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Intervention targeting different visual attention span components in Chinese children with developmental dyslexia: a study based on Bundesen's theory of visual attention

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Abstract

Within the framework of the theory of visual attention (TVA), the visual attention span (VAS) deficit among individuals with developmental dyslexia has been ascribed to the problems entailed by bottom–up (BotU) and top–down (TopD) attentional processes. The former involves two VAS subcomponents: the visual short-term memory storage and perceptual processing speed; the latter consists of the spatial bias of attentional weight and the inhibitory control. Then, what about the influences of the BotU and TopD components on reading? Are there differences in the roles of the two types of attentional processes in reading? This study addresses these issues by using two types of training tasks separately, corresponding to the BotU and TopD attentional components. Three groups of Chinese children with dyslexia—15 children each in the BotU training, TopD training, and non-trained active control groups were recruited here. Participants completed reading measures and a CombiTVA task which was used to estimate VAS subcomponents, before and after the training procedure. Results showed that BotU training improved both the within-category and between-category VAS subcomponents and sentence reading performance; meanwhile, TopD training enhanced character reading fluency through improving spatial attention capacity. Moreover, benefits on attentional capacities and reading skills in the two training groups were generally maintained three months after the intervention. The present findings revealed diverse patterns in the influences of VAS on reading within the TVA framework, which contributes to enriching the understanding of VAS-reading relation.

Keywords Bottom-up attention · Developmental dyslexia · Theory of visual attention · Top-down attention · Training · Visual attention span

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Extended author information available on the last page of the article

Introduction

Developmental dyslexia (DD) is characterized by impaired reading acquisition that cannot be explained by deficient neurological or sensorial functioning or inadequate schooling (VandenBos, 2015). A core deficit of DD is impairment in reading fluency, which refers to low speed in reading words or sentences correctly (Langer et al., 2015). This deficit may lead to lower academic achievement and further problems in social adaptation (Lyon et al., 2003). Therefore, it is necessary to design effective interventions that target critical cognitive deficits among readers with dyslexia to improve their reading fluency.

The phonological problem as a dominant view of the cognitive deficits in dyslexia has been widely reported in alphabetic and non-alphabetic languages (Snowling & Melby-Lervåg, 2016). Although phonological interventions have been found to enhance reading accuracy of DD (Thurmann-Moe et al., 2021), they have limited benefits for reading fluency (Snowling & Melby-Lervåg, 2016) and lacked far transfer effects (Green & Bavelier, 2012). Meanwhile, the training benefits of these phonological interventions have been observed to fade over time and could not be retained (Snowling & Melby-Lervåg, 2016). In light of the limitations of phonological trainings, we intended to explore the intervention to improve fluent reading in a new perspective—visual attention span (VAS).

VAS refers to the ability to process multiple visual elements simultaneously in a briefly presented array (e.g., the number of letters which could be processed simultaneously in a letter string; Bosse et al., 2007) and plays a crucial role in fluent reading (Zhao et al., 2022a). Both bottom–up (BotU) and top–down (TopD) attentional processes contribute to VAS. Previous studies in alphabetic languages have found the close relationship between BotU attention and reading fluency. However, due to the language characteristics of Chinese such as the complex visual features of Chinese script and lack of the word boundary in sentences, fluently reading Chinese requires not only the bottom–up processing but also the topdown attention. So, what is the relationship between these two types of attentional processes regarding VAS and Chinese reading fluency? To answer this question, the present study aims to investigate the effects of interventions separately targeting BotU and TopD attentional components regarding VAS and reading fluency in Chinese children with dyslexia.

The top–down and bottom–up attentional processes regarding VAS

According to the theory of visual attention (TVA; Bundesen, 1990), VAS capacity mainly involves stimulus-driven bottom–up (BotU) and goal-directed top–down (TopD) control processes. When processing multiple characters simultaneously, bottom–up processing is driven by the salience of stimuli, for example, the attention may be attracted by the red letters in a word; top–down processing refers to the voluntary allocation of attention to certain stimuli based on previous experience and goals, such as identifying previously encountered characters within a string.

Based on the TVA framework, BotU processing mainly involves two VAS subcomponents: the visual short-term memory (VSTM) storage and perceptual processing speed. In particular, the VSTM storage is related to the number of competing items in parallel, participants with larger VSTM storage are able to process a greater number of characters simultaneously. The VSTM temporarily stores the current representation of visual information to support subsequent orthographic processing (Bogon et al., 2014). The perceptual processing speed is associated with priority access to the VSTM system (Bogon et al., 2014), for example, stimuli with salient and unattended characteristics features enter the visual system at a higher speed and can be processed more rapidly. The perceptual processing speed closely related to fast and automatic access to whole words, and in turn, predict reading speed (Stefanac et al., 2019). Meanwhile, the VAS capacity is also influenced by TopD modulation. Specifically, the processing probability of a given item could be affected by attentional weight (i.e., the probability that different stimuli are processed during the competition for selection; Stefanac et al., 2019). There are two types of attentional weight: the spatial bias reflecting attentional lateralization between left and right hemifields (e.g., when searching for a target among multiple characters, previous experience can cause us to allocate more attentional resources to the left or right side), and inhibitory control reflecting attentional weight to the target item over irrelevant items (e.g., if the distractor is related to prior experience such as familiar characters, it may attract attentional resources). Spatial attentional weight exerts an influence on the distribution of attentional resources for further orthographic decoding of texts' visual forms (Jewell & McCourt, 2000); while inhibitory control involves conflict monitoring and suppression, which can reduce interruption from surrounding distractors on the currently reading process (Fan et al., 2002).

By integrating the mathematical model into the TVA framework, four parameters can be estimated to correspond to the four abovementioned VAS subcomponents (Bogon et al., 2014; Habekost, 2015; Stefanac et al., 2019). In detail, the BotU parameter C represents perceptual processing speed (i.e., the number of visual elements processed per second) and K represents VSTM storage (i.e., the maximum storage capacity of visual elements processed in parallel). The TopD parameter ω represents spatial bias of attentional weight (i.e., the differential attentional weight between items presented in the left versus the right visual fields) and α represents inhibitory control (i.e., the relative attentional weights of distractors compared to targets, especially, the lower α value corresponds to better inhibitory control). An illustration of these VAS subcomponents and relevant parameters in the TVA framework is shown in Fig. 1.

