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Reduced perceptual processing speed and atypical attentional weight at the cores of visual simultaneous processing deficits in Chinese children with developmental dyslexia: a parameter-based assessment of visual attention

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Abstract

Individuals with developmental dyslexia usually exhibit a problem in simultaneous processing of multiple visual elements. However, the relationship between impaired visual simultaneous processing (VSP) and reading difficulty is still debated. These inconsistencies may be associated with a wide range of participants' age, variation in orthographic depth of background languages, and complex subcomponents underlying VSP. The present study thus examined the VSP capacity of children with dyslexia in the language context of Chinese (i.e., a logographic writing system with deep orthography) through the developmental trajectories method in which participants' age was considered as a continuous variable. This visual multiple-element processing skill was fractionated into four parameters (processing speed, visual short-term memory storage, attentional weight, and irrelevant inhibition) within the framework of the theory of visual attention (TVA). Forty-seven children with dyslexia and fifty-three age-matched normal readers from primary schools were recruited to take a combined TVA test using symbols as non-verbal stimuli. Results showed that the developmental trajectories of children with dyslexia exhibited a delayed pattern in perceptual processing speed and an atypical pattern in attentional weight compared to the controls. Further mediation analyses showed the triangular relationship of "TVA subcomponent-linguistic awareness-reading," revealing the possible roles of these subcomponents regarding VSP in Chinese reading. The current findings suggested that the VSP deficit of Chinese children with dyslexia may stem from impairments in perceptual processing speed and attentional weight, revealing the possible modulation of language specificity (i.e., Chinese) on cognitive deficits of dyslexia, which may have implications for the diagnosis and remediation of dyslexia.

Keywords Visual simultaneous processing · Chinese children · Developmental dyslexia · Theory of visual attention · Linguistic skills

Introduction

Developmental dyslexia (DD) is a long-lasting impairment in learning how to read accurately and fluently and in reading comprehension, which occurs despite normal intelligence and adequate reading instruction (World Health Organization, 2011). Recent research has suggested that DD is caused by a multifaceted disorder (Pennington & Peterson, 2015). Consistent with this multi-deficit view, individuals with DD usually scored lower on linguistic tests (Franceschini et al., 2018) and visual perceptual analysis and visual spatial attention tasks (Vidyasagar, 2019) compared to their typically developing peers. A striking impairment of individuals with dyslexia has been repeatedly reported in tasks commonly involving visual simultaneous processing (VSP). It has been suggested that impaired VSP is indicative of a visual attention span deficit in individuals with DD, defined as the number of distinct visual elements in a briefly presented array (e.g., a letter string) that can be processed in parallel (Bosse et al., 2007; Chen et al., 2019; Valdois et al., 2019). To understand the role of this VSP deficit in reading disorders, it is necessary to examine the internal mechanisms of this impaired visual

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skill. As has been argued previously (Stefanac et al., 2019; Stenneken et al., 2011), this specific VSP deficit might potentially arise from multiple underlying contributing processes (Valdois et al., 2019). Relevant literature usually used parameter-based measures within the framework of the theory of visual attention (TVA; Bundesen, 1990) to disentangle the subcomponents underlying the VSP deficit in DD (e.g., Bogon et al., 2014b; Dubois et al., 2010; Stefanac et al., 2019). TVA describes the process of selecting and encoding visual categorizations into short-term memory and can be utilized to estimate attentional parameters at the individual level with whole/partial report tasks (Habekost, 2015). There are two types of parameters related to VSP: one type of parameter reflects the stimulation-driven bottom-up visual attention, including visual processing speed (parameter *C)* and the storage capacity of visual short-term memory (VSTM, parameter *K*), which can be estimated by inputting performances of the whole report task into the TVA model; the other type of parameter reflects the top-down regulation of visual attention, including spatial bias of attentional weight (parameter ω) and efficiency of attentional control (parameter α), which can be estimated by the participants' performance in the partial report task. Vangkilde et al. (2011) intermixed whole and partial report trials and used six display stimuli to develop a combined TVA (CombiTVA) paradigm to better constrain the total set of parameter estimates regarding the VSP skill. This paradigm has already been widely used in many clinical studies focusing on neurodevelopmental disorders (see the review of Habekost, 2015). TVA-based assessments have also been preliminarily applied in research on DD. TVA permits us to explore the potential contributions of reduced VSTM storage capacity, low speed of information processing, lateralized impairments in the spatial distribution of attention, and the inability to inhibit distractors to the multiple-element processing deficits in DD, and thus, it can contribute to deepening our understanding of the underlying mechanisms of impaired VSP in individuals with dyslexia.

The first case study by Dubois et al. (2010) investigated possible cognitive impairments underlying the VSP deficit in two 9-year-old French children with dyslexia by using the CombiTVA paradigm with letters as stimuli. Their results showed a reduction in perceptual processing speed in both of these children with dyslexia and a limitation of the VSTM storage in one of the children with dyslexia, but a normal lateralization of visual attentional distribution for both children with DD. Similar results were observed in a larger sample size of 9-year-old German children with DD (Bogon et al., 2014b), reporting lower perceptual processing speed and reduced VSTM storage capacity underlying the VSP deficits in DD. However, the above studies all used letters as stimuli with oral report as the response, and the relevant procedure might be implicated by linguistic-related processing, which is impaired in dyslexia (Goswami, 2015). Therefore, the group differences in the above studies may arise from the reduction in reading experience that is inherent in being dyslexic compared to the controls. To further examine the directionality of the relationship between impaired VSP and reading disabilities, a recent study by Stefanac et al. (2019) utilized a CombiTVA paradigm with symbols as the non-verbal stimuli to measure a purer capacity of VSP in 12-year-old native English speakers with DD. Their results showed that a remarkable deficit was only observed in the parameter of perceptual processing speed rather than in other TVA-related parameters for children with dyslexia. The above results from participants with backgrounds in alphabetic languages suggested that VSP deficits in children with DD may be closely related to impairments in subcomponents of bottom-up attentional processing (i.e., *C* and *K*) but not to problems in top-down attentional subcomponents. Moreover, it has been suggested that there is a close relationship between these bottom-up attentional subcomponents of VSP and word/text reading performance in alphabetic languages (Bogon et al., 2014b; Lobier et al., 2013; Stefanac et al., 2019; Zoubrinetzky et al., 2019). The multi-trace memory model proposed by Ans et al. (1998) predicted that VSP contributed to reading via two procedures: a global reading procedure that requires distributed attention extending over a long string of globally orthographic units, in which better multiple-element processing skills facilitated capturing and connecting between orthographic units (i.e., orthographic processing), and an analytic procedure that indirectly explained reading via phonological decoding skills (Chen et al., 2016). Whether different subcomponents underlying VSP played special roles in the two aforementioned procedures remains to be further examined.

