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# The Roles of Various Forms of Attention in Temporal Processing Deficits in Chinese Children With and Without Dyslexia

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**Abstract**

This study examined the extent to which Chinese children with dyslexia show temporal processing deficits in addition to deficits in various forms of attention. In total, 104 Chinese children in primary school (Grades 3–6) were recruited in Taiwan. Half of the children were identified as having dyslexia, and the other half were typically developing children who were matched by gender, IQ, and age with the children with dyslexia. Our results indicated that Chinese children with dyslexia performed significantly worse on tasks of temporal processing, selective attention, and switching attention. Furthermore, both visual and auditory temporal processing, in addition to various attention types, could be significant distinguishing predictors between the two groups. Moreover, we found that visual temporal processing, but not auditory temporal processing, significantly contributed to Chinese character reading. This study was among the first to confirm the unique role of visual temporal processing in Chinese character reading.

**Keywords**

reading, learning disabilities, identification, thinking/cognition

## Introduction

According to the International Dyslexia Association (2002), dyslexia, a specific learning disability, is primarily characterized by difficulties with accurate and/or fluent word recognition and by poor spelling and decoding abilities that are not accounted for by a specific sensory deficit or by a more general intellectual impairment; in addition, 5% to 17% of children are estimated to suffer from reading difficulties or dyslexia (Chan, Ho, Tsang, Lee, & Chung, 2007). In alphabetic languages, there is abundant evidence showing that children with dyslexia have consistent difficulties with phonological processing—involving mostly phonological awareness (an individual's explicit awareness of the phonological structure of words) and/or rapid automatized naming (the speed at which an individual can retrieve the pronunciation of a stimulus from memory) (e.g., Wolf, Bowers, & Biddle, 2000). However, some scholars suspect that more fundamental abilities, such as basic domain-general deficits in the rapid processing of sequencing components and information—also known as temporal processing—are attributable to deficient cognitive and reading-related abilities as well as the reading and writing competences of dyslexia (Ramus, 2003). That is, based on such a perspective, the deficient phonological processing of children with dyslexia may also be influenced by their slower processing speed, especially when they must handle rapid, consecutive stimuli. Previous works have indicated children with dyslexia are less sensitive than are children without dyslexia to rapidly presented stimuli, achieving lower accuracy when the time interval between two stimuli is short. Such a deficit could influence phonological processing and transfer to reading competence (Farmer & Klein, 1995). Thus, temporal processing deficit is considered to be the core cause of dyslexia (Habib, 2000).

Investigations and debates concerning temporal processing deficits in children with dyslexia have been ongoing in recent decades. Many researchers have aimed to examine how temporal processing influences reading, but there has been insufficient clarification of the role of other cognitive abilities, such as attention, in the association between

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children's temporal processing and reading, especially for those suffering from reading difficulties (Landerl & Willburger, 2010). Recently, studies relevant to temporal processing deficits in Chinese children with dyslexia have begun to earn the attention of scholars (e.g., Chung et al., 2008; Meng et al., 2005; Wang & Yang, 2018); however, their research was not able to clarify the influence of attention on the associations between temporal processing and Chinese dyslexia and reading. Studies on this topic are crucial for enhancing our understanding of the universal implications of the importance of temporal processing in reading as well as temporal processing deficits in dyslexia. Therefore, this study aims to explore the extent to which Chinese children with dyslexia show temporal processing deficits in addition to deficits in various forms of attention.

## *Temporal Processing Deficits in Dyslexia*

Temporal processing refers to the processing of rapidly presented stimuli to detect the target stimuli or to identify changes in them based on their presenting sequence (Klein, 2002). An example of the assessment of temporal processing is the assessment of an individual's capability to detect the presentation order of two auditory stimuli (e.g., /da/ and /sa/) (Tallal, 1984). The underlying mechanism of temporal processing is believed to involve "time," so it is considered to relate to abilities such as verbal time estimation, time reproduction, and time discrimination (Moll, Göbel, Gooch, Landerl, & Snowling, 2016).

Based on this perspective, it is unsurprising that temporal processing is relevant to reading. Reading is believed to be a type of processing that requires readers to quickly detect elements in the written script (e.g., letters or suffixes among words; subjects or verbs among sentences), derive information (e.g., relevant semantic or phonetic information) from each element (Just & Carpenter, 1980), and combine the information to obtain the meaning (Cain, Oakhill, & Bryant, 2004). During this process, lower automaticity of word decoding would burden cognitive loading for higher level processing, such as reading comprehension. Thus, these two timely processes, temporal processing and reading, have a close relationship with each other (e.g., Bretherton & Holmes, 2003), and the causal relationship between auditory temporal processing and reading and spelling has also been preliminarily demonstrated (e.g., Strehlow et al., 2006).

Theoretically, it has been speculated that a neuropsychological mechanism is responsible for difficulty in processing very rapidly presented objects occurring in both auditory and visual modalities—a dysfunctional magnocellular system (Ramus, 2003). However, the deficits in auditory and visual modalities are thought to influence reading in different ways. Visual temporal processing deficits are considered to be one of the main causes of orthographic processing deficits in children, and these deficits are associated with the problematic processing of diverse levels of words (e.g., encoding letter position within letter strings or perceiving whole word forms in scripts), while auditory temporal processing deficits are suggested to be associated with phonological processing deficits, leading to difficulties in manipulating letter–sound correspondence (Booth, Perfetti, MacWhinney, & Hunt, 2000). In this sense, auditory and visual temporal processing deficits may reflect different degrees of reading problems due to the differentiated importance of phonological processing and orthographic processing for English word reading (Castles & Coltheart, 1993). In addition, rapid naming, an index of how quickly individuals can retrieve the name of a stimulus and then read it aloud (Powell, Stainthorp, Stuart, Garwood, & Quinlan, 2007), is also thought to involve both the visual and auditory modalities of temporal processing (Boets, Wouters, van Wieringen, & Ghesquière, 2007).