The relationship between VAS subcomponents and reading in alphabetic and non-alphabetic languages

In the context of alphabetic languages, previous studies based on the TVA framework indicated that children with dyslexia showed significant dysfunction in perceptual processing speed and VSTM storage capacity, revealing their deficits in BotU attention rather than in the TopD attentional regulation during simultaneous visual processing (Bogon et al., 2014; Stefanac et al., 2019). Niolaki and Masterson (2013) found that VAS training using a letter-array report task significantly improved VAS and reading performance of a Greek child with dyslexia, and these training gains were sustained in the follow-up assessments eight months later. The training task requires VSTM storage, and therefore, the above result possibly suggested the benefit of BotU attentional training on reading. However, the use of linguistic stimuli in the above study may confound the training effect. Valdois et al. (2014) further conducted a VAS intervention using both verbal and non-verbal stimuli on a French–Spanish bilingual child with dyslexia and observed training benefits on VAS and reading speed at the end of this intervention as well as ten months after the training. The training tasks consisted of visual matching (i.e., to immediately determine whether the two strings of stimuli were identical), visual search (i.e., to identify the target among distractors

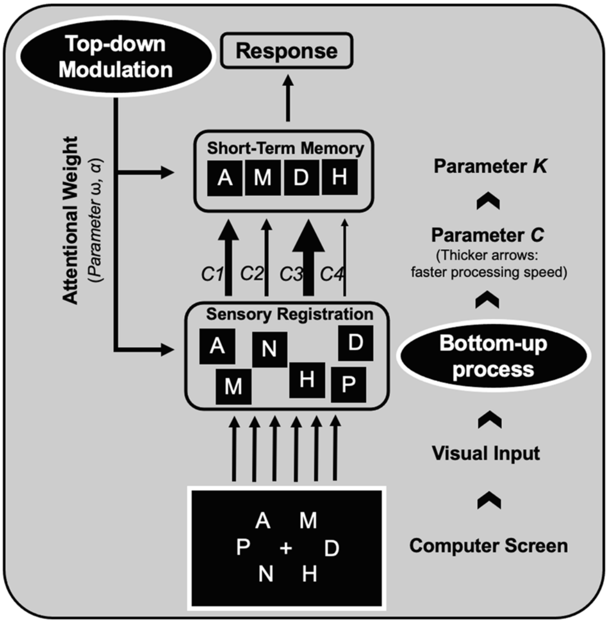

Fig. 1 Schematic diagram of theory of visual attention. Parameter C, the perceptual processing speed; parameter K, visual short-term memory storage; parameter ω, a spatial bias of attentional weight; parameter α, inhibitory control

with high visual similarities as the target), and visual parsing (i.e., to retrieve a target letter combination from a long letter string). The visual matching task may be related to processing speed and VSTM storage capacity, while the latter two tasks necessitate attentional resource distribution and inhibition of distractors. Therefore, this mixed training program did not provide us a clear picture on which of the two attentional components had a stronger link to reading fluency.

Besides these two case studies, recently, Zoubrinetzky et al. (2019) carried out a VAS training study using a modified paradigm on the basis of a whole-report task with nonverbal symbols and found significant intervention effects in VAS-related performance and reading fluency. In the training task, participants were required to determine the categories of the stimuli within the string, or the number of categories within a string, or the number of elements in one category, which might tap into visual processing speed and VSTM storage. Accordingly, this result revealed the relationship between BotU attentional training and improvements in reading fluency (Zoubrinetzky et al., 2019).

Unlike alphabetic languages, Chinese has a logographic writing system. Chinese characters have high visual complexity, as they are constructed by multiple strokes and radicals within a square block in an identical size (Liu & Liu, 2020). There are a great number of Chinese characters with similar visual forms but different meanings (Liu et al., 2018), for example, 大 (big), 太 (very), and 犬 (dog). Efficient visual attentional control, especially the volitional distribution of spatial attention resources, is critical for processing Chinese characters precisely. Meanwhile, there is no inter-word spacing within one continuous sentence in Chinese. Fluent reading of Chinese sentences requires not only rapid visual decoding but also the sufficient inhibition of distractors around the target and the effective attentional distribution for correct identification of words/phrases in one sentence (Liu et al., 2018). These characteristics in Chinese may specialize the roles of both BotU (e.g., visual processing speed) and TopD (e.g., spatial attentional distribution and distraction inhibition) attentional components in reading.

Although deficits in VAS have been reported in Chinese children with DD (Chen et al., 2019; Zhao et al., 2019), we are still unclear whether BotU and TopD attentional component(s) underlying the VAS dysfunction in Chinese DD show universality or language specificity. Previous studies using TVA paradigms indicated that Chinese children with DD exhibited reduced visual processing speed similar to that in alphabetic languages and the language-specific abnormality in the spatial bias of attentional weight during multiple element processing (Li et al., 2021; Zhao et al., 2021). Recently, an intervention study (Zhao et al., 2019) adopted a comprehensive training on VAS by covering both the BotU and TopD attentional processing and found the contribution of this training program to sentence reading of Chinese children with DD. These results revealed that VAS deficits of Chinese children with DD might arise from difficulties in both of the BotU and TopD processes. Nevertheless, it is still unclear whether BotU and TopD visual attentional components play different roles in Chinese reading or not. It is necessary and important to address this issue to deepen our understanding about the relationship between VAS deficits and reading disorders, with further contributing to designing effective remediation for the dyslexics with impairments in special attentional components.