Previous findings from alphabetic languages have indicated that a sustained deficit in perceptual processing speed was observed in individuals with dyslexia of different ages (Bogon et al., 2014b; Dubois et al., 2010; Stefanac et al., 2019); the impairment in VSTM storage capacity was not stable, which seemed to be more obvious in DDs from lower primary school grades (i.e., corresponding to 9 year olds; Bogon et al., 2014b; Dubois et al., 2010) than DDs from higher primary school grades (i.e., corresponding to 12 year olds in Stefanac et al., 2019), revealing a developmental decrease in this subcomponent deficit. Therefore, it is better to take the participants' age into consideration in exploring the intrinsic subcomponents underlying VSP by DDs.

The possible influences of language characteristics should also be considered. In an alphabetic language background, DDs exhibited significant deficits in bottom-up attentional subcomponents rather than in top-down attentional subcomponents during VSP. Reading linear words in alphabetic languages requires the readers to efficiently and rapidly encode letters and words in parallel, in which perceptual processing speed and VSTM storage capacity would greatly contribute to the spelling procedure. Different from alphabetic languages, Chinese, as a logographic writing system, has complex visual features, and there is no inter-word spacing in Chinese sentences. Effective spatial attention may be critical for global and visual spatial analyses of all radicals in a Chinese character and could help the reader identify target words by efficiently inhibiting irrelevant stimuli in a sentence with ambiguous word boundaries (Liu et al., 2015). Then, what about the potential mechanisms underlying VSP in Chinese children with DD? It is interesting and necessary to address this issue to help understand the nature of impaired multiple-element processing and the possible modulation of language background. However, to our knowledge, there has been no relevant research. It has been suggested that VSP skill and visual spatial analyses play important roles in Chinese reading development (Huang et al., 2019, 2020). Accordingly, it could be proposed that Chinese children with DD may exhibit remarkable abnormality in top-down attentional parameters (e.g., spatial attentional distribution and top-down attentional control) during visual simultaneous processing, revealing the possible influence of language specificity.

Given this void in the literature, the present study attempted to examine the different intrinsic subcomponents underlying VSP among Chinese children with DD, using a CombiTVA paradigm with symbols as non-verbal stimuli. *The first goal of the current study* was to derive TVA subcomponents from the performance in the CombiTVA paradigm with symbol stimuli in Chinese children with dyslexia. Meanwhile, since VSP deficits became more remarkable in Chinese children with dyslexia from higher primary school grades (Zhao et al., 2018), the developmental trajectories method proposed by Thomas et al. (2009), instead of group-matching comparison, was adopted here to analyze the TVA subcomponents in which participants' age was regarded as a continuous variable. *The second goal of the present study* was to explore how the impairments in these TVA subcomponents exerted influences on reading procedures for disabled readers, and mediation analyses were conducted according to relevant literature (Chen et al., 2016). Previous research suggested that VSP first plays a role in the interplay between orthographic, phonological, and semantic representations (i.e., linguistic skills), and then, a high-level reading procedure can be achieved (Huang et al., 2020). Accordingly, referring to the two reading procedures in the multi-trace memory model (Ans et al., 1998), we predicted that distinct subcomponents may separately link with global/analytic reading procedures by the mediation of special linguistic skills (e.g., orthographic and phonological processing).

Method

Participants

Forty-seven children with dyslexia and fifty-three chronologically age-matched normal readers participated in the present study; participants were screened from Grade 3 to 6 of primary schools. According to the relevant literature in Mainland China (Meng et al., 2011), the Chinese character recognition test (Wang & Tao, 1996) and the Raven's standard progressive matrices test (RSPM, Zhang & Wang, 1985) were adopted to screen children with dyslexia. The inclusion criteria were as follows: The score on the Chinese character recognition test was at least −1.5 standard deviations from the average of same-grade children, and the non-verbal intelligence measured by the RSPM test was in the normal range (i.e., the test score of one participant was higher than the value of the 5th percentile of the norm). Following these criteria, 60 children at risk of dyslexia were selected from 1105 primary school students (prevalence of 5.43%). Additionally, the teachers, who taught Chinese to children with dyslexia at a school, were invited to judge whether the selected children showed any reading difficulty and to evaluate whether they had attention deficit and hyperactivity disorder (ADHD) according to the Chinese Classification of Mental Disorder 3. Accordingly, 54 children from the above pool were identified as individuals with dyslexia, and 54 typically developing children were selected as a group of age-matched controls. To further ensure the validity of the dyslexic screening, reading tests at single-character and sentence levels were utilized. Relevant details of the psychometric screening tests were described in the following section. The datasets for eight children (including 7 children with dyslexia and 1 normal reader) were excluded due to their incompletion of reading measurements. The remaining 47 children with dyslexia and 53 age-matched normal readers were valid participants who were enrolled in the following CombiTVA test. Information on the descriptive statistics is shown in Table 1. All participants were right-handed without ADHD, neurological or ophthalmological abnormalities and had normal or corrected-to-normal vision. This work has been conducted in accordance with the ethical principles in the *Declaration of Helsinki*. Written informed consent was provided by the children's parents and teachers before the assessment. The research project was approved by the Research Ethics Committee of the authors' university.

Psychometric Tests to Identify Children with DD

Referring to relevant literature (e.g., Meng et al., 2011), we adopted the Chinese character recognition test and the non-verbal intelligence test to select children with DD from a pool of primary school students. In addition, single-character and sentence reading tests were used to further ensure the screening validity.

Chinese Character Recognition Test

The standardized test of Chinese character recognition is utilized to measure participants' reading level (Wang & Tao,

Table 1 Descriptive statistics of the two groups

Characteristics	Dyslexic readers $N=47$	Normal readers $N=53$	Group comparisons	
			t test or χ^2 tests	*p* values
Age (years)	10.44 (1.29)	10.25 (1.22)	0.74[a]	0.46
Gender	37 boys/10 girls	36 boys/17 girls	1.47[b]	0.26
Chinese character recognition test score	1640 (684)	2547 (716)	6.47[a***]	<0.001
RSPM test score	41.43 (5.02)	41.91 (4.28)	0.52[a]	00.61
Single-character reading test score	90.37 (18.77)	110.37 (20.35)	4.94[a***]	<.001
Sentence reading test score	133.71 (54.80)	191.37 (97.52)	3.45[a***]	<0.001
Linguistic skills				
Phonological awareness	14.87 (4.64)	20.02 (5.32)	5.12[a***]	<0.001
Orthographic awareness	0.77 (0.11)	0.85 (0.10)	3.61[a***]	<0.001
TVA subcomponents				
VSTM storage capacity (K)	3.28 (0.05)	3.28 (0.05)	0.28[a]	0.78
Processing speed (C)	6.23 (1.57)	7.01 (1.25)	2.77[a**]	0.007
Attentional weight (ω)	0.47 (0.06)	0.52 (0.03)	5.07[a***]	<0.001
Top-down control (α)	1.02×10^{-6} ($.87\times10^{-6}$)	1.02×10^{-6} (2.38×10^{-6})	0.01[a]	0.99
Numbers of individuals with special dysfunction in each subcomponent (Relevant percentage of these individuals is in parentheses)				
VSTM storage capacity (K)	3 (6.38%)	2 (3.77%)	0.36[b]	0.66
Processing speed (C)	17 (36.17%)	8 (15.09%)	5.90[b*]	0.02
Attentional weight (ω)	24 (51.06%)	4 (7.55%)	23.40[b***]	<0.001
Top-down control (α)	8 (17.02%)	11 (20.75%)	0.23[b]	0.80