Although an increasing number of researchers have accepted this hypothesis, critiques have also been posed from different aspects (e.g., Moll et al., 2016). Some scholars believe that this inconsistency may be attributable to other factors, such as participant background, including age, or to other cognitive factors, including attention. This belief is theoretically reasonable because attention is undoubtedly required when processing occurs as a temporary activation of a sequence of elements that were presented in a rapid and capacity-limited (usually serial in nature) manner, based on information processing theory (Schneider & Shiffrin, 1977). However, some debates about the relationships of temporal processing, attention, and reading as well as dyslexia have been raised.

## *The Effects of Attention on Temporal Processing*

In recent decades, there has been abundant research on the effects of attention on reading, including switching attention (switching from one attentional focus to another; for example, Kieffer, Vukovic, & Berry, 2013), selective attention (consciously ignoring distractors and selecting an attentional focus; for example, Jaśkowski, 1993), and sustained attention (maintaining focus on repetitive stimuli; for example, Lam & Beale, 1991). In addition, although an increasing amount of evidence documents the importance of temporal processing for reading, only a few researchers have posed hypotheses regarding the relationships between attention and temporal processing.

The association between attention and temporal processing can be explained from two perspectives. First, scholars believe that temporal processing and attention are two distinct mental processing processes that have a hierarchical relationship. For instance, in the hierarchical model of different auditory processing levels in reading and spelling development (Schulte-Körne, Deimel, Bartling, &

Remschmidt, 1999), auditory temporal processing, which is located at Level 2 in their model, requires the participant's attention to consciously handle the successively presented stimuli. Furthermore, attention may play the role of "gatekeeper" during the handling of rapidly presented stimuli because the participants must be selectively attentive to become consciously accessible and aware (Eimer & Grubert, 2015). Scholars who support this view believe that attention serves as a prerequisite, to a certain degree, to temporal processing. Therefore, it is believed that children with dyslexia have both poor attention and poor temporal processing and that attention can only partially account for their deficient handling of rapidly presented stimuli.

Second, some scholars have argued that temporal processing deficits may not actually exist in dyslexia and that the poor temporal processing performance of children with dyslexia is solely the product of poor attention, especially attentional switching (Hari, Renvall, & Tanskanen, 2001; Lum, Conti-Ramsden, & Lindell, 2007). These scholars believe that children with dyslexia experience problems processing rapidly presented stimuli because they need more time to shift attention between the stimuli. This view is supported by a few studies on poor temporal processing, mainly in the auditory modality, in children with attention deficit hyperactivity disorder (ADHD) relative to typically developing children (e.g., Breier, Gray, Fletcher, Foorman, & Klaas, 2002). The introduction of medical treatment in children with ADHD led to great improvements in temporal processing, allowing these children to attain the performance level of their peers and temporarily curing their inattention (e.g., Fostick, 2017; Sawada et al., 2010).

To resolve this contradiction, Landerl and Willburger (2010) were the first to examine the independent importance of temporal processing for reading in addition to attention. They recruited a large sample size ($N = 439$) of primary-school-aged children of typical development to investigate this issue, and they reported that various forms of attention contributed significantly to temporal processing and that the combination of visual and auditory temporal processing significantly contributed to word reading but not to spelling, after controlling for attention. Their results proved the relationships among attention, temporal processing, and reading and support the view that both attention and temporal processing could be independently important for reading (Eimer & Grubert, 2015; Schulte-Körne et al., 1999).

Notably, the results from Landerl and Willburger (2010) were obtained from a combination of children with and without dyslexia. However, previous studies have indicated that primary-school-aged children with and without dyslexia tend to have distinct developmental profiles in their temporal processing (Wang, Liu, Chen, & Wu, 2018; Wang & Yang, 2018). In this sense, the results of Landerl and Willburger (2010) may not be comprehensive enough to explore the entirety of this issue, so further exploration and follow up on this topic is necessary. This study involves both children with and without dyslexia to more extensively examine the importance of temporal processing, in addition to various forms of attention, on reading ability.

In addition, all the previous studies that examined the aforementioned issue were conducted in alphabetic languages. However, based on the diverse nature of language, which has been preliminarily suggested to influence the role of temporal processing in reading (Tavassoli, 1999), evidence from studies on alphabetic languages may not be generalizable to research on nonalphabetic languages, such as Chinese.

