participants from treating the characters as wholes instead of as components. For instance, four stimuli for beginners were 貓 (cat), 狗 (dog), 雞 (chicken), and 溪 (river), and only 氵 contains the semantic radical 吵 (water); therefore, it is the only character that is nature related rather than animal related. For the *Phonetic Radical Task*, 17 multiple-choice items were constructed with unusual characters with phonetic radicals with a "different position of the phonetic radical" and "different phonics" (Hung & Fang, 2006a). In this test, a target character is presented. Then, the participants are given four options and expected to choose the one with the same pronunciation as the target character. For instance, the participants are expected to choose 爐 (/chao3/), which is pronounced exactly the same as 炒 (/chao3/), from 爐(/lu2/), 尖(/chien1/), and 菜 (/tsai4/).

All three of these tasks are suitable for third- to ninth-grade students. All of the test-retest reliabilities were tested over a 2-week period, and all of the values were .88.

Rapid Automatized Naming Test. The *Rapid Automatized Naming Test* (Tzeng, Chang, Chien, & Ling, 2011) consists of four types of stimuli and five high-frequency items for each type: figure (i.e., [hand], [bowl], [pig], [tree], and [door]), digit (i.e., 1, 2, 3, 4, 5), color (i.e., [black], [red], [blue], [yellow], and [white]), and Zhuyin Fuhao (i.e., ㄅ/b/, ㄇ/m/, ㄧ/i/ or /yi/, ㄨ/u/ or /wu/, and ㄚ/a/). The participants were asked to name the stimuli in left-to-right order as quickly and accurately as possible. The mean total naming times were calculated. All of the test-retest reliabilities were tested over a 2-week period, and the values were .77 ~ .91.

Data Analysis

First, multivariate analyses of covariance and analyses of covariance (ANCOVAs) were employed to compare the means of the visual and auditory TOJ tasks for the children with and without dyslexia in the different primary school age groups. In addition, Pearson's correlation was used to calculate the data for the children with and without dyslexia in each primary school age group. Finally, hierarchical regressions were employed to examine the contributions of visual and auditory TOJ and literacy ability tasks to the variance in the character reading of children with and without dyslexia in each primary school age group.

Three types of analyses are presented. The first set of analyses compares the visual and auditory temporal processing performance and literacy abilities of the dyslexic and typically developing groups in each primary school age group. The second set of analyses correlates the visual and auditory TOJ, literacy ability tasks, and character reading of the six groups separately. The final set of analyses examines the contributions of the visual and auditory TOJ to literacy ability tasks and the variance in character reading of the six groups separately.

Results

Group Comparisons of Visual and Auditory Temporal Processing at Different Ages

The data were analyzed in two steps. First, a 2 × 3 ANCOVA—Categories (with and without dyslexia) ×

Table 2. Comparison of Visual and Auditory TOJ Tasks of Dyslexic and Typically Developing Children in Each Grade.

	Dyslexia (n = 30)		Typically developing (n = 30)		Main effect				Interaction	
					Grade		Category		Grade × Category	
Grades	M	SD	M	SD	F	η_p^2	F	η_p^2	F	η_p^2
Visual TOJ task										
First and second	31.58	8.77	51.06	6.14	112.01***	0.54	107.55***	0.36	1.20*	0.01
Third and fourth	49.86	10.26	64.36	5.67						
Fifth and sixth	59.08	11.3	65.72	6.88						
Auditory TOJ task										
First and second	39.98	10.18	52.59	8.05	71.08***	0.42	42.49***	0.18	1.03*	0.01
Third and fourth	55.67	10.10	60.65	6.18						
Fifth and sixth	61.05	9.97	64.07	5.82						

Note. With main effects and interactions from the 2 × 3 analysis of covariance. TOJ = temporal order judgment.
*p < .05. **p < .01. ***p < .001.

Primary School Ages (first and second graders, third and fourth graders, and fifth and sixth graders)—controlling for age and nonverbal IQ revealed a main effect for grade and category on both the auditory TOJ task and the visual TOJ task. The results are shown in Table 2.