Note. RSPM, Raven's Standard Progressive Matrices. VSTM, visual short-term memory. In the "*t test* or χ^2 tests" column, the values with superscript "a" mean t values and the values with superscript "b" mean χ^2 values; *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$

1996); this test is a paper-pencil test with a time limitation of 40 min. Participants were asked to make compound words by using the given target morphemes and to write them down on the test paper. When a proper word including the target morpheme was generated, this correct response was awarded one point. Characters in this test were divided into 10 sets based on testing difficulty from low to high. The score for each set was the product of the total points and the relevant coefficient of difficulty. The sum of the scores of all ten sets was the final score.

Raven's Standard Progressive Matrices (RSPM)

RSPM is a standardized test of non-verbal intelligence with a time limitation of 40 min. There are five sets of testing items and 60 items in total, the difficulty of which gradually increases. For each item, an incomplete figure was presented in the testing sheet, and participants were asked to complete the figure by selecting the target from six to eight options. Each correct response was awarded 1 point. The raw score was the number of correct responses, which was converted to the standardized score based on the Chinese norms established by Zhang and Wang (1985).

Reading Tests

A character-list reading task (Huang et al., 2019) was conducted at the single-character level, which contains a list of 400 Chinese characters. The split-half reliability was 0.93. Participants were required to orally read Chinese characters as quickly and accurately as possible within the time limitation of 1 min. At the end of this test, the last item they read was marked. The final score was computed as the number of correctly read items in one minute with a unit of character/min (c/min).

At the sentence level, a sentence verification task (Huang et al., 2019) was adopted. The split-half reliability was 0.85. This test was programmed by E-Prime 1.1 on a Dell laptop. There were 25 true sentences and 25 false sentences in this test. Participants were required to accurately and quickly read one sentence aloud and to press the space bar after they had read this sentence. The reading time was the interval between the onset of the sentence and the time of pressing the space bar. The sentence reading speed could be calculated as the ratio between the length of this sentence and the corresponding reading time, with a unit of c/min. Then, the participants were required to judge the correctness of this sentence by pressing different keys. The accuracy of the correct judgment was also recorded to ensure the validity of the sentence reading procedure. Because the judgment accuracy was high for most of the participants (>85%), it was not submitted to the following analyses.

TVA-Based Assessment of Visual Attentional Subcomponents

Materials and Procedure in the CombiTVA Paradigm

A CombiTVA paradigm (Stefanac et al., 2019) was adopted here. To measure a purer capacity of VSP without the influence of linguistic processing, we used symbols as non-verbal stimuli and key pressing as a non-verbal response. Before the experiment, 35 university students who did not take part in the formal study evaluated the visual complexity and visual familiarity of the 10 symbol stimuli with a five-point rating scale (1 point = The symbol is extremely simple/extremely familiar; 5 points = The figure is extremely complex/extremely strange). Results showed that the averages of visual complexity and visual familiarity of these figures were 2.30 ± 0.05 and 2.36 ± 0.04, respectively, revealing mid-level degrees of complexity and familiarity. The visual complexities and familiarities of any two of the 10 figures did not significantly differ from each other ($p > .1$, Bonferroni corrected).

The presentation format of each trial was as follows (Fig. 1a): a 1000-ms red fixation cross in the center of a black screen, one of three stimulus arrays (two target symbols in red; six target symbols in red; two target symbols in red and four distractors in blue, as shown in Fig. 1b) presented for a specific duration, a 500-ms post-mask of a black blank screen, and finally a target of a single symbol. Participants were required to quickly and accurately judge whether the last symbol was present or absent in the stimulus array by pressing different keys (i.e., "Z" key for target presence and "B" key for target absence). Between two neighboring trials, there was a black screen with a random interval changing from 1000 ms to 1500 ms. The stimulus arrays consisted of symbols locating on an imaginary circle ($r = 2.02°$ of visual angle) around the fixation cross with six possible positions (Fig. 1b), and no array included the same symbol twice. The visual angle of each symbol was $0.7° \times 0.7°$ at a viewing distance of 50 cm. There were 432 trials in total, including 216 trials for the six-target condition, 108 trials for the two-target condition, and 108 trials for the four-distractor condition. Moreover, the amount of target-present and target-absent trials was balanced in each condition of stimulus arrays. Consistent with relevant literature (Stefanac et al., 2019), presentation duration varied across different conditions, in which a fixed duration of 80 ms was adopted in the trials containing two target symbols irrespective of distractors, and variable durations (i.e., 40, 80, 160, or 200 ms) were utilized in the trials containing six target items. All trials were intermixed and were equally divided into 12 experimental blocks, with each containing 36 trials. The test trials were preceded by 10 practice trials. The entire CombiTVA task took approximately 50 min to complete. However, considering the possible fatigue effect in child participants, this experiment was separately performed in three sections with 4 blocks each time taking approximately 12–18 min. This test was programmed by E-Prime 1.1, which was run on a Dell laptop with a display resolution of 1024 × 768 pixels and a monitor refresh rate of 75 Hz. The accuracy was recorded for the follow-up estimation of attentional parameters.

Estimation of TVA Parameters

A TVA program designed by Kyllingsbaek (2006) was adopted to estimate relevant parameters through the maximum likelihood fitting procedure. Average accuracy in the CombiTVA paradigm was computed in each type of target presence (including presented location in the array, with or without the distractors, different numbers of target items and different duration of target presentation), which was further put into the TVA program to estimate four parameters regarding VSP. The four parameters are as follows: (1) The