### *Temporal Processing Deficits With the Chinese Language in Dyslexia*

In contrast to alphabetic languages, Chinese is considered to be a logographic language, and the basic graphic unit of Chinese is a character (equal to a morpheme, the smallest unit of meaning; Liu & McBride-Chang, 2010). The basic writing unit is a "stroke," and certain stroke patterns can construct a "radical." For instance, the radical 木 is formed by four strokes. There are two main kinds of radicals: semantic radicals, which represent the meaning of the entire character, and phonetic radicals, which provide information about the sound of the whole character. Under different circumstances, the radical itself is treated as part of a character or as a whole character (Chung et al., 2008). For instance, 好 (good) is made up of a radical 女 (woman) and a character 子 (child). After children become familiar with radicals, they then move to the next stage, namely, how the pieces of radicals come together to construct a Chinese character (Ho, Yau, & Au, 2003). Knowledge in this stage can not only significantly predict a child's competence (e.g., Ho, Ng, & Ng, 2003) but also enhance the number of characters that are familiar to them and help them detect the meaning and sound of each Chinese character (Ho & Bryant, 1997). Thus, Chinese reading is expected to rely heavily on reader's basic level of visual processing skills as well as his or her visual-orthographic knowledge, which has been proven by previous studies (Ho, Chan, Lee, Tsang, & Luan, 2004; Liu, Chen, & Chung, 2015). Based on such assumptions, temporal processing deficits of dyslexia in the Chinese language are different from those in alphabetic languages; the importance of visual temporal processing was found to dominate that of auditory temporal processing (Chung et al., 2008).

Although most relevant studies conducted in Chinese contexts have consistently indicated that both Chinese children with and without dyslexia were able to distinguish between visual and auditory temporal processing (e.g., Chung et al., 2008; Meng et al., 2005; Wang & Yang, 2018), the significant predictors of temporal processing related to

Chinese character reading remain controversial, especially in the auditory modality.

For instance, Meng et al. (2005) reported that auditory temporal processing made a significant contribution to phonological awareness when first controlling for nonverbal IQ and tone frequency discrimination, and such importance was also found to affect participants' reading fluency and character naming speed. Similarly, Wang and Yang (2018) also disclosed the crucial role of auditory temporal processing in both phonological awareness and rapid naming, and the independent prediction of auditory temporal processing when controlling for phonological awareness and rapid naming regarding Chinese character reading remains if the participants are relatively young. In contrast, Chung et al. (2008) found that the contribution of temporal processing to Chinese character reading was mediated by rapid naming, but only visual temporal processing was significant. Likewise, Zhang and McBride-Chang (2014) failed to find the independent prediction of auditory temporal processing for phonological awareness, rapid naming, or Chinese character reading.

As shown by our review of the clear association between temporal processing and attention as well as their importance in reading, the aforementioned controversial evidence in the Chinese context in this field may be affected by the failure to consider attention. In particular, the controversy relates mostly to the auditory modality, which was found to be more easily affected by attention than was the visual modality (Shinn-Cunningham, 2008).

Furthermore, although the significant influence of attention on reading has been widely investigated in both Chinese and alphabetic languages and has been recognized as a global phenomenon (Skottun & Skoyles, 2006), the influence of cultures and languages should not be ignored. More specifically, evidence indicates that different structures of languages may influence children's development or performance in reading-related abilities, such as phonological awareness. For instance, bilingual students in Toronto were found to perform better than bilingual students in China in English phonological awareness tasks (e.g., McBride-Chang, Bialystok, Chong, & Li, 2004). In addition, culture may affect individual performance in cognitive tasks, such as attention tasks. For instance, children in the United States were found to outperform Japanese children in locating a specific object in a cluttered, but organized as a scene, visual field in which object-centric attention was expected to potentially aid performance while relational attention was expected to potentially hinder it (e.g., Kuwabara & Smith, 2012).

Although attentional deficits in children with dyslexia have been well documented by studies conducted in alphabetic languages, this evidence cannot be directly generalized due to the potential influence of differences in languages and cultures. Notably, only a few studies have indicated the presence of deficient attention in Chinese children with dyslexia (e.g., Ding et al., 2016); therefore, the role of attention in the relationship between temporal processing and Chinese reading in children with and without dyslexia remains unclear.

## Current Study

To explore whether Chinese children with dyslexia indeed show temporal processing deficits when various forms of attention are considered, three research aims were addressed: first, to compare the performance on various tasks of attention between Chinese children with and without dyslexia; second, to examine whether the discriminant function of visual and auditory temporal processing remains in Chinese children with and without dyslexia when reading-related abilities and various forms of attention are first introduced; and finally, to examine whether the importance of temporal processing remains for Chinese character reading, after controlling for reading-related abilities and various forms of attention.

## Method

### *Participants*

A total of 104 native Chinese-speaking children from Taiwan in primary school (Grades 3–6) were recruited. Half of the participants ($n = 52$; 20 male) had been identified as having dyslexia. There were two steps for recruiting the students in this group. First, the pool of students with dyslexia was referred from those who had been officially identified as having or who had been suspected of having learning disabilities by local authorities in Taiwan. Furthermore, the defining criteria of dyslexia in this study include the following: an earned standardized score on the *Chinese Character Recognition Test* (Huang, 2001) of 1.5 standard deviations below the mean, normal intelligence (an IQ score greater than 80), normal or corrected-to-normal vision and hearing, and the absence of ADHD. All the recruited children with dyslexia were placed in the mainstreaming classroom/school, and most of them were receiving pullout service from their special education teachers.

In addition, the remaining participants ($n = 52$; 20 male) were typically developing children who met the following criteria: standard scores on the *Chinese Character Recognition Test* (Huang, 2001) close to or above the mean, grade-appropriate reading achievement levels, normal intelligence, and normal or corrected-to-normal visual acuity and normal hearing. The participants in the latter group comprise the chronological age control group.