Second, simple main effects were examined with t tests across visual and auditory TOJ tasks that were carried out in separate ANCOVAs to examine the group differences. According to the results, the children with dyslexia performed significantly worse than those without dyslexia in both modalities in the first and second grades (visual: t = 10.62, p = .000; auditory: t = 6.63, p = .000), in the visual modality in third and fourth grades (t = 7.87, p = .000) but not in the auditory modality in those grades (t = 1.65, p = .103), and in neither the visual nor auditory modality in fifth and sixth grades (visual: t = 1.67, p = .100; visual: t = 1.72, p = .093).

Moreover, among the children without dyslexia in three age groups, the first and second graders performed significantly worse than the third and fourth graders in both modalities (visual: t = −14.19, p = .000; auditory: t = −4.65, p = .000) and significantly worse than the fifth and sixth graders in both modalities (visual: t = −10.22, p = .000; auditory: t = −6.50, p = .000). However, there was no significant difference between the children without dyslexia in the third and fourth grades and the fifth and sixth grades in both modalities (visual: t = −0.62, p = .537; auditory: t = −2.09, p = .079).

Conversely, developmental differences among children with dyslexia in three age groups are more obvious than among children without dyslexia. The first and second graders performed significantly worse than the third and fourth graders in both modalities (visual: t = −6.67, p = .000; auditory: t = −8.06, p = .000) and worse than the fifth and sixth graders in both modalities (visual: t = −11.24, p = .000; auditory: t = −8.74, p = .000). However, among the children with dyslexia in the third and fourth grades and in the fifth and sixth grades, a significant difference was found in the visual modality (t = −4.53, p = .000) but not in the auditory modality (t = −0.71, p = .478).

Correlations Between Literacy Abilities and Temporal Processing

Partial correlations across all tasks, with nonverbal IQ and age statistically controlled, are presented in Table 3. The correlation patterns of children with and without dyslexia were similar in first to fourth grades. For the children with and without dyslexia in first and second grades—aside from the relationship between OK and PA—character reading, both types of temporal processing, and all other literacy abilities significantly correlated with each other. Auditory temporal processing showed significant correlations only with PA and RAN for children with and without dyslexia in third and fourth grades; significant correlations were also found with character reading, visual temporal processing, OK, and RAN. In particular, all of the literacy abilities and visual temporal processing results of the children with dyslexia in fifth and sixth grades significantly correlated with character reading but not with auditory temporal processing. Unlike the children with dyslexia, the children with typical; development showed a significant correlation only between character reading and OK and PA. Notably, RAN was significantly correlated with other literacy abilities and both temporal processing types for both groups of fifth and sixth graders.

Contributions of Temporal Processing Abilities to Literacy Abilities

Hierarchical regression analyses were used to examine the relationships between auditory and visual TOJs and OK, PA, and RAN for each group after controlling for nonverbal IQ and age. Table 4 indicates that the visual TOJ contributed

Table 3. Correlations of Visual and Auditory TOJ Tasks, Literacy Abilities, and Character Reading.

Grades: Measures	1	2	3	4	5	6
First and second						
1. Chinese character reading	—	.69**	.76**	.69**	.54**	.84**
2. Auditory temporal order judgment	.58**	—	.59**	.46**	.50**	.69**
3. Visual temporal order judgment	.61**	.52**	—	.62**	.47**	.73**
4. Orthographic knowledge	.63**	.66**	.48**	—	.11	.66**
5. Phonological awareness	.59**	.49**	.57**	.15	—	.62**
6. Rapid automatized naming	.77**	.63**	.70**	.51**	.65**	—
Third and fourth						
1. Chinese character reading	—	.12	.56**	.51**	.51**	.55**
2. Auditory temporal order judgment	.19	—	.19	−.04	.24*	.32**
3. Visual temporal order judgment	.58**	.20	—	.44**	.15	.53**
4. Orthographic knowledge	.62**	.09	.61**	—	−.17	.49**
5. Phonological awareness	.49**	.33**	.12	.09	—	.22+
6. Rapid automatized naming	.59**	.42**	.49**	.55**	.27*	—
Fifth and sixth						
1. Chinese character reading	—	−.10	−.05	.22+	.36**	−.17
2. Auditory temporal order judgment	.07	—	.11	−.09	−.09	.36**
3. Visual temporal order judgment	.29*	.13	—	.16	.16	.49**
4. Orthographic knowledge	.33**	−.07	.42**	—	.20	.46**
5. Phonological awareness	.27*	.10	.04	.08	—	.35**
6. Rapid automatized naming	.20+	.44**	.39**	.41**	.30**	—