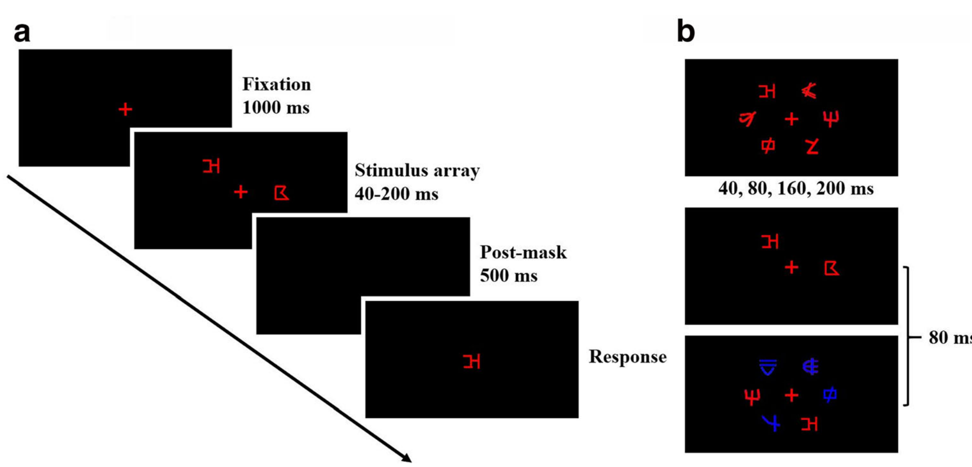

Fig. 1 Presentation format of each trial in the CombiTVA paradigm (a) and examples of symbol arrays in three types (b)

parameter K represents the VSTM storage capacity, which is measured by the maximum number of accurately reported targets. (2) The parameter C represents processing speed, which uses a unit of the rate of visual targets processed per second. (3) The parameter ω represents the laterality index of attentional weight, indicating differential attentional weighting between items in the left versus the right visual fields. The laterality of the attentional weight is computed using the equation "$\omega = \omega_L/(\omega_L + \omega_R)$." If ω is significantly higher than 0.5, then the attentional weight exhibits left lateralization; if ω is significantly lower than 0.5, then the attentional weight exhibits right lateralization; if ω does not significantly differ from 0.5, then the attentional weight is balanced between left and right visual fields. (4) The parameter α represents the top-down controlled selection, which is calculated as a ratio of the attentional weights between distractors and targets. If the estimation of the α parameter is close to 0, then it indicates efficient selection of targets over distractors. If the α value is near 1, then it suggests no distinction between targets and distractors.

Linguistic Processing Tests

To further examine the roles of cognitive subcomponents underlying VSP in the Chinese reading procedure, orthographic processing skills and phonological decoding ability were also measured, corresponding to the two reading procedures (i.e., global and analytic procedures) in the multi-trace memory model.

Orthographic Awareness (OA)

We used the OA test designed by Qian et al. (2015), with an internal consistency reliability of 0.72. There are three types of stimuli in this test, including 40 real characters, 20 pseudo-characters, and 20 non-characters. The real characters were all semantic-phonetic compounds. The visual forms of the pseudo-characters followed the orthographic rules, but they did not exist. The visual forms of the non-characters did not obey the orthographic rules of Chinese characters with misplaced radicals. The task was to judge whether an item was a real character or not. The accuracy was recorded.

Phonological Awareness (PA)

The PA test (Qian et al., 2015) measured sensitivity to the onsets, rimes and tones of spoken Chinese monosyllabic words, and its split-half reliability was 0.92. An odd-one-out paradigm was utilized. There were three types of oddity separately corresponding to the onset, rime, and tone conditions with 10 trials for each type of oddity. Within each trial, a series of three monosyllabic words were presented auditorily for approximately 2500 ms, were spoken by a female voice and were played by Microsoft PowerPoint software. Participants were asked to choose the phonologically odd item from the above series. The accuracy was recorded.

Data Analyses

First, descriptive statistics were calculated to illustrate performances in each TVA subcomponent of VSP for individuals with DD and normal readers. Odds ratios were computed to preliminarily investigate the relationship between these subcomponent deficits and reading disability.

Second, to compare the parameter-based assessments of these cognitive subcomponents between children with dyslexia and normal readers while considering the impact factor of the participants' age, we adopted the developmental trajectories method to examine whether the TVA subcomponents of dyslexic readers exhibited a developmental delay or atypical development compared to the controls. Based on a growth model, the developmental trajectories method attempted to generate a linear function linking performance of the CombiTVA task with age and then to examine whether this function differed between normal readers and children with dyslexia within a wide age range. The results may indicate a dissociation between developmental delay and atypical development in each of the TVA subcomponents. If the development was identified as "delayed" through this method, then the children with dyslexia should develop to the same end point as the typically developing children after sufficient practice. However, if the developmental trajectories analysis indicated that the development of one TVA subcomponent was "atypical," then the dyslexic readers may never reach the end point achieved by the typically developing population. Of note, the pattern of atypical development would further support the case that one impaired TVA subcomponent of the dyslexic readers might not be a consequence of their poor reading performance. Referring to previous literature (Kuppen & Goswami, 2016), the developmental trajectories of TVA subcomponents in each group were separately analyzed for the aspects of both chronological age (CA) and reading age (RA). Consistent with the classification procedure and decision trees in the study of Kuppen and Goswami (2016), for the CA aspect, the measures for dyslexic readers were classified as "delayed" compared to the normal readers when a main effect of group or an age × group interaction or both of the above were significant. The trajectories of children with dyslexia in the TVA subcomponents were considered as "atypical" when the measurements of these TVA subcomponents were not linearly correlated with the chronological ages for the dyslexic readers but were for the typically developing children. Regarding the RA analyses, developmental trajectories of the TVA subcomponents were classified as "atypical" when task performance and increasing RA were linearly related to each other in only one of the dyslexic or control groups but not in the other group.

Furthermore, correlation analyses were conducted as preliminary analyses to examine the possible relationship between the impaired TVA subcomponents and reading-related skills in children with DD. Since visual decoding is the basic step before linguistic processing, some researchers indicated that visual attention at the basic cognitive level may contribute to reading procedure by the mediation of linguistic factors such as phonological processing (Chen et al., 2016; Huang et al., 2020). Accordingly, we conducted mediation analysis among the dyslexic readers to further explore the possible mechanism underlying the relationship between impaired TVA subcomponents and reading difficulties in Chinese.

The descriptive statistics, developmental trajectories method, and correlation analyses were conducted in SPSS 20.0. The bootstrapping PROCESS procedure (Hayes, 2013) was used to implement the mediation analyses, with the covariates of participants' ages and non-verbal intelligence. In the analyses, a resampling strategy of 5000 bootstraps was utilized, and statistical significance of 0.05 indicated whether the range from the upper to the lower bounds of the bias-corrected 95% confidence intervals did not include zero.