We recruited children with dyslexia first and then matched the sample with typically developing children. To eliminate those factors, such as socioeconomic status, that

**Table 1.** Characteristics of the Two Groups.

| Measures | Dyslexia | | Typically developing | | | |
|---|---|---|---|---|---|---|
| | *M* | *SD* | *M* | *SD* | $t(102)$ | Cohen's *d* |
| Age | 10.42 | 1.07 | 10.28 | 1.26 | 0.59 | 0.12 |
| IQ | 105.81 | 8.52 | 105.85 | 7.56 | −1.92 | −0.37 |
| Chinese character reading | 28.65 | 6.50 | 42.92 | 6.02 | −11.61** | −2.28 |
| Visual temporal processing | 45.33 | 7.93 | 56.94 | 8.02 | −7.43** | −1.47 |
| Auditory temporal processing | 45.12 | 7.57 | 56.65 | 8.03 | −7.54** | −1.49 |
| Phonological awareness | 50.90 | 11.23 | 58.90 | 8.70 | −4.06** | −0.80 |
| Orthographic knowledge | 42.83 | 9.68 | 50.40 | 9.72 | −3.98** | −0.79 |
| Rapid naming | 102.32 | 7.44 | 95.41 | 6.27 | 5.12** | 1.01 |
| Sustained attention | 57.13 | 12.69 | 60.90 | 8.70 | −1.77 | −0.35 |
| Selective attention | 47.25 | 12.97 | 59.85 | 6.40 | −6.28** | −1.24 |
| Attentional switching | 44.85 | 9.64 | 60.40 | 6.77 | −9.53** | −1.89 |

*Note.* There were 52 participants in each group.
** $p < .01$.

were not controlled for in this study, we invited children from the same school, or at least a nearby school in the same district (which is a unit of the administrative subdivision of provincial cities of Taiwan), as those with dyslexia to join the study as the chronological age control group.

In addition, the participants in the two groups were carefully matched in terms of age, IQ, and gender, and there were no significant differences between the groups regarding age, whereas the group difference in Chinese character reading was significant. The descriptive statistics of the two groups are shown in Table 1.

## Measures

*Raven's standard progressive matrices-parallel.* This instrument is a standardized test for nonverbal IQ. In this test, 60 items are arranged in order of increasing difficulty; each item has a target visual matrix with one missing part. The children were asked to select the response that completed the missing piece in the visual matrix from six to eight options. Nonverbal IQ was calculated based on the Taiwanese norm established by the Chinese Behavioral Science Co. in 2006 (Chen & Chen, 2006).

*Chinese Character Recognition Test.* The *Chinese Character Recognition Test* was developed by Huang (2001). In this test, participants are asked to orally pronounce characters as quickly as possible. During the task, teachers are asked to record the participants' responses without giving any cues or hints. The task arrangement includes 20 lines, and each line includes 10 Chinese characters, for a total of 200 Chinese characters. The applicable targets of this task are first graders to ninth graders. In terms of the manual, the test–retest reliability, based on tests at two time points over a 4-week period, was .94. Furthermore, to minimize student weariness and maintain motivation, especially since half of the students had dyslexia, the participants were given a 1-min time limit as suggested by previous works (e.g., Ho, Chan, Tsang, & Lee, 2002; Ho et al., 2004; Zhao, Liu, Liu, & Huang, 2018). Research has shown that the results of character reading tasks using such approaches are sufficiently representative.

*Visual and auditory temporal processing.* This task was constructed based on tests devised by Bretherton and Holmes (2003). In terms of the modality stimulus presented, there is a visual version and an auditory version in this study. The visual stimulus included a pair of white circles (O) and crosses (×) measuring 25 × 25 mm, and the auditory stimulus included a pair of pure tones, that is, a low tone (250 Hz) and a high tone (500 Hz). For both modalities, the stimuli each had a 75-ms duration and appeared consecutively, separated by intervals of 8, 15, 30, 60, 150, or 305 ms. The stimuli were presented with four possible pair sequences: ×O, O×, ××, and OO in the visual modality and high-high, low-low, high-low, and low-high in the auditory modality. The order of presentation of the conditions was counterbalanced.

Each modality had eight practice trials, with visual feedback for both correct responses and incorrect responses, followed by 72 experimental trials consisting of 12 trials per interstimuli interval, with no visual feedback given for the experimental trials. The number of trials with correct responses across the intervals was calculated. Based on the investigation by Wang and Yang (2018), this paradigm has good test–retest reliability (the time interval was 4 weeks) for the tasks in both modalities (the visual modality is .88, whereas the auditory task is .81).

*Phonological Awareness Test.* These tasks were adapted from Tzeng, Chen, and Hsieh's (2006) work on testing the phonological awareness of primary and secondary school-aged students. Five tasks, with 15 items in each task, were used to test the participants' phonological awareness in this study: vowel identification, consonant identification, phoneme deletion, phoneme blending, and tone awareness. In both identification tasks, the participants were asked to identify the vowel/consonant in a compound sound. In the phoneme deletion task, the participants were invited to delete the onset sound from a compound sound and then to read aloud the rest of the sound. In the phoneme blending task, the participants were asked to combine two or three sounds provided orally by the examiner. Finally, in the tone awareness task, the participants were asked to identify the lexical tone of each combined sound. The composite score was the combination of the standardized scores from all five tasks used in this study. All Cronbach's α coefficients were found by Wang and Yang (2018) to be between .60 and .73.