Note. Controlling for the IQ and age of children with and without dyslexia in different primary school grades. The numbers highlighted in gray are for the children with dyslexia.
+*p* < .06. **p* < .05. ***p* < .01.

significantly to OK in first and second graders with and without dyslexia, even when the auditory TOJ was introduced first. The visual TOJ's contribution to the two groups of third and fourth graders was similar to that for the first and second graders. However, for the fifth and sixth graders, a nearly significant contribution of visual TOJ to OK was found only for the children with dyslexia (p = .061). Conversely, auditory TOJ contributed significantly to PA for first and second graders with and without dyslexia, even when the visual TOJ was introduced first. The contribution of the auditory TOJ to the two groups of third and fourth graders was similar to that for first and second graders.

The literacy ability that was most influenced by auditory and visual TOJs was RAN. In all three primary school age groups, the RAN of the children with and without dyslexia received significant contributions from auditory or visual TOJ, even when the other modality was introduced first. However, in most cases, visual TOJ had a greater contribution than auditory TOJ to RAN.

Contribution of Temporal Processing Abilities to Character Reading

In the subsequent regression analysis, we examined the relationships among auditory and visual temporal processing, OK, PA, and RAN for character reading of children with and without dyslexia in different primary school age groups. The information in Table 5 indicates that auditory or visual TOJ significantly influenced the character reading of children with and without dyslexia in the first and second grades after controlling for IQ, age, and literacy abilities. However, for third and fourth graders, only visual TOJ was found to contribute significantly to character reading among children with and without dyslexia. The contributions of visual and auditory TOJ were not significant for fifth and sixth graders. A nearly significant contribution of visual TOJ was found only in the children with dyslexia (p = .062) and not in those without dyslexia.

Discussion

Regarding the development of temporal processing in children with standard development, this study's results indicate that auditory and visual modalities revealed the same developmental trend (in which first and second graders performed significantly worse than third through sixth graders) as those revealed in previous studies that focused on the amodal dimension of auditory temporal processing (Davis & McCroskey, 1980; Irwin et al., 1985). However, the development of the children with

Table 4. Hierarchical Regression of ATOJ and VTOJ Tasks on Literacy Abilities for Children With and Without Dyslexia.

	First and second graders				Third and fourth graders				Fifth and sixth graders			
Variable	R^2	ΔR^2	R^2	ΔR^2	R^2	ΔR^2	R^2	ΔR^2	R^2	ΔR^2	R^2	ΔR^2
					Orthographic knowledge							
1. IQ/age	.02	.02	.07	.07*	.12	.12*	.10	.10*	.08	.08*	.09	.09*
2. ATOJ	.23	.20**	.33	.26**	.13	.01	.12	.02	.08	.01	.11	.02
3. VTOJ	.42	.19**	.50	.16**	.30	.17**	.33	.21**	.11	.02	.16	.05+
2. VTOJ	.40	.38**	.48	.41**	.29	.17**	.32	.22**	.10	.02	.16	.07*
3. ATOJ	.42	.01	.50	.02	.30	.00	.33	.01	.11	.01	.16	.00
					Phonological awareness							
1. IQ/age	.09	.09*	.05	.05*	.04	.04	.05	.05+	.03	.03	.05*	.05*
2. ATOJ	.32	.23**	.32	.27**	.09	.05*	.12	.07**	.04	.01	.07	.02
3. VTOJ	.36	.05*	.34	.02	.11	.02	.15	.03	.06	.02	.08	.01
2. VTOJ	.29	.21**	.22	.17**	.06	.02	.09	.04	.05	.03	.06	.01
3. ATOJ	.36	.07**	.34	.11**	.11	.05*	.15	.05*	.06	.01	.08	.01
					Rapid automatized naming							
1. IQ/age	.08	.08*	.04	.04	.07	.07+	.09**	.09**	.03	.03	.04	.04
2. ATOJ	.52	.44**	.54	.50**	.16	.10**	.18	.09**	.16	.13**	.23	.19**
3. VTOJ	.67	.15**	.65	.11**	.41	.25**	.42	.24**	.41	.26**	.39	.16**
2. VTOJ	.57	.49**	.41	.37**	.33	.26**	.36	.27**	.27	.24**	.26	.22**
3. ATOJ	.67	.10**	.65	.24**	.41	.08**	.42	.06*	.41	.14**	.39	.12**