Results

Descriptive Statistics

Table 1 shows descriptive statistics for the two groups. Results of independent sample t-tests showed that the current cohort of Chinese children with dyslexia had lower perceptual processing speed and a rightward trend in spatial attentional distribution compared to the normal readers. Moreover, the number of individuals with impairments in one TVA subcomponent was computed according to the deviance analysis method. Consistent with relevant literature (Meng et al., 2011), one individual was classified as having special dysfunction in one TVA subcomponent if his/her performance was lower than −1 standard deviation of normal readers' average score in this subcomponent. Results of chi-square (χ^2) statistical analysis (Table 1) showed a higher percentage of individuals with abnormal TVA subcomponents of perceptual processing speed and spatial attentional weight in DDs than that in typically developing children. Furthermore, we computed the odds ratios to examine the relationship between these TVA subcomponents and dyslexia based on previous research (Bertoni et al., 2019). The odds ratio is the ratio of the chance of an event appearing in one group (i.e., DD showing deficits in one TVA subcomponent) to the percentage of it occurring in the other group (i.e., normal readers showing deficits in this TVA subcomponent). Accordingly, the odds ratio of the parameter K was 1.74 ($\chi^2 = .36$, $p = 0.55$, $\varphi = 0.06$), suggesting a non-significant relation between this parameter and reading disability. The odds ratio of the parameter C was 3.19 ($\chi^2 = 5.90$, $p = 0.02$, $\varphi = 0.24$; 95% confidence interval: [0.01,795.23]), suggesting that the VAS impairment in processing speed may be moderately related to poor reading skills. The odds ratio for the parameter ω was 12.78 ($\chi^2 = 18.27$, $p < 0.001$, $\varphi = 0.43$; 95% confidence interval: [3.97,1136.42]), revealing the close relationship between abnormalities between the attentional weight and reading disability parameters. For the α parameter, the odds ratio was 0.78 ($\chi^2 = 0.23$, $p = 0.64$, $\varphi = 0.05$), revealing that the relationship between this subcomponent and dyslexia may be not remarkable.

Analyses of the Developmental Trajectories Method

Following the classification procedure stated in the above "Data analyses" section and decision trees in the study of Kuppen and Goswami (2016), results of trajectories analyses (Table 2 and Fig. 2) showed that for the TVA subcomponent of processing speed (i.e., parameter C), the trajectories for the children with dyslexia were significantly linearly related to CA, and there was a significant group effect in the CA analyses. Accordingly, the DD trajectories were classified as "delayed." For the RA analyses, while the children with DD showed a significant linear relationship between processing speed and reading age, no such relationship was present for the normal readers, and therefore, the dyslexic group was classified as showing "atypical" developmental trajectories for this TVA parameter. However, as shown in Fig. 2b, the perceptual processing speed of the children with dyslexia seemed to reach the same end point with the typical population as would be the case for reading development. Considering the results of both CA and RA analyses, the dyslexic group was judged as showing "delayed" trajectories in the TVA subcomponent of processing speed.

For the parameter ω, task performance for the children with DD did not show a linear relationship with CA or RA. As this was not the case for the typically developing children in either the CA or RA assessments, the children with DD were judged as showing "atypical" developmental trajectories in this TVA component regarding the attentional weight of spatial distribution.

There were no significant developmental changes in the parameters of K or α for either children with dyslexia or normal readers in CA or RA analyses (Table 2 and Fig. 2).

Mediation Analyses

Based on the above analyses, we found that the current cohort of Chinese children with dyslexia showed significant deficits in the TVA parameters of perceptual processing speed (C) and attentional weight (ω). To further explore the possible

Table 2 Summary of trajectory outcomes

Measures	CA or RA	Classification procedure		Overall trajectory classification
		Decision 1	Decision 2	
VSTM (*K*)	CA	Measures linear with CA in DRs? NO. R^2=0.02, F(1,45)=0.73, p=0.40, η^2=0.02.	Measures linear with CA in NRs? NO. R^2=0.02, F(1,51)=1.21, p=0.28, η^2=0.04.	**ns**
	RA	Measures linear with RL in DRs? NO. R^2=0.03, F(1,45)=1.34, p=0.25, η^2=0.05.	Measures linear with RL in NRs? NO. R^2=0.03, F(1,51)=1.54, p=0.22, η^2=0.05.	**ns**
Processing speed ©	CA	Measures linear with CA in DRs? YES. Y=.36x+1.61, R^2=0.13, F(1,45)=6.86, p=0.012, η^2=0.22.	Main effect of group? YES. F(1, 99)=9.08, p=0.003, η^2=0.37.	**Delayed**
	RA	Measures linear with RL in DRs? YES. Y=.28x+4.81, R^2=0.08, F(1,45)=3.76, p=0.04, η^2=0.19.	Measures linear with RL in NRs? NO. R^2=0.10, F(1,51)=0.50, p=0.48, η^2=0.02.	**Delayed**
Attentional weight-laterality (ω)	CA	Measures linear with CA in DRs? NO. R^2=0.005, F(1,45)=0.24, p=0.63, η^2=0.01.	Measures linear with CA in NRs? YES. F(1, 51)=3.28, p=0.046, η^2=0.16.	**Atypical**
	RA	Measures linear with RL in DRs? NO. R^2=0.002, F(1,45)=0.10, p=0.76, η^2=0.01.	Measures linear with RL in NRs? YES. R^2=0.06, F(1,51)=2.89, p=0.07, η^2=0.13.	**Atypical**
Top-down control selectivity (α)	CA	Measures linear with CA in DRs? NO. R^2=0.05, F(1,44)=2.28, p=0.14, η^2=0.05.	Measures linear with CA in NRs? NO. R^2=0.01, F(1,50)=0.42, p=0.52, η^2=0.02.	**ns**
	RA	Measures linear with RL in DRs? NO. R^2=0.04, F(1,44)=1.71, p=0.20, η^2=0.04.	Measures linear with RL in NRs? NO. R^2=0.01, F(1,50)=0.28, p=0.60, η^2=0.01.	**ns**

Note. CA, chronological age; RA, reading age, which was the grades converted from the vocabulary size referred to the norm in Wang and Tao (1996). DR, dyslexic readers; NR, age-matched normal readers. ns, non-significant

mechanism underlying the relationship between these impaired TVA subcomponents and reading disabilities, preliminarily correlation analyses were conducted in children with DD. As shown in the *Supplementary Material*, the results of the correlation analyses showed that age and non-verbal intelligence were positively correlated with linguistic skills and reading test scores ($p < 0.05$). Moreover, there were significant triangular correlations across these TVA subcomponents, linguistic skills, and Chinese reading skills within the children with DD. In detail, perceptual processing speed was significantly correlated with phonological awareness (r = 0.46, $p < 0.001$) and single-character reading speed (r = 0.27, p = 0.03), in which higher processing speed corresponded to higher scores in PA and character reading tests. Meanwhile, phonological awareness was positively correlated with single character reading (r = 0.42, $p = 0.002$). The parameter of attentional weight was positively correlated with the scores in the orthographic awareness test (r = 0.30, $p = 0.03$) and sentence reading test (r = 0.28, $p = 0.04$); moreover, better performance in sentence reading corresponded to higher accuracy in the OA test (r = −0.48, $p < 0.001$).

Referring to the prediction of the multi-trace memory model, we conducted mediation analyses to examine whether different subcomponents of VSP were linked with Chinese reading difficulties by the mediation of special linguistic skills within the children with DD. As shown in Tables 3 and 4 and Fig. 3, the total effect of perceptual processing speed on Chinese character reading was significant. When phonological awareness was added into the model as a mediator, there was not a significant direct effect of this visual attentional subcomponent on character reading via phonological awareness, suggesting a total mediating role of phonological awareness in the relationship between the TVA subcomponent of processing speed and character reading performance. A similar pattern was observed in mediation analysis regarding the triangular relationship across attentional weight, orthographic awareness, and sentence reading skill. Orthographic awareness was a (total) mediator in the relationship between attentional weight and sentence reading speed.