*Orthographic knowledge tests.* In the present study, orthographic knowledge was determined by two standardized measurements, namely, the semantic radical task and the phonetic radical task created by Hung and Fang (2006a, 2006b), for testing functional and positional knowledge of semantic radicals and phonetic radicals, respectively. Each task consisted of 17 multiple-choice items with four choices each. In the semantic radical task, the stimuli were constructed of exceptional characters with semantic radicals of "different frequencies of the constructing character," "different positions of the semantic radical," and "deformations of the semantic radical" (Hung & Fang, 2006a). Four real but low-frequency characters were presented visually in each item, and the participants were asked to choose the character that did not have a relevant meaning. For instance, the participant should choose a character that is not related to wood from the following options: 柏 (cypress), 棋 (chess), 槊 (spear), and 跑 (run); the answer is 跑 because it is the only option that does not contain the semantic radical 木 (wood). On the contrary, the stimuli in the phonetic radical task were constructed of unusual characters using phonetic radicals with a "different position of the phonetic radical" and with "different phonics" (Hung & Fang, 2006b). The participants were asked to choose the right character from four options that were pronounced identically to the target character. For instance, the participants are expected to choose 塘 (/tang2/) to match 糖 (/tang2/) from 聽 (/ting1/), 想 (/xiang3/), and 沾 (/zhan1/). Both tasks are suitable for third- to ninth-grade students. All test–retest reliabilities, based on tests at two time points over a 2-week period, were .88.

*Rapid Automatized Naming Test.* This measure was taken from the *Rapid Automatized Naming Test*, developed by Tzeng, Chang, Chien, and Ling (2011), to test the participants' information retrieval speed. This test consists of four types of stimuli: figure, digit, number, and zhuyin fuhao. During this test, one type of stimulus was implemented each time, and the participants were asked to name the stimuli in order from left to right as quickly and accurately as possible. The mean total naming times were calculated. All test–retest reliabilities involving a 2-week interval were .77 to .91. The response time for each type of stimulus was recorded, and the combination of the types was used to represent their rapid naming.

*Attention measurements.* In terms of the empirical analysis in Manly et al. (2001), one of the best models to assess children's attention divides it into sustained attention, selective attention, and attentional switching; this kind of classification was used in this study. In this study, three tests adapted from the *Test of Everyday Attention for Children* (Manly, Robertson, Anderson, & Nimmo-Smith, 1998) were administered: SCORE! for sustained attention, Opposite Worlds for attentional control/switching, and Map Mission for selective attention. All three tests are suitable for kindergarten to secondary-school-aged children (Manly et al., 2001).

*SCORE!* This subtest was used to measure sustained attention by requiring the child to silently listen to an audiotape without the use of finger counting and to report the number of irregular bleeps detected over a continuous time interval. Two practice sessions were provided, and then 10 test trials were given. For each trial, the tones ranged in number from 9 to 15.

*Map mission.* This subtest was used to test selective attention. The participants were presented with a city map containing eighty randomly distributed targets representing restaurants (i.e., small knife and fork symbols) and eighty distracting symbols (i.e., supermarket trolleys, cups, or cars), and they need to circle as many targets as possible in 1 min. The performance score was the number of target symbols correctly marked (maximum score = 80).

*Opposite worlds.* This subtest, which requires the inhibition of a familiar response, was used to measure attentional switching. In the task, the children were presented with a stimulus sheet showing a mixed, quasi-random array of the digits 1 and 2, and they were asked to say the opposite of each digit ("one" for 2 and "two" for 1) as quickly as possible, inhibiting the prepotent verbal response. The number of accurate responses within 2 min was recorded.

## Data Analysis

To achieve the research aims in this study, many statistical methods were used. Analyses of covariance (ANCOVAs) were applied, while controlling for IQ and age, to meet the first research aim. Furthermore, binary hierarchical logistic regression analysis was introduced to test the discriminant function of visual and auditory temporal processing in Chinese children with and without dyslexia, while controlling for reading-related abilities and various forms of attention. Finally, two sets of hierarchical multiple linear regression analyses were used to examine the predictions of visual and auditory temporal processing with regard to the Chinese character reading of the two groups separately, while controlling for IQ, age, reading-related abilities, and various forms of attention. The sample size for the statistical methods we used, 52 participants per group, is sufficient or close to sufficient for implementing all statistical methods with a statistical power of .8 with certain effect sizes, and an $\alpha$ error probability of .05, according to G*Power—ANCOVA (effect size = .35): 55/group; partial correlation analysis (effect size = .35): 46; binary hierarchical logistic regression analysis, $P(Y = 1) = .2$: 60/group; hierarchical multiple linear regression analysis (effect size = .35): 57/group.

## Results

To compare the performance on various attention tasks between Chinese children with and without dyslexia, ANCOVA was carried out. The results indicated that, except for sustained attention, $F(1, 103) = 3.34$, $p > .05$, the performance of children with dyslexia on most of the temporal processing—visual temporal processing, $F(1, 103) = 58.03$, $p < .01$, $\eta_p^2 = 0.37$; auditory temporal processing, $F(1, 103) = 57.38$, $p < .01$, $\eta_p^2 = 0.37$—and attention tasks, selective attention: $F(1, 103) = 40.32$, $p < .01$, $\eta_p^2 = 0.29$; attentional switching: $F(1, 103) = 46.29$, $p < .01$, $\eta_p^2 = 0.32$, was significantly worse, while controlling for IQ and age, than the performance of those without dyslexia. In addition, the effect sizes between the two groups tended to be similar for all the abilities that were found to have significant group differences.