Note. The numbers highlighted in gray are for the children with dyslexia. ATOJ = auditory temporal order judgment; VTOJ = visual temporal order judgment.
$^{+}p < .07$. $^{*}p < .05$. $^{**}p < .01$.

Table 5. Hierarchical Regression of VTOJ and ATOJ Tasks on Character Reading of Children With and Without Dyslexia.

	First and second graders				Third and fourth graders				Fifth and sixth graders			
Variable	R^2	ΔR^2	R^2	ΔR^2	R^2	ΔR^2	R^2	ΔR^2	R^2	ΔR^2	R^2	ΔR^2
1. IQ/age	.09	.09*	.07	.07*	.21	.21**	.14	.14**	.21	.21**	.17	.17**
2. VTOJ	.61	.53**	.54	.47**	.45	.24**	.47	.33**	.21	.00	.23	.06**
3. ATOJ	.70	.08*	.66	.12**	.46	.01	.50	.03	.22	.01	.23	.00
2. ATOJ	.52	.43**	.46	.39**	.22	.01	.19	.04	.22	.01	.18	.01
3. VTOJ	.70	.18**	.66	.20**	.46	.24**	.50	.31**	.22	.00	.22	.04*
2. PA/OK/RAN	.78	.69**	.72	.65**	.72	.51**	.63	.49**	.43	.22**	.46	.29**
3. VTOJ	.80	.02*	.76	.03*	.75	.03*	.72	.09**	.43	.00	.49	.03*
4. ATOJ	.81	.01*	.77	.01*	.75	.00	.72	.00	.45	.02	.50	.00
2. PA/OK/RAN	.78	.69**	.72	.65**	.72	.51**	.63	.49**	.43	.22**	.46	.29**
3. ATOJ	.79	.02*	.75	.03*	.72	.00	.64	.01	.44	.01	.47	.01
4. VTOJ	.81	.01*	.77	.02*	.75	.03*	.72	.07**	.45	.01	.50	.02+

Note. The numbers highlighted in gray are for the children with dyslexia. VTOJ = visual temporal order judgment; ATOJ = auditory temporal order judgment; PA/OK/RAN, phonological awareness/orthographic knowledge/rapid automatized naming.
$^{+}p < .07$. $^{*}p <.05$. $^{**}p <.01$.

dyslexia differed from that of the children without dyslexia, especially with respect to the visual modality. In terms of the development of the visual modality in the children with dyslexia, significant improvements were observed with increasing age across the primary school ages. Our results partially contradict Farmer and Klein's (1995) assumption that temporal processing in the visual modality, compared with the auditory domain, may improve in older children with dyslexia.

This inconsistency may be due to the different characteristics of English and Chinese. In an English context, phonological processing, especially PA, is considered key for reading abilities (Torgesen, Wagner, & Rashotte, 1994), and those who struggle with phonological processing may have problems with reading (Plaza & Cohen, 2003). Unlike English, however, the visual complexity of Chinese has been established by a large amount of evidence and is considered a core aspect of Chinese reading (Liu et al., 2015). The discrepancy might be reflected in the present study's finding that temporal processing developed later in the visual modality than in the auditory modality.