The present study

The present study is among the first to develop two training programs separately targeting BotU and TopD attentional components for Chinese children with DD within the TVA framework and examined their effects on VAS subcomponents and character-/sentence-level reading outcomes. Based on the VAS deficit theory of dyslexia (Bosse et al., 2007), the convergent deficits across languages probably correspond to generic cognitive signatures of DD (Yan et al., 2021), which may be a critical candidate for the etiological factor of dyslexia. Training focusing on these generic cognitive factors such as visual attentional components may thus lead to significant improvement in reading among children with DD. Accordingly, we expected that intervention program targeting BotU attentional components may enhance the reading performance of Chinese children with dyslexia, which would be in line with that of alphabetic languages (Zoubrinetzky et al., 2019). Meanwhile, considering that TopD attentional control has an important role for reading in Chinese (Li et al., 2021; Zhao et al., 2021), as especially supported by previous findings showing that TopD attentional control could predict Chinese reading (Liu & Liu, 2020), we hypothesize that intervention program that targets the TopD attentional components will also enhance the reading performance of Chinese children with DD.

Method

Participants

In the present study, 45 children with DD from Grades 3 to 6 of a primary school in (city name blinded) were equally divided into three groups, including a BotU attentional training group, a TopD attentional training group, and an active control group receiving non-attentional training (“NonA control” hereafter). Referring to previous literature (Zhao et al., 2019), we identified children with dyslexia by using a standardized Chinese character recognition test (Wang & Tao, 1996), and Raven’s standard progressive matrices test (RSPM, Zhang & Wang, 1985). Moreover, metalinguistic skills, including phonological, orthographic, and morphological awareness, were also measured to further ensure the validity of dyslexic screening. Fifteen age-matched typically developing children were recruited to provide a reference of a normal reading level. As shown in Table 1, there were no differences in gender, grade, age and non-verbal intelligence across the four groups. Children in the three DD groups performed worse than children in the TD group in tests regarding character recognition, reading fluency, metalinguistic awareness skills (including the morphological and phonological awareness but not orthographic awareness), and the BotU attentional component of processing speed, with no significant differences across the three dyslexic groups. Details about screening criteria of DD and the above psychometric tests were descripted in Appendix A. All the participants were native Mandarin speakers. They were right-handed and had normal or corrected-to-normal vision, with no neurological abnormalities or attention deficit hyperactivity disorder (ADHD). This study was approved by the local research ethics committee and was conducted in accordance with the ethical principles of the *Declaration of Helsinki*. Written informed consent was obtained from the children's parents and teachers before assessment.

Two children with DD (i.e., one in the TopD group and one in the NonA group) did not complete the post-test, and their data were excluded from the following analyses. Moreover, another four children in the BotU group, five children in the TopD group, and six children in the NonA group did not take part in the follow-up test because they had graduated from the primary school, and thus, their data were eliminated in the analyses of retention effects (details in Table S1 of Appendix B). Because of the attrition, we conducted preintervention comparisons in all the measures across three testing stages within each group, as well as across three dyslexic groups of the remained participants in the post- and the follow-up test in Appendix B. Results revealed general homogeneity of the children with dyslexia across different testing stages and across different groups.

Procedure

There are four stages in this intervention study: pre-test, training stage, post-test, and follow-up test. During the pre-test, post-test, and follow-up tests, the CombiTVA task and reading fluency tests were administered in the three groups. Each participant took approximately 40 min to complete all the tasks in each testing session. The pre-test and post-test sessions were conducted within two weeks before and after training; the follow-up test session was conducted three months after the intervention. In order to comply with the requirements of the primary school, the attentional trainings lasted for 6 weeks and included 12 training sessions (two sessions per week), and each session took about 25 min (approximately 300 min in total); meanwhile, children of the NonA control group underwent a NonA intervention with 8 training sessions (two sessions per week) within 4 weeks, about 40 min per session (approximately 320 min in total). Referring to the school timetables of the children, the children were divided into several subgroups, and each of them included about 4 to 8 children who were arranged to engage in each training session together with 2–4 experimenters supervising. The experimenters were postgraduate students majoring in psychology who had been trained standardly. The present study was double-blinded, and none of the authors played the role in the experiment. All trainings were conducted in a quiet room and the children were seated approximately 1.5 m from each other to minimize mutual interference.

Table 1 Descriptive statistics of three DD subgroups and a TD group

Characteristics	① BotU training group ($n=15$)	② TopD training group ($n=15$)	③ NonA control group ($n=15$)	④ TD group ($n=15$)	χ^2 or F	p value	Pairwise comparisons
Gender (boys: girls)	10:5	12:3	14:1	10:5	4.10^a	0.30	-
Grade (3:4:5:6)	5:2:4:4	2:5:3:5	4:4:1:6	2:4:3:6	5.60^a	0.80	-
Age (months)	120.53 (14.83)	127.33 (12.95)	125.73 (20.00)	127.85 (14.98)	0.66^b	0.58	-
Non-verbal intelligence (percentile rank)	72.07 (20.18)	63.93 (22.05)	69.27 (22.55)	78.27 (10.54)	1.14^b	0.25	-
Character recognition (Z score)	−2.11 (0.62)	−2.55 (1.06)	−2.25(0.86)	0.83 (0.29)	64.55^{b***}	<0.001	①=②=③<④
CharS (c/min)	141.59 (59.57)	132.31 (57.41)	168.51 (56.65)	232.00 (91.86)	6.56^{b***}	<0.001	①=②=③<④
SenA	0.73 (0.13)	0.80 (0.06)	0.71 (0.18)	0.88 (0.05)	6.65^{b***}	<0.001	①=②=③ ①③<④
Phonological awareness (score)	13.73 (3.51)	15.93 (5.19)	15.33 (4.95)	23.93 (3.95)	15.72^{b***}	<0.001	①=②=③<④
Morphological awareness (*Z*-score)	−0.62 (0.81)	−0.16 (0.81)	−0.75 (0.64)	0.63 (0.53)	11.58^{b***}	<0.001	①=②=③<④
Orthographical awareness (accuracy)	0.74 (0.13)	0.81 (0.06)	0.76 (0.10)	0.83 (0.15)	1.96^b	0.13	-
VAS subcomponents							
K	3.27 (0.05)	3.27 (0.05)	3.30 (0.05)	3.28 (0.06)	0.90^b	0.45	-
C	6.34 (1.16)	6.86 (1.80)	6.73 (1.85)	8.35 (1.09)	5.02^{b**}	0.004	①=②=③<④
ω	0.50 (0.05)	0.49 (0.04)	0.48 (0.04)	0.50 (0.02)	1.21^b	0.32	-
α	1.86×10^{-6} (3.11×10^{-6})	4.61×10^{-4} (1.66×10^{-3})	1.03×10^{-3} (3.71×10^{-3})	4.70×10^{-7} (4.42×10^{-7})	0.87^b	0.46	-