Discussion

The present study aimed to examine the underlying cognitive processes of impaired VSP in Chinese children with dyslexia within the framework of TVA. The results showed that the VSP deficit in children with DD may stem from dysfunction of perceptual processing speed and atypical attentional distribution. Analysis based on odds ratios confirmed the close relationship between reduced processing speed, abnormal attentional weight and poor reading skills. Results of developmental trajectories analyses revealed that the children with dyslexia showed a "delayed" pattern in the cognitive development of perceptual processing speed and "atypical" trajectories in the development of attentional weight regarding the VSP skills. To explore the possible mechanisms underlying the roles of these impaired cognitive subcomponents in reading difficulty, mediation analyses were conducted,

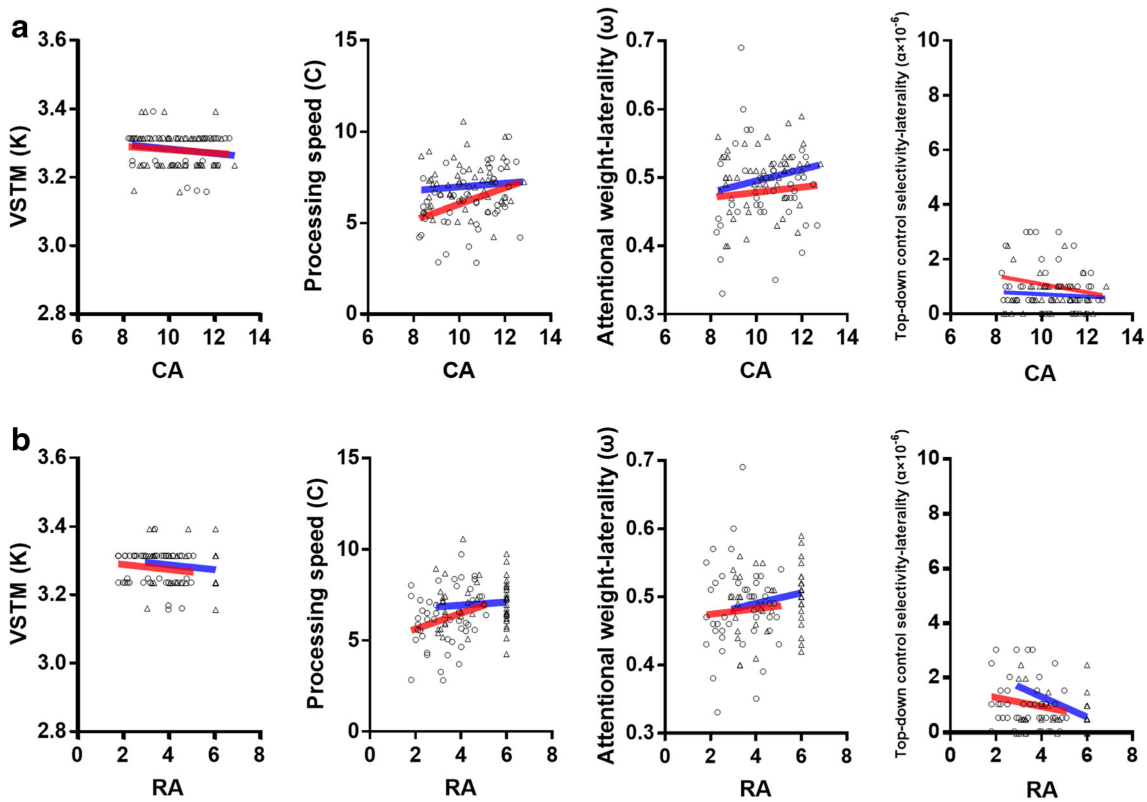

Fig. 2 Performance of the four parameters against chronological age (a) and reading age (b). The four parameters regarding visual simultaneous processing included visual short-term memory (VSTM) storage, perceptual processing speed, the laterality of attentional weight, and the irrelevant inhibition. The circles and red lines represent children with dyslexia; the triangles and blue line represent typical developing children. CA, chronological age, with the unit in years; RA, reading age, with the unit in grade which was converted from vocabulary size referred to the norm in Wang and Tao (1996). Because the values of α are all near zero, we multiplied the raw α by 10^6 so as to illustrate the data more clearly

reporting two models of the "TVA subcomponent-linguistic awareness-reading" relationship.

Reduced Perceptual Processing Speed and its Delayed Pattern of Developmental Trajectories in Chinese Children with Dyslexia

As predicted, the current cohort of Chinese children with dyslexia showed markedly reduced perceptual processing speed during visual simultaneous processing. This result confirms the most consistent finding of previous TVA research in alphabetic languages, reporting that dyslexic readers processed multiple elements more slowly than their age-matched typically developing readers (Dubois et al., 2010; Stefanac et al., 2019), suggesting language is universal in this impaired processing speed underlying the VSP deficit of DDs. This result aligned with relevant theories indicating deficits in visual rapid temporal processing and in sluggish attentional shifting for dyslexic readers (Hari et al., 2001).

Results of the developmental trajectories method showed a delayed developmental pattern in perceptual processing speed for children with dyslexia, suggesting that the dyslexic group may reach the end point achieved by the typically developing population in the development of this TVA subcomponent. To

Table 3 Models summaries for total (without mediator) and direct (with mediator) effects of impaired TVA subcomponents on reading difficulties

Outcomes	ΔR^2	*F* values	*df*	*p values*
Processing speed➔single character reading				
Single character reading	7.50%	4.06	1, 50	0.049
Single character reading with phonological awareness	18.20%	5.47	2, 49	0.007
Attentional weight➔sentence reading speed				
Sentence reading speed	7.80%	4.31	1, 50	0.04
Sentence reading speed with orthographic awareness	21.86%	6.86	2, 49	0.002

Table 4 Direct and indirect effects of impaired TVA subcomponents to reading difficulties

	Effect	β	SE (boot)	95% CI	99% CI
Processing speed➔single character reading (with a mediator of phonological awareness)					
Direct effect	1.6443	0.10	2.3586	[−3.10, 6.39]	[−4.68, 7.97]
Indirect effect	2.7847	0.17**	1.2393	[0.68, 5.65]	[0.33, 7.45]
Attentional weight➔sentence reading speed (with a mediator of orthographic awareness)					
Direct effect	1083.43	0.15	918.91	[−762.28, 2929.14]	[−1377.31, 3544.17]
Indirect effect	914.59	0.13*	498.77	[52.66, 1932.36]	[−294.08, 2651.73]