Greater individual differences among the children with dyslexia than among those without were evident across the different types of attentional performance tasks (sustained attention *SD*: 12.69 for dyslexia, 9.64 for typically developing; selective attention *SD*: 12.97 for dyslexia, 6.40 for typically developing; switching attention *SD*: 8.70 for dyslexia, 6.77 for typically developing).

To delve more deeply into this phenomenon, descriptive statistics are reported. We adopted the percentage of children with dyslexia whose scores fell more than 1 standard deviation below the mean of the control group on each of the attention tasks; this method has been used in many previous studies (Birch & Chase, 2004; Chung et al., 2008). Our results indicated that individual differences in diverse attention among the children with dyslexia were large. Specifically, only 5.77%, 15.38%, and 11.53% of the children with dyslexia performed significantly worse than the typically developing children on sustained attention, selective attention, and attentional switching tasks, respectively. Furthermore, 3.85% of the children with dyslexia had significant problems with both sustained and selective attention, whereas 5.77% performed significantly worse than the children without dyslexia on both selective attention and attentional switching. In addition, 11.54% of the children with dyslexia performed significantly worse than the typically developing children on all three attention tasks.

To examine whether the importance of temporal processing remains for Chinese character reading, while controlling for reading-related abilities and various forms of attention, partial correlations were first introduced to separately test the overall relationships of attention, temporal processing, reading-related abilities, and the reading performance of children with and without dyslexia. The results, which are shown in Table 2, indicated that the two groups have similar relationship patterns for reading, temporal processing, and attention.

In addition, binary hierarchical logistic regression analysis was used to test the discriminant functions of auditory and visual temporal processing in distinguishing Chinese children with and without dyslexia while controlling for phonological awareness, orthographic knowledge, rapid naming, sustained attention, selective attention, and attentional switching. In Step 1, visual temporal processing and auditory temporal processing were entered first, and the results revealed that both types of processing significantly predicted the membership of the two groups—visual temporal processing: $\chi^2 = 45.09$, Wald = 25.04, significance = .000, $\exp(\beta) = 1.21$; auditory temporal processing: $\chi^2 = 17.20$, Wald = 12.89, significance = .000, $\exp(\beta) = 1.17$. Further logistic regression analysis was conducted, and three reading-related abilities were introduced together before visual temporal processing and auditory temporal processing. The results indicate that the predictors of visual temporal processing, $\chi^2 = 12.63$, Wald = 9.60, significance = .002, $\exp(\beta) = 1.15$, and auditory temporal processing, $\chi^2 = 12.96$, Wald = 10.11, significance = .001, $\exp(\beta) = 1.16$, remained significant and that even reading-related abilities were a significant predictor ($\chi^2 = 38.21$). Finally, in another logistic regression, three attentional tasks were entered together in Step 2 before visual temporal processing and auditory temporal processing. The results suggested that the three attentional tasks significantly predicted the membership of the two groups ($\chi^2 = 46.30$) and that both visual temporal processing, $\chi^2 = 4.86$, Wald = 4.19, significance = .041, $\mathrm{Exp}(\beta) = 1.15$, and auditory temporal processing, $\chi^2 = 8.93$, Wald = 6.67, significance = .010, $\exp(\beta) = 1.17$, were also significant predictors.

Finally, to examine whether the importance of temporal processing remains for Chinese character reading when

**Table 2.** Correlations of Attention, Visual, and Auditory Temporal Processing; Reading-Related Abilities; and Character Reading in Children With and Without Dyslexia, Controlling for IQ and Age.

| Measures | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| 1. Chinese character reading | — | .67** | .33* | .20 | .43** | −.42** | .46** | .54** | .38** |
| 2. Visual temporal processing | .72** | — | .18 | .20 | .35* | −.40** | .43** | .54** | .21 |
| 3. Auditory temporal processing | .44** | .62** | — | .14 | .14 | −.31* | .34* | .18 | .32* |
| 4. Phonological awareness | .19 | .39* | .53** | — | .02 | −.06 | .04 | .20 | .18 |
| 5. Orthographic knowledge | .53** | .55** | .14 | .06 | — | −.07 | .27† | .17 | .06 |
| 6. Rapid naming | −.52** | −.64** | −.37** | −.04 | −.62** | — | −.38** | −.30 | −.29* |
| 7. Sustained attention | .49** | .62** | .38** | .12 | .44** | −.46** | — | .42** | .18 |
| 8. Selective attention | .55** | .56** | .23 | .14 | .28* | −.30** | .54** | — | .33* |
| 9. Attentional switching | .36* | .53** | .29* | .12 | .38** | −.49** | .50** | .36** | — |

*Note.* The numbers highlighted in gray are for children with dyslexia.
†$p < .06$. *$p < .05$. **$p < .01$.

**Table 3.** Contributions of Attention and Temporal Processing to Character Reading of Children With and Without Dyslexia.