Standard deviants are in the parentheses

DD developmental dyslexia, *TD* typically developing, *BotU training group* children with dyslexia receiving bottom–up attentional training, *TopD training group* children with dyslexia receiving top–down attentional training, *NonA control* children with dyslexia receiving non-attentional training, *a* values of *chi-square* tests, *b* values of *F* tests, *K* visual short-term memory storage capacity. *C* visual processing speed, *ω* spatial bias of attentional weight, *α* efficiency of attentional control, *CharS* character reading speed in the character-list reading task, *SenA* reading accuracy in the sentence reading task

$^*p<0.05$

$^{**}p<0.01$

$^{***}p<0.001$

Assessments in the pre-test, post-test, and follow-up tests

TVA-based assessment of VAS subcomponents

The CombiTVA paradigm (Habekost, 2015) with non-verbal symbols (Fig. 2a) was adopted to evaluate a pure capacity of VAS subcomponents without the influence of oral processing. This test was programmed by E-Prime 2.0. The presentation format of each trial is shown in Fig. 2b. There were three types of stimulus arrays: 1) a six-target condition, six red targets with variable durations, 2) a two-target condition, two red targets, and 3) a four-distractor condition, two red targets, and four blue distractors. After the stimulus array, a single symbol appeared at the center of the screen. The participants were required to accurately ascertain whether the last symbol was present in the stimulus array or not by pressing different keys. Accuracy was recorded. Detailed information regarding this task and materials are provided in Appendix C.

This study adopted a program package of LIBTVA (Kyllingsbaek, 2006) to estimate the parameters relating to the four VAS subcomponents (i.e., the parameters of K, C, ω, and α) based on average accuracy of each type of target presence. Detailed statements regarding the parameter estimation are provided in in Appendix C.

Reading fluency tests

A character-list reading task (Zhao et al., 2017) was used to evaluate reading fluency at the single-character level. This list is consisted of 387 high-frequency characters and 13 non-characters. Children were required to silently read the real character one by one within one minute, and to occasionally cross out the non-character quickly during reading. The usage of a small number of randomly arranged non-characters in this test was to ensure the validity of silent reading. Average accuracy of detecting non-characters was higher than 90%, showing the validity of silent reading. The final score of the character reading test was the number of Chinese characters read in one minute.

A sentence reading task (van den Boer et al., 2014; Zhao et al., 2019) was used to assess reading fluency at the sentence level. This was a computerized test. There were 25 true sentences and 25 false sentences in the formal test. Participants were required to press different keys to quickly verify the sentence, with “F” key for false and “J” for true. The accuracy rate of the veracity judgement was recorded.

Training tasks

Tasks in the BotU and TopD training programs were separated into different difficulty levels according to stimulus properties (e.g., visual complexity) or paradigm settings (e.g., presentation duration). General procedures of each training task were introduced as below, and more detailed information is provided in in Appendix D.

Bottom–up attentional training

All-target TVA task (Fig. 3a) was developed on the basis of the CombiTVA paradigm with two types of stimulus arrays (i.e., six-target array and two-target array). Twenty-seven symbols (Fig. S1a) were additionally designed for training, which were different from those used in the pre-test, post-test, and follow-up tests to reduce the practice effect. The accuracy