Note. CI, confidence interval. The lower and upper limit of confidence intervals are respectively for the bias-corrected 95% confidence intervals and the bias-corrected 99% confidence intervals. *, p < 0.05; **, p < 0.01

our knowledge, few studies have explored visual simultaneous processing with TVA-based methods from a developmental aspect. The current results of the developmental trajectories method showed that the perceptual processing speed of children with dyslexia developed to a normal level with increases in chronological ages and reading age, revealing a developmental decrease in the deficit of perceptual processing speed while simultaneously processing multiple elements. This finding was different from the results in a background of alphabetic languages, which reported a sustained deficit in processing speed regarding VSP with development (Bogon et al., 2014a; Stefanac et al., 2019). This difference might be associated with variations in the developmental characteristics of perceptual processing speed across languages. It has been suggested that perceptual processing speed continues to develop during the primary school period in alphabetic languages (Sperling et al., 2003), which may be required due to the special role of perceptual processing speed in sublexical reading acquisition. However, typically developing children in China did not exhibit significant enhancements in processing speed from the 2nd grade to the 5th grade of primary school (Xiao et al., 2014), which might be related to less involvement of perceptual processing speed as the increasing requirement of globally lexical processing in Chinese reading. Therefore, the normal level of processing speed seemed to be stable during this primary school period in the context of Chinese, creating an opportunity for the children with dyslexia to catch up to normal readers, reflecting a possible modulation of language specificity.

It is unknown how the reduced perceptual processing speed in the TVA framework relates to reading difficulties in DDs. The lower processing speed may be associated with a reduction in naming speed and slow decoding mechanisms (Bogon et al., 2014b; Lobier et al., 2013). Based on these hypotheses,

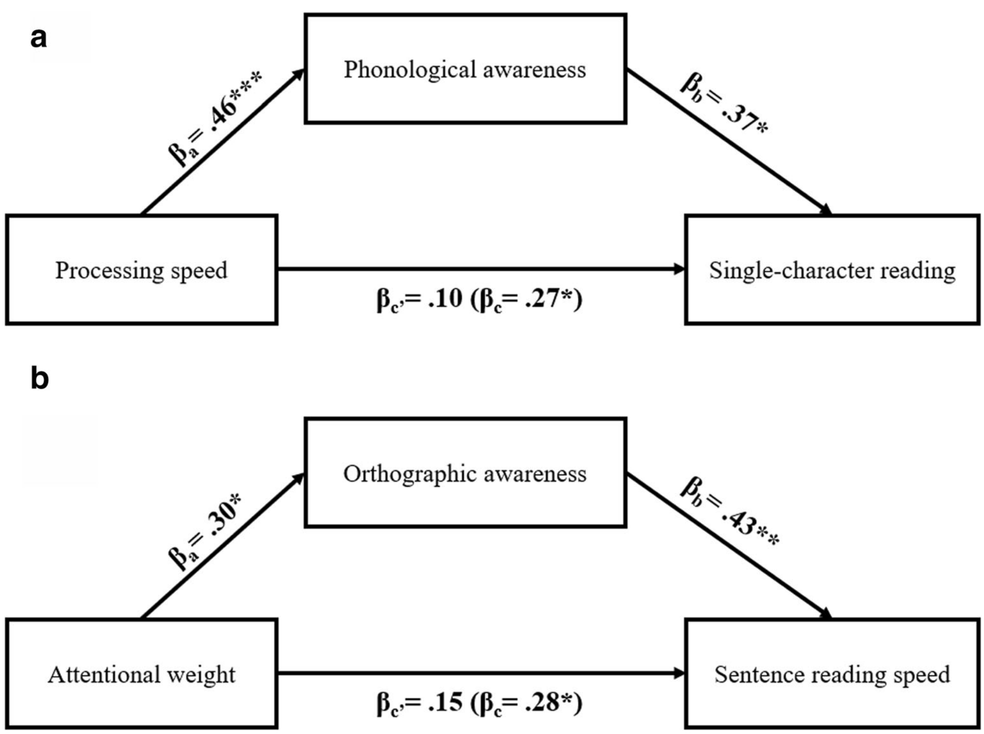

Fig. 3 The mediation effect of linguistic skills between impaired TVA parameters regarding visual simultaneous processing and Chinese reading disabilities. (a), the relationship between perceptual processing speed and single-character reading was mediated by phonological awareness; (b), the relationship between attentional weight and sentence reading performance was mediated by orthographic processing skill. *, $p < .05$; **, $p < .01$; ***, $p < .001$

the current results of the mediation analysis provided a further explanation to the relevant mechanism, which highlighted the role of perceptual processing speed in phonological retrieval. It could be inferred that the impaired processing speed in children with dyslexia would decrease the efficiency of visual multiple-element processing within a short framework, delaying the decoding of orthographic units. This fact may continue to exert a negative influence on orthographic-to-phonological mapping and on the discrimination of phonological representation, further affecting the efficiency of decoding and identifying characters and in turn slowing down the speed of character-list reading. An alternative explanation of the link between perceptual processing speed and reading skills with a mediation of phonological processing could be a multi-sensory (visual and auditory) attentional deficit as proposed by the sluggish attentional shifting theory (Hari et al., 2001), in which visual and auditory processing speed are sluggish in dyslexia, hampering the development of orthographic and phonological processing skills and further affecting reading efficiency.

Abnormal Attentional Weight and its Atypical Developmental Pattern in Chinese Children with Dyslexia

The visual simultaneous processing of Chinese children with DD was also constrained by the atypical attentional distribution, which was captured by the laterality index of attentional weight. According to relevant literature (Stenneken et al., 2011), we utilized one-sample independent t tests to compare the parameter ω with 0.5 to further examine whether there was a significant lateralization in the attentional weight. Results showed that ω values of the dyslexic readers were significantly lower than 0.5 ($t_{46} = -3.95$, $p < 0.001$), but the opposite pattern was observed for the normal readers who exhibited ω values higher than 0.5 ($t_{52} = 2.74$, $p = 0.008$). In particular, the normal readers tended to allocate more attentional resources to the left visual field, whereas the children with dyslexia tended to distribute more attentional resources to the right visual field. The leftward distribution of spatial weight for the current cohort of typically developing children was consistent with relevant literature (Bogon et al., 2014a, 2014b; Huang et al., 2019). A left advantage has been previously reported in attentional distribution regarding multiple-element processing for children in high grades and adult readers (Bogon et al., 2014b; Huang et al., 2019). Skilled reading requires the parallel processing of several characters within a single fixation, and the fixation location is often slightly left of the center of the string for left-to-right reading systems (Ducrot & Pynte, 2002). This more efficient initial viewing position has been observed during reading both alphabetic and Chinese scripts and seems to generalize to letter-like nonverbal stimuli (Spinelli et al., 2002). The symbols in the present study possibly contain some visual characteristics that overlap with real Chinese characters, which may be why a leftward bias, similar to that found for verbal strings, was also observed with the symbols in the present study.