| | Character reading | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Measures | $R^2$ | $\Delta R^2$ | β | *t* | $R^2$ | $\Delta R^2$ | β | *t* |
| 1. IQ | .18 | .18** | .35 | 2.67** | .16 | .16* | .30 | 2.30* |
| Age | | | .26 | 2.00† | | | .25 | 1.92† |
| 2. Visual temporal processing | .58 | .40** | .58 | 5.88** | .59 | .44** | .72 | 5.73** |
| Auditory temporal processing | | | .20 | 2.05* | | | .02 | 0.15 |
| 2. Phonological awareness | .47 | .30** | .15 | 1.41 | .46 | .30** | .15 | 0.20 |
| Orthographic knowledge | | | .36 | 3.34** | | | .33 | 2.18* |
| Rapid automatized naming | | | −.34 | −3.18** | | | −.30 | −2.03* |
| 3. Visual temporal processing | .63 | .16** | .45 | 4.04** | .63 | .16** | .60 | 3.56** |
| Auditory temporal processing | | | .14 | 1.44 | | | .09 | 0.65 |
| 3. Sustained attention | .61 | .14** | .14 | 1.16 | .58 | .11* | .34 | 2.74** |
| Selective attention | | | .28 | 2.44* | | | .08 | 0.58 |
| Attentional switching | | | .16 | 1.46 | | | −.03 | −0.22 |
| 4. Visual temporal processing | .68 | .07* | .34 | 2.83** | .66 | .08* | .46 | 2.32* |
| Auditory temporal processing | | | .08 | 0.82 | | | .13 | 0.95 |

*Note.* The numbers highlighted in gray are for children with dyslexia.
†$p < .06$. *$p < .05$. **$p < .01$.

considering attention, another two sets of two-round hierarchical multiple linear regressions were introduced to test the contributions of visual and auditory temporal processing to the character reading of children with and without dyslexia, while controlling for IQ, age, three reading-related abilities (i.e., phonological awareness, orthographic knowledge, and rapid naming), and three attentional tasks (i.e., sustained attention, selective attention, and attentional switching). In selecting the predictors for hierarchical regression analyses from Chinese character reading, the participants' age and IQ were first entered as covariates in Step 1 for both groups. In Step 2, visual and auditory temporal processing were entered without introducing all other controlled variables to test their pure predictions for Chinese character reading for children with and without dyslexia, respectively. After that, another round of regressions was conducted, and three reading-related abilities (in Step 2) and three attentional tasks (in Step 3) were entered after participants' age and IQ (in Step 1) before visual and auditory temporal processing (in Step 4). All the results are presented in Table 3.

In summary, our findings indicated that Chinese children with dyslexia performed significantly worse on tasks involving temporal processing and most forms of attention than did typically developing children. In addition, both visual and auditory temporal processing were demonstrated to be significant predictors for distinguishing Chinese children with and without dyslexia in addition to reading-related abilities and various forms of attention. Finally, we found a similar cognitive profile between the two groups of students, in which visual temporal processing significantly contributed to Chinese reading ability, first introducing their background information, reading-related abilities, and various forms of attention.

## Discussion

In this study, we aimed to explore whether Chinese children with dyslexia have temporal processing deficits in forms of attention. Our results are among the first to demonstrate the specific characteristics of temporal processing deficits in Chinese children with dyslexia.

First, we intended to compare the performance on various attention tasks between Chinese children with and without dyslexia. Considering the high comorbidity of dyslexia and ADHD (Wang & Chung, 2018), most previous studies of children with dyslexia excluded those with ADHD during recruitment to avoid the influence of poor attention. Undeniably, however, children with dyslexia have been demonstrated to have mild attention problems even though they do not meet the diagnostic criteria of ADHD (Cohen, 1994). Thus, we were not surprised to find that the recruited participants with dyslexia in our study showed significantly poor performance on two of the three forms of attention, namely, selective attention and attentional switching. Previous studies in alphabetic languages have consistently found that the children with dyslexia have significant attentional problems, mainly involving selective attention (e.g., Kershner, 2016; Sterr, 2004) and attentional switching (e.g., Lallier et al., 2010; Lum et al., 2007; Sterr, 2004). Considering that recognizing Chinese characters requires visually selecting target stimuli and then switching from one stimulus to another, the poor performance related to these two forms of attention in Chinese children with dyslexia is understandable and consistent with previous works (e.g., Ding et al., 2016; Liu, Chen, & Wang, 2016).

Our second research aim is to examine whether the discriminant function of visual and auditory temporal processing remains in Chinese children with and without dyslexia. Our results indicate that various forms of attention could significantly distinguish between Chinese children with and without dyslexia, after controlling for other reading-related abilities, while visual and auditory temporal processing, in addition to attention, could also be significant predictors separately. In this case, it is clearly evident that temporal processing still has its own unique predictive power for distinguishing between the two groups.

In addition, our results in which auditory temporal processing is a significant predictor for distinguishing between Chinese children with and without dyslexia are consistent with those of Meng et al. (2005) and Wang and Yang (2018) but not with those of Chung et al. (2008) and Zhang and McBride-Chang (2014). This inconsistency across studies may be due to the different methods used when learning to read Chinese, that is, with or without receiving training in the phonological coding system. Children in Hong Kong learn to read Chinese characters using the look-and-say method, without a system of phonetic symbols to label their pronunciations, whereas those in mainland China and Taiwan learn to read Chinese characters using a system that contains phonetic symbols and includes a series of visual cues for sounds (Lin et al., 2010). Learning a phonological coding system is believed to strengthen children's phonological processing, especially their phonological awareness (McBride-Chang et al., 2004) and other underlying mechanisms of Chinese reading (Lee, Hung, & Tzeng, 2006).

As with Meng et al. (2005) and Wang and Yang (2018), our participants were recruited from a location where children learned the phonological coding system, while the participants in the studies of Chung et al. (2008) and Zhang and McBride-Chang (2014) were recruited in Hong Kong, where children did not receive training in the phonological coding system. Thus, it is reasonable to infer that the inconsistency with regard to the importance of auditory temporal processing in Chinese reading ability is due to the different locations used for participant recruitment. However, as direct evidence is still lacking, further examination is necessary.