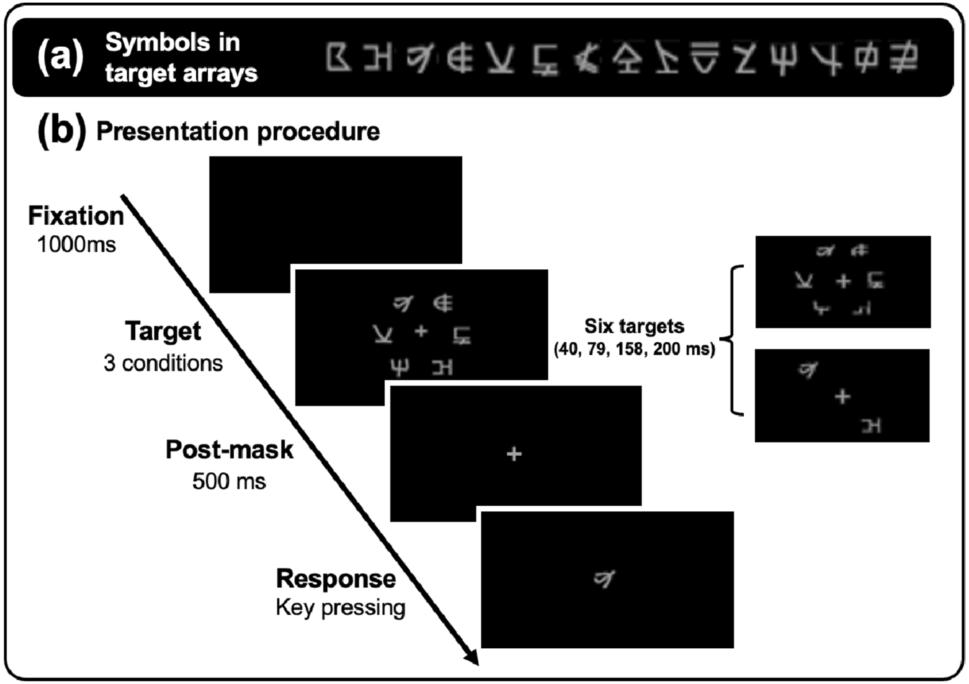

Fig. 2 Presentation formation of combiTVA paradigm

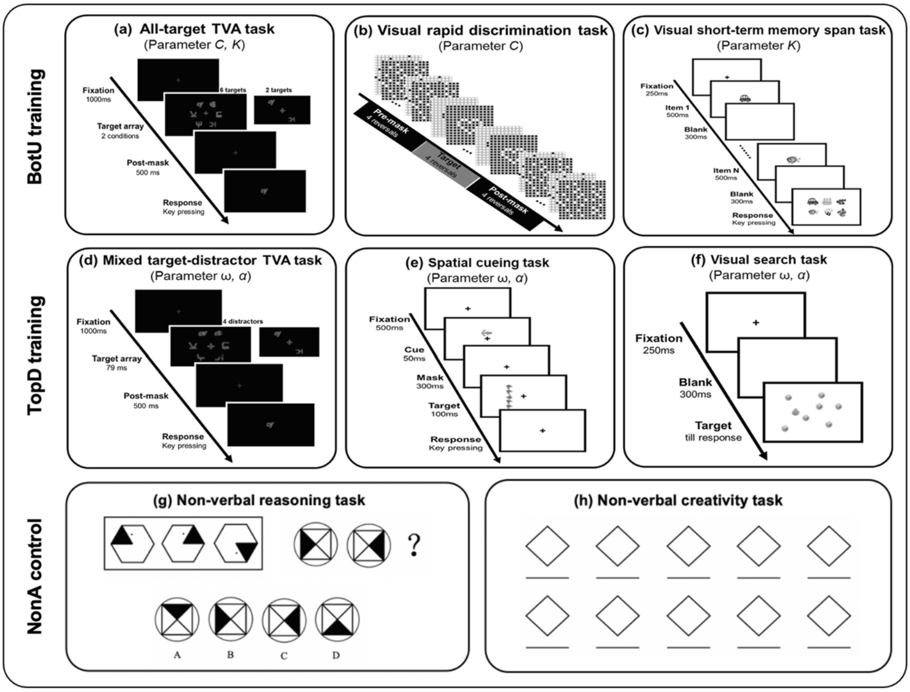

Fig. 3 Training tasks in different intervention groups

and response time of each trial were recorded. *Visual rapid discrimination task* was used to train perceptual processing speed (Fig. 3b). In this task, a pair of dot matrices containing one shape were alternatively presented four times with a self-adaptive presentation duration. Participants were required to press different keys to judge whether there was a target shape in the dots matrix or not. The percentage of target presence was 50%. We adopted a 2-yes-1-no staircase procedure (see Appendix D for details) to estimate the threshold of temporal resolution with reflecting processing speed. *VSTM span task* (Fig. 3c) was used. In this task, after a series of pictures were successively presented in the screen center, participants were asked to select objects from a picture matrix by clicking relevant items in the presentation order of the target series. The accuracy was recorded.

Top–down attentional training

Mixed target-distractor TVA task (Fig. 3d) was designed based on the CombiTVA paradigm with the stimulus arrays consisting of two targets and four distractors. The stimuli and training procedure were the same as that used in the all-target TVA training task mentioned above. *Spatial cueing task* was utilized to train the top–down attention. In this task (Fig. 3e), a fishhook as a cue was briefly presented before the target fish at the midline of the screen. In half of the trials, the orientation of the fishhook was consistent with the presentation location of the following target; in the other half of the trials, the orientation of the fishhook was opposite to the location of the target. Participants were asked to judge the orientation of the target fish in the center of the stimulus array by pressing different keys.

Reaction time and accuracy of each trial were recorded. In *visual search task*, participants were asked to search for a target picture among the several distractors as quickly and accurately as possible and then to click the target via the mouse (Fig. 3f). Response time and accuracy of each trial were recorded.

Non-attentional control

Children in the NonA group received a non-linguistic reasoning test and a figural creativity test in each session, which were both paper-and-pencil tests. These tasks were less related to visual rapidly simultaneous processing. In the reasoning task (Fig. 3g), participants were required to make inductive reasoning according to the given premise and to choose an answer from the four options. Non-verbal creativity tasks were from the figural subsets of Torrance Test of Creative Thinking, in which participants were asked to draw with the given figure (e.g., draw with diamonds in Fig. 3h).

Plans of statistical analyses

Training effects on the VAS subcomponent capacity and reading

1) We computed progress rate ("PR" hereafter) to reflect the training effect by the following formula PR = (post-test – pre-test)/pre-test (Mahdieh et al., 2020). One-sample *t*-tests were adopted to explore whether the PR significantly differed from zero within each of the dyslexic groups. Training effects were defined if the PR in training groups (i.e., BotU and TopD training groups) but not in the NonA control group was significantly higher (or lower especially for the parameter regarding inhibitory control) than zero. 2) Correlation analyses were used to examine a. the relationship between PRs of VAS subcomponents and of reading outcomes and b. the relationship between learning changes in each training task and PRs of VAS subcomponents/reading outcomes, in order to test the direct and transfer training effects. Referring to previous research (Zhao et al., 2019), we used repeated measures ANOVAs to examine whether the main effects of training session in each difficulty level of all the training tasks were significant or not. We propose a significant learning change in this training task if the main effect of training session is significant. We conducted the curve fitting based on the tasks showing significantly learning changes and used slopes of the fitted curves to reflect relevant learning changes during the training procedure.

Retention effects

Only the outcomes showing direct training effects and transfer effects were explored. Participants' performances in the follow-up test were compared with that in post-tests via paired samples *t*-tests. Particularly, retention effect was identified if there were no significant differences in performances between follow-up and post-tests.

Partial eta squared (η_p^2) values and Cohen's *d* effect sizes were reported for the repeated measures ANOVAs and *t*-test analyses, respectively. According to Cohen (1988), for η_p^2, a value between 0.01 and 0.06 represents a small effect, a value between 0.06 and 0.14 is considered as a moderate effect, and a value more than 0.14 is considered as a large effect; for Cohen's *d*, a value between 0.2 and 0.5 is considered as a small effect, a value between 0.5 and 0.8 is considered as a moderate effect, and a value greater than 0.8 is considered as a large effect.