By contrast, the current children with dyslexia exhibited an atypical pattern of right lateralization in the TVA parameter of attentional weight. This abnormality in attentional weight in the children with dyslexia has not been observed in previous TVA literature in alphabetic languages, revealing a modulation of language specificity. During sentence reading in Chinese, there is no intercharacter spacing, and effective distribution of spatial attention may be critical for global visual processing of phrases (Liu et al., 2015). Therefore, the atypical attentional weight might be more obvious in Chinese children with dyslexia compared to that in alphabetic languages. Furthermore, this result supported the hypothesized left neglect in dyslexic readers (Facoetti et al., 2006). Such visual field asymmetry is thought to play a crucial role in reading difficulty, especially in Chinese (Liu et al., 2015). In combination with the current results of the mediation analysis, the impairments in attentional weight would correspond with sentence reading performance through the mediation of orthographic processing. Of note, the atypical pattern of spatial attentional distribution in children with dyslexia would exert a negative influence on the integrated processing of orthographic structures of a phrase (i.e., multiple characters), further impacting orthographic-to-semantic mapping during sentence reading and comprehension.

From a developmental point of view, the typical readers loaded increasing spatial attention to the left visual filed with development, while the children with dyslexia stably showed a right lateralization or even bilateral patterns in allocating attentional resources for VSP, and this group difference became obvious with increasing chronological age and reading age. This atypical developmental pattern for the dyslexic group provided a supplement for directionality between this abnormal attentional distribution and reading difficulty; that is, the atypical attentional weight in children with dyslexia may not be due to their lagging reading ability. A combination of the results based on odds ratios and the developmental trajectories method revealed that the atypical attentional distribution may be a core problem underlying the VSP deficit in Chinese children with dyslexia, compared to their delayed perceptual processing speed. Based on our prediction in the Introduction section, Chinese reading requires greater global lexical processing in high grades, in which the visual spatial distribution of attentional resources is suggested to play an important role (Liu et al., 2015), and thus, the abnormality of the dyslexic readers in this TVA parameter would be more remarkable with development.

Different TVA Subcomponents Relating to Various Levels of Chinese Reading

It has been suggested that the TVA subcomponent of perceptual processing speed reflects bottom-up stimulus-driven attention (Stefanac et al., 2019), and the stimulus-driven attention recruited the ventral attention network (VAN) to re-orient the visual spatial attention, which mainly included the inferior frontal gyrus and temporal-parietal junction (Corbetta & Shulman, 2002). These brain areas are also responsible for detailed processing of visual word/character forms and orthographic-to-phonological mapping during reading (Jobard et al., 2011). By contrast, spatial attentional distribution was highly related to top-down attention (Stefanac et al., 2019). Top-down attentional control mainly relies on the dorsal attention network (DAN), including frontal eye fields and the posterior parietal cortex (Corbetta & Shulman, 2002), which function in the global processing of character/word contours, radical position decoding, and visual-to-semantic mapping during reading (Kellenbach et al., 2005). Therefore, it could be inferred that the above dissociation between perceptual processing speed and attentional weight in the triangular models regarding the "TVA parameter-linguistic awareness-fluent reading" relationship is mainly based on different visual attentional networks. Slow perceptual processing speed, linked with dysfunction in VAN, may exert a negative influence on detailed orthographic analysis and orthographic-to-phonological mapping, which would markedly hinder the identification of single characters. Atypical attentional weight reflecting dysfunction in DAN might affect global visual processing and semantic retrieval, further reducing reading efficiency, especially that involving global analysis (i.e., sentence reading).

Additionally, the present study did not observe significant deficits in VSTM storage (K parameter) or irrelevant inhibition (α parameter). Some studies with the TVA framework found that children with dyslexia had limited VSTM storage compared to age-matched controls (Dubois et al., 2010; Bogon et al., 2014b). One possible explanation for these conflicting findings might be associated with the heterogeneity of dyslexia. The case study of Dubois et al. (2010) only observed that one of the two children with DD exhibited impairment in VSTM storage. Further research is needed to consider the possible influence of subtypes of dyslexia to test whether parameter K provides a marker for the VAS deficit in certain subtypes of dyslexia. Additionally, consistent with previous research (Stefanac et al., 2019; Bogon et al., 2014a, 2014b), the present study indicated normal capacity in irrelevant inhibition in the TVA task, suggesting that the impaired VSP in DDs may not be attributable to the inability to suppress surrounding stimuli. In the TVA-based tasks, the stimulus spacing is sufficient, which may induce less influence of a crowding effect and may weaken the possibility that the dyslexic readers exhibited impaired inhibition control. Moreover, the target and irrelevant stimuli in the present study were in different colors. It has been suggested that crowding is nullified when lateral flankers are in different colors (Zorzi et al., 2012), which may be another possibility for presenting a normal level of irrelevant inhibition in the current dyslexic readers.

Limitations and Suggestions for Future Research

The current study only had one time point for data collection, which might influence the mediation analyses to some extent. Future longitudinal and intervention studies are required to better define the causality of the relationship between TVA subcomponents regarding the impaired VSP and reading disability. Screening for dyslexia in the present study was mainly based on the Chinese character recognition test, which heavily depends on writing skills. Although it has been suggested that there is a close relationship between writing and reading skills, future studies are required to use tests involving reading processes to identify individuals with dyslexia. Moreover, the importance of dyslexic heterogeneity should also be further accounted for to compare the TVA subcomponents in different subtypes of dyslexia.

Conclusions

The present study expanded on previous literature by exploring underlying cognitive processes contributing to VSP deficits in Chinese children with dyslexia in the TVA framework and considering participant age as a continuous variable. Reduced perceptual processing speed and atypical attentional weight differentiated the dyslexic readers from their age-matched controls during simultaneous processing of multiple elements, in which a decreased deficit in perceptual processing speed and an increased abnormality in attentional weight were observed with development. Of note, the atypical pattern of attentional distribution might reveal Chinese language specificity. Mediation analyses uncovered the possible mechanisms underlying the relationship between deficits in these TVA subcomponents and Chinese reading difficulty. Moreover, the current results may provide useful directions for future intervention for reading disabilities, which could be designed to focus on training special subcomponents underlying visual simultaneous processing to further improve the reading proficiency of children with dyslexia.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s12144-021-01691-x.

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Code Availability Not applicable.

Authors' Contributions **Jing Zhao:** Conceptualization; Funding acquisition; Project administration; Resources; Visualization; Supervision;

Validation; Writing - Original draft preparation; Writing - Reviewing and Editing. **Jie Li:** Investigation; Methodology; Data curation; Formal analysis; Software; Validation; Writing - Reviewing and Editing. **Yue Yang:** Methodology; Data curation; Software.

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Data Availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics Approval (Include Appropriate Approvals or Waivers) The research was approved by the Research Ethics Committee of School of Psychology, Capital Normal University. This study was carried out in accordance with *The Code of Ethics of the World Medical Association (Declaration of Helsinki)* for experiments involving humans.

Consent to Participate Informed consents were obtained from all participants' parents and teachers.

Consent for Publication The participants' parents and teachers signed informed consent regarding publishing their data.

Conflicts of Interest/Competing Interests The authors declare that they have no conflict of interest.

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