Furthermore, the present study's finding that auditory TOJ is a predictor of character reading in first and second graders is inconsistent with Chung and colleagues' (2008) results, although both studies found significant contributions of visual TOJ to character reading. The major reason for this inconsistency may be that the participants in the present study resided in Taiwan and those in Chung colleagues' study resided in Hong Kong.

Readers in Hong Kong typically learn Chinese with the "look and say" instructional method and without phonological coding training, which may lead Hong Kong children to rely on the visual rather than the auditory modality when they read Chinese characters (Ho, Chan, Lee, Tsang, & Luan, 2004). In contrast, a large amount of evidence shows that phonological coding training, including both Pinyin and Zhuyin Fuhao, facilitates onset awareness among young Chinese children (Lin et al., 2010). Phonological coding training is especially relevant to the Chinese learning goals of Taiwanese children in the first and second grades, which focus on both Chinese characters and Zhuyin Fuhao. The difference between children with and without phonological coding training might explain why the early primary school–aged Taiwanese children (first and second graders) in this study relied on both modalities when they processed Chinese character reading.

Moreover, although the participants in both Meng and colleagues' (2005) study and this study received phonological coding training, the contribution of auditory TOJ to character reading for the students in third and fourth grades is inconsistent with the findings of Meng and colleagues' study. This inconsistency may be due to disregard for the visual TOJ in Meng and colleagues' design, as we reviewed earlier. Additionally, it might be influenced by the different Chinese scripts where two studies were conducted. The participants in Meng and colleagues' study resided in mainland China, and they read simplified Chinese characters, whereas Taiwanese children in this study read traditional Chinese characters. The differences between two scripts of Chinese characters have been demonstrated to influence readers' cognitive and literacy abilities (McBride-Chang, Chow, Zhong, Burgess, & Hayward, 2005).

In addition to the similar pattern of temporal processing roles in OK and PA, auditory and visual TOJs showed a greater impact on RAN, which is consistent with Chung and colleagues' (2008) findings. The reason why both TOJs make significant contributions to RAN might be related to a similar mechanism (i.e., processing speed). This view was demonstrated in a wide-reaching investigation conducted by Catts et al. (2002), in which the processing speed of multiple aspects and RAN contributed to two aspects of reading performance. Therefore, the underlying mechanism of processing speed may strongly affect the performance of temporal processing and RAN, regardless of modality and grade.

This study has at least three limitations. First, the methods employed for the temporal processing task have recently been discussed as an important factor. In the traditional method of collecting temporal processing data, established in Tallal's studies (1980), a constant stimulus with predefined ISIs is used to measure rapid temporal processing abilities, and a score is calculated per the correct responses. However, advanced methods, such as temporal order thresholds or gap detection thresholds, require the repeated presentation of critical ISIs, which some have suggested increases the efficiency and reliability of the measurement (Steinbrink, Zimmer, Lachmann, Dirichs, & Kammer, 2014). In addition, this study compared visual and auditory temporal processing in children with and without dyslexia across primary school age groups, with a cross-sectional design. However, a developmental trajectory could not be precisely calculated or compared due to the limitations of the cross-sectional design, especially the slopes. Therefore, to provide more reliable evidence of the differences in visual and auditory temporal processing in children with and without dyslexia, a longitudinal design should be employed. Finally, this study showed differences in temporal processing between children with and without dyslexia in lower grades but not in upper grades. It is plausible, then, that reading experience (or a certain amount of reading experience) might explain the difference. This is an important limitation, and a longitudinal study following children from the prereading stage to the reading stage might clarify this limitation.

Despite the limitations listed here, the present study is among the first to show how temporal processing distinguishes children with and without dyslexia and predicts literacy abilities and character reading across primary school ages. The age-related change in the importance of temporal processing in Chinese children with and without dyslexia that we found in this study could enhance our understanding in this field and be useful for practitioners when developing teaching materials and delivering instructions.

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