Results

Training effects on VAS subcomponents and reading skills

As shown in Table 2, PR of parameter C for children in the BotU training group was significantly higher than zero ($p < 0.05$), and their PR in parameter α was significantly lower than zero ($p < 0.001$). By contrast, PRs of the above two VAS subcomponents did not differ from zero in either the TopD group or the NonA group ($ps > 0.10$). Besides, PRs of the other parameters (i.e., ω and K) did not differ from zero for any attentional training groups ($ps > 0.10$). See *Appendix* E for the descriptive data in the pre- and post-tests and progress rate for each group.

Results of one sample t-tests (Table 2) showed that PR of sentence reading accuracy was higher than zero only in the BotU training group (marginally significant) but not in the other groups ($ps > 0.10$). Moreover, only children in the TopD group exhibited PR in character reading speed higher than zero ($p < 0.05$).

Most of the significant results mentioned above were with moderate to large effect sizes, suggesting that these results were reliable. One exception is the training effect on sentence reading accuracy in BotU training condition, which showed a relatively small effect size.

Results of correlation analyses (Table S7 in *Appendix F*) showed that in the BotU training group, PR in sentence reading accuracy was significantly correlated with PR in parameter α ($r = -0.58$, $p < 0.05$), while in the TopD training group, the correlations between the PR of VAS subcomponents and that of the character reading speed were nonsignificant ($ps > 0.10$).

Correlations between learning changes during intervention and training benefits

As shown in Table 3, participants exhibited significant learning changes in all the training tasks with large effect sizes, in which the learning differences were present in some training tasks with low-level difficulty (e.g., training tasks of all-target TVA and VSTM span). Then, a curve fitting method was adopted according to previous literature (Zhao et al., 2019). The slopes of the fitted curve based on each participant's performance in the training conditions were used to reflect relevant learning changes during training. The reciprocal function ($y = a\ (1/x) + b$) was selected to fit the training-related datasets in each difficulty level of the training tasks, in which ''a'' indicates the slope of the learning curve. Results of correlation analyses (see Table S8 in *Appendix F*) showed that learning changes in the training task of spatial cueing paradigm were positively correlated with the PR of character reading speed of children in the TopD group ($r = 0.58$, $p = 0.06$, marginally significant), without any other significant correlations ($ps > 0.1$).

Retention effect on improved VAS subcomponents and reading skills

The above results showed intervention improvements in VAS subcomponents of processing speed and inhibitory control, and a tendency of improvement in sentence reading accuracy for the BotU training group and in character reading speed for the TopD training group. Therefore, the following analyses regarding retention effects focused on these indexes showing training benefits.

Results of paired samples t-tests (Table 4) on the scores of post-test and follow-up tests showed that, for the participants receiving the BotU training, improvements on parameter

Table 2 Results of direct training effects and transfer effects

Characteristics (progress rate)	① BotU training group ($n = 15$)			② TopD training group ($n = 14$)			③ NonA control group ($n = 14$)		
	Mean (SD)	t	Cohen's d	Mean (SD)	t	Cohen's d	Mean (SD)	t	Cohen's d
VAS subcomponents									
K	9.87×10^{-5} (2.58×10^{-2})	0.02	0.00	1.90×10^{-3} (1.23×10^{-2})	0.58	0.15	2.47×10^{-3} (1.72×10^{-2})	0.54	0.14
C	0.32 (0.44)	2.81*	0.7	0.16 (0.42)	1.45	0.39	−0.004 (0.13)	−0.12	0.03
ω	−0.02 (0.12)	−0.06	0.01	0.03 (0.16)	0.73	0.19	0.09 (0.11)	3.02*	0.81
α	−0.48 (0.43)	−4.29**	1.11	0.24 (1.40)	0.65	0.17	−0.21 (0.91)	−0.86	0.23
Reading skills									
CharS	0.26 (0.58)	1.72	0.45	0.51 (0.75)	2.51*	0.67	0.21 (0.59)	1.33	0.35
SenA	0.11 (0.24)	$1.82^{\#}$	0.47	0.03 (0.09)	1.35	0.36	0.33 (1.17)	1.05	0.28

BotU training group children with dyslexia receiving bottom–up attentional training, *TopD training group* children with dyslexia receiving top–down attentional training, *NonA control* children with dyslexia receiving non-attentional training, K VSTM storage capacity, C visual processing speed, ω spatial bias of attentional weight, α efficiency of attentional control, *CharS* character reading speed in the character-list reading task, *SenA* reading accuracy in the sentence reading task

$^{\#}p < 0.10$

$^{*}p < 0.05$

$^{**}p < 0.01$

Table 3 The performance of children in each difficulty level of training tasks

Types	Scores in training tasks	Level	*F* values	η_p^2
BotU	Acc in all-target TVA task	Level 1	3.20*	*0.19*
		Level 2	0.78	*0.05*
		Level 3	-	-
	Acc in VSTM span task	Level 1	2.62*	*0.16*
		Level 2	0.64	*0.04*
		Level 3	-	-
	Temporal frequency in visual rapid discrimination task	Self-adaption	2.87**	*0.17*
TopD	Acc in mixed target-distractor TVA task	Level 1	6.32***	*0.31*
		Level 2	7.93***	*0.36*
		Level 3	-	-
	RTs in spatial cueing task	Level 1	18.72***	*0.57*
		Level 2	12.74***	*0.48*
		Level 3	0.16	*0.01*
	RTs in visual search task	Level 1	63.71***	*0.85*
		Level 2	31.30***	*0.69*
		Level 3	132.94***	*0.91*

BotU training group children with dyslexia receiving bottom–up attentional training, *TopD training group* children with dyslexia receiving top–down attentional training

* $p < 0.05$

** $p < 0.01$

*** $p < 0.001$

C and α, and sentence reading accuracy kept stable in the follow-up stage ($ps > 0.10$). Regarding the participants in the TopD training group, their training benefit on character reading speed was maintained in the follow-up test ($p > 0.10$).