Our final research aim is to test whether the importance of temporal processing remains for Chinese character reading, after controlling for reading-related abilities and various forms of attention. Our results revealed the significant contribution of visual temporal processing to Chinese character reading, but this pattern could not be found with auditory temporal processing. In addition, this pattern was consistent for children with and without dyslexia. This pattern, in which visual temporal processing outperforms auditory temporal processing in predicting Chinese character reading, is consistent with Chung et al. (2008) and Wang and Yang (2018).

The most unique design aspect of this study is that we involved not only reading-related abilities (i.e., phonological awareness, rapid naming, and orthographic knowledge) but also various forms of attention before the introduction of visual and auditory temporal processing in predicting Chinese character reading. Notably, the significant predictive power of visual temporal processing, but not auditory temporal processing, regarding Chinese character reading remained when various forms of attention were first introduced in the hierarchical regressions.

Our results essentially echo those of Landerl and Willburger (2010). In both Landerl and Willburger's (2010) study and this study, the temporal processing predictors of character and word reading, in addition to diverse attention, of primary-school-aged children were investigated, and all the results indicated that attention along with temporal processing could significantly predict character and word reading. However, the main differences between the study of Landerl and Willburger (2010) and the present study are as follows: (a) children with and without dyslexia were tested separately and (b) the various forms of attention were examined independently in this study. Thus, our results were one step further to disclosing the diverse patterns related to how attention predicts character reading in children with and without dyslexia.

In addition, we recruited the participating children in Taiwan, where Chinese is the sole official language, and the difference between the natures of alphabetic and nonalphabetic languages has been proven to influence readers' processing of their reading (e.g., McBride-Chang et al., 2004). As mentioned above, Chinese characters are highly demanding in the area of visual processing, and readers must recognize radicals and how these radicals are constructed. These visual stimuli must be recognized and then matched with the meaning of the information and with sounds in the mental lexicon (Yin & Weekes, 2003). To reach automaticity for reducing cognitive load, rapid processing of this detection and matching is necessary. Thus, it is unsurprising that visual temporal processing influenced Chinese character reading.

The findings of this study prove the predictive power of temporal processing in regard to proficiency in reading Chinese and distinguishing groups of people with and without dyslexia regardless of fundamental cognitive ability, namely, attention and reading-relevant abilities, that is, phonological awareness, rapid naming, and orthographic knowledge. In other words, our findings further demonstrate the role of temporal processing in Chinese reading.

In addition, it is worth noting that children with and without dyslexia tend to rely on different forms of attention when they read Chinese characters. Our results in Table 3 show that sustained attention might be a significant predictor of Chinese character reading in children with dyslexia but not in typically developing children. In contrast, the selective attention of typically developing children could significantly predict their Chinese character reading, while the same was not true for children with dyslexia. This phenomenon, which is consistent with the findings of a few previous studies, may reflect that children with dyslexia tend to rely on sustained attention, which is intact (Alloway, Wootan, & Deane, 2014), rather than selective attention, which is relatively poor (Sterr, 2004), when processing Chinese character reading.

This study has a few limitations. First, the measurements of various forms of attention in this study mainly relied on the visual modality. Considering that visual and auditory temporal processing were involved in the present study, the measures used for testing attention should also cover both modalities, echoing the multisensory temporal deficits of dyslexia (Krause, 2015).

Second, the ages of the recruited participants spanned Grades 3 to 6 in primary school, and a range of this size could lead to vast individual differences, considering the development of the participants' cognitive and reading-related abilities. In addition to the rapid development of different components of the executive function of typically developing children during this period (Anderson, 2002), Wang and Yang (2018) explicitly indicated differences between middle primary school ages and high primary school ages in visual and auditory temporal processing and their importance for Chinese reading in Chinese children with and without dyslexia. Thus, the combination of these two age levels may lead to unclear patterns.

Finally, recent increasing attention has been paid to the influence of children's socioeconomic status and their relationships with parents/teachers in their academic competence as well as cognitive abilities (e.g., Bradley & Corwyn, 2002; Hackman & Farah, 2009). In this study, we tried to match the schools in which the participants of the two groups were recruited; however, data on family–school environment were not collected because this topic was not the main focus. Thus, this study did not consider the influence of family–school environment on attention and temporal processing study, so future research should involve this factor.

Despite the limitations above, the present study is among the first to reveal the relationships among attention, temporal processing, and Chinese reading. The diverse influence of various forms of attention on both distinguishing between Chinese children with and without dyslexia and predicting Chinese character reading in the two groups was clearly evident. That is, selective attention and attentional switching were effective predictors for distinguishing between children with and without dyslexia. In addition, selective attention was a significant predictor of Chinese character reading in typically developing children, whereas sustained attention in children with dyslexia significantly predicted their Chinese character reading abilities. In addition to the contributions of attention, temporal processing in both modalities is a good discriminator for distinguishing between Chinese children with and without dyslexia, further confirming the unique role of visual temporal processing in Chinese character reading.

## *Implications for Practice*

Our results further demonstrated the importance of temporal processing in distinguishing between Chinese children with and without dyslexia as well as in recognizing Chinese characters and provide evidence for use by practitioners when designing teaching materials and instructional methods and adapting examinations to better fit their needs. In addition, although this study involves another fundamental ability, that is, attention, for examining the role of temporal processing, all of the constructs used were behavioral in nature and may be less sensitive than biological or neuropsychological evidence. Thus, future research should expand the paradigms in data collection to further examine the importance of temporal processing.

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