Discussion

This study implemented training programs separately tapping into the BotU and TopD attentional components regarding VAS on Chinese children with DD and systematically examined their intervention effects and retention effects on VAS subcomponents and reading fluency. Results indicated that the BotU training showed direct training effects on both the bottom–up (i.e., visual processing speed) and top–down (i.e., inhibitory control) attentional processes, while the TopD training did not exert a direct influence on VAS subcomponents. For transfer effects, the BotU training led to an increase in the sentence reading accuracy in children with DD, which was correlated with their training gains in the inhibitory control, while the TopD training improved character reading speed, reflected by the association between the learning changes in the training task of spatial cueing and PR of character reading speed. As to retention effects, intervention benefits in the VAS subcomponents and reading skills were maintained in both training groups. The above results revealed a language-universal role of BotU attentional components (especially perceptual processing speed) in reading, and also indicated a possible influence of TopD attentional

Table 4 Results of retention effects on improved VAS subcomponents and reading skills

Group	Characteristics	T1 Mean (SD)	T2 Mean (SD)	$t_{(\text{T2-T1})}$ test t	Cohen's d
BotU training group ($n = 11$)	SenA	0.79 (0.08)	0.76 (0.08)	1.23	*0.32*
	C	8.09 (2.82)	8.72 (1.40)	0.93	*0.25*
	α	5.80×10^{-7} (4.26×10^{-7})	8.64×10^{-7} (7.45×10^{-7})	1.10	*0.47*
TopD training group ($n = 10$)	CharS (c/min)	215.00 (92.87)	201.40 (49.62)	0.48	*0.18*

BotU training group children with dyslexia receiving bottom–up attentional training, *TopD training group* children with dyslexia receiving top–down attentional training, *T1* post-test, *T2* follow-up test after three months, *SenA* reading accuracy in the sentence reading task, C visual processing speed, α efficiency of inhibitory control, *CharS* reading speed in the character-list reading task, $t_{(\text{T2-T1})}$ the statistic of paired t-test between the follow-up and post-tests control on Chinese reading, which may reflect the modulation of language specificity on the attention-reading relation.

Effects on within-category VAS subcomponents of the two training programs

The BotU training directly improved the within-category VAS subcomponent especially on perceptual processing speed but not on VSTM storage; meanwhile, the TopD training did not significantly influence the VAS subcomponents regarding the top–down attentional modulation. We attempted to explain this different pattern from three aspects as below. *The first aspect* relates to the relevance between training tasks and the VAS subcomponents. The training tasks in the BotU program mainly tapped into visual temporal processing closely related to perceptual processing speed, such as the all-target TVA task. However, given that there was no time limit in the training task of VSTM span and the successive presentation of stimulus series in the task, the VSTM storage during rapidly simultaneous processing might not be sufficiently boosted by this training. As to the TopD program, non-verbal materials were used in all the training tasks. It has been suggested that the lateralized pattern of spatial attentional distribution was markedly observed in conditions involving verbal materials (e.g., letters and characters), rather than in the conditions involving non-verbal stimuli such as symbols (Li et al., 2021). When processing non-verbal materials, individuals can flexibly allocate attentional resources with less influence of reading experience, showing a balanced distribution of attentional weight. Therefore, the attentional distribution might not be significantly changed during this training. Moreover, given that the training tasks in the TopD program involves unlimited time visual search and spatial cueing paradigms, special tests of attentional shifting and orientation might be more suitable to detect the training benefits rather than the combiTVA paradigm regarding the rapidly visual simultaneous processing. In the future, the parameters in these training tasks, as mentioned above, could be further modified, in order to explore their effectiveness in training children's VAS.

Secondly, previous studies indicated that children benefit more from training focusing on their relative weaknesses than on their relative strengths (Gustafson et al., 2007). The current cohort of children with DD had deficits in the VAS subcomponent of perceptual processing speed (see Table 1) but not in the top–down attentional components, which may lead to the lack of obvious gains in the TopD attentional training.

The third aspect is the differences in data characteristics across various VAS subcomponents. The sensitivity of dependent measures would influence the detection of training effects (Dale et al., 2020). Parameter C regarding processing speed is sensitive and continuous in all groups, which are conducive to reflect training benefits in this VAS subcomponent. By contrast, parameter K of VSTM storage clustered between 3 and 4 in most individuals. The characteristic of the parameter might impede us from capturing the training changes.

Effects on between-category VAS subcomponents of the two training programs

The BotU training can also exert a between-category influence on VAS subcomponents related to top–down processing, especially with improving inhibitory control. whereas TopD training did not enhance the other type of VAS subcomponents. Moreover, the benefit of the BotU program on inhibitory control was maintained three months after the intervention, revealing the reliability of this training gain to some extent. There are several possibilities for the different between-category influences of the two attentional trainings. *The first* is about the directionality of the relationship between BotU and TopD attentional components. The BotU program focused on enhancing perceptual processing speed, which is a critical and basic cognitive skill (Schneider & McGrew, 2012). It has been found that processing speed is closely related to inhibition (Liebel et al., 2017), and cognitive training involving processing speed can improve top–down attentional modulation and executive function (Kollins et al., 2020). Accordingly, it can be inferred that training improvement in perceptual processing speed via the BotU program might contribute to the between-category enhancement in the TopD attentional component of inhibitory control. On the other hand, for the TopD attentional training, the absence of direct training effects on the within-category VAS subcomponents might further reduce the possibility to exhibit a cross-category gains regarding the VAS skills within the same TVA model.

Secondly, the two types of attentional processes have (partially) separate mechanisms in the neural aspect (Corbetta & Shulman, 2002; Zhao et al., 2022b). To be specific, the TopD attentional control mainly relies on dorsal attention network (DAN), and the BotU attention remarkably activates ventral attention network (VAN; Corbetta & Shulman, 2002). It has been reported that the VAN-to-DAN connectivity is associated with reaction time in the visual-spatial attentional task; meanwhile, DAN-to-VAN connectivity is closely related to accuracy in the attentional task (Wen et al., 2012). Given the abnormality in functional connectivity between DAN and VAN (Taran et al., 2022), it thus could be proposed that the BotU training in the present study may ameliorate the connectivity from VAN to DAN and in turn improve the processing speed in visual attention task, whereas the TopD training might normalize the connectivity from DAN to VAN and further enhance the accuracy in attentional processing. However, VAS subcomponents emphasized cognitive processes in the background of visual rapidly processing, which may focus more on speed rather than accuracy, and then effects from BotU to TopD attention (or from VAN to DAN) might be obviously presented. Future studies could ensure this possibility via neuroimaging techniques.

Thirdly, given the cognitive skills implicated in the training tasks, it is possible that the tasks in our BotU training also required to invoke cognitive processing regarding the TopD attention, and then relevant VAS subcomponents would directly get benefits. Although there were non-significant correlations between the learning changes in BotU training tasks and PR in TopD attentional components, the absence of these relationship might be due to the insensitive measurements in BotU training tasks (e.g., temporal thresholds and VSTM span). Later studies need to strictly distinguish the BotU training and TopD training programs so as to examine the possible transfer effects between these two interventions.

Effects on Chinese reading fluency between the two attentional trainings

The present study demonstrated that both of the BotU and TopD attentional training programs regarding VAS could significantly improve the reading fluency of Chinese children with DD. The possible link between BotU attentional component and reading fluency is consistent with previous findings in alphabetic languages, which supported the universal deficits of BotU attention (especially perceptual processing speed) in developmental dyslexia across different writing systems. Moreover, the present study also found that the intervention tapping into the TopD process improved reading fluency of Chinese dyslexic children, revealing the possible modulation of language specificity on training effects. The language characteristics of the Chinese writing system, such as the lack of work boundaries in sentence, highlight the importance of the TopD process regarding the VAS ability in reading in Chinese (Liu & Liu, 2020; Liu et al., 2018).

Furthermore, after subdividing different types of visual attentional components within the TVA framework and distinguishing different levels of reading, we found a dissociation in the influence of VAS on Chinese reading. Although both reading in character and sentence levels require the involvement of BotU and TopD attentional processes (Freedman et al., 2020), the present study using a training method demonstrated the greater contribution of BotU training program to sentence reading performance and more facilitation of TopD training to character reading speed. The patterns of these results are consistent with previous findings based on the correlation analyses on the relationship between VAS subcomponents and reading (Li et al., 2021).

In this study, sentences in the reading test which were generally composed of high-frequency characters. While reading these sentences, the readers could automatically process several characters as a whole in parallel and rapidly ascertain the mapping between orthography and semantic information (Ekstrand et al., 2019). Based on relevant studies (Corbetta & Shulman, 2002; Ekstrand et al., 2019), BotU attention is required in automatic cognitive processing without putting too much effort into the task. This type of attention recruits VAN to re-orient visual spatial attention, which mainly includes the temporal–parietal junction and inferior frontal gyrus (Corbetta & Shulman, 2002). These brain areas are also responsible for automatic mapping between orthography and phonology and semantic retrieval during reading (Martin et al., 2015). Therefore, it could be concluded that sentence reading in this study relied more on the BotU attention. Meanwhile, based on the current findings regarding the linkage between the training benefits of the VAS subcomponent of inhibitory control and the gains in sentence reading, it is also possible that the BotU training made a contribution to the between-category VAS subcomponents (i.e., attentional control), and in turn affected the sentence reading efficiency. Especially, the cognitive inhibition might be important for reducing the probability of irrelevant information to be maintained in working memory during text reading (Arrington et al., 2014).

The stimuli in the character-level reading task were selected from Chinese books of Grades 1 to 3 from primary school; the participants in this study were familiar with these characters (accuracy > 99%). The character-list reading involves the analysis of orthographic structures and further assembled the retrieval of corresponding phonological representations. Meanwhile, the participants in this study were also required to cross out the non-character when they occasionally met one during character-list reading. This procedure is relatively similar to the visual search paradigm, both of which involve the retrieval and match of past experience or memory. This process requires TopD attention, which is a type of volitional attentional regulation to allocate cognitive resources to different tasks (Ekstrand et al., 2019; Stefanac et al., 2019). This type of attention mainly relies on DAN, including the frontal eye fields and the posterior parietal cortex (Corbetta & Shulman, 2002). These brain areas are involved in the visual search procedure based on experience, and in the processing of visuo-orthographic information and phonological representation (Martin et al., 2015). Therefore, it could be concluded that TopD attention contributes to allocating attentional resources to the globally orthographic decoding of each of the characters, to achieve the following orthographic-to-phonological mapping and lexical decision.

It is worth mentioning that although the TopD attentional training failed to enhance the VAS subcomponents in children with DD, this program significantly improved the character reading fluency of these children and the benefits were maintained for three months after the training. Based on the result of correlation between learning change in the training task of spatial cueing and the PR of character reading speed, it could be inferred that the intervention gains in character reading might attribute to the enhancement in visual spatial attention regarding TopD processing which was not fully reflected by the TVA model.

Limitations

This study has the following limitations: 1) the training setting of the present study should be optimized, especially the manipulation of difficulty levels of training tasks, the correspondence between trained tasks and relevant training groups, as well as the properties of training procedures. There were inflexible arrangements of difficulty levels across different training tasks in the present study. Given the heterogeneity of dyslexia, it is necessary to consider the individualization in manipulating the difficulty levels of the training tasks. Based on the relevant literature (Chang et al., 2017), the self-adaptation procedure could be adopted in future intervention studies. Meanwhile, the relevance between trained skills and visual attentional components should be strengthened, and more efforts were required to make on distinguishing interventions separately tapping into the two types of attentional components regarding VAS, with more sensitive measurements to be used to examine the contribution of each training task to the intervention benefits. Moreover, the tasks used in the NonA control group may also involve the visual spatial ability, as significant improvement of the spatial bias of attentional weight (i.e., parameter ω) was only found in the NonA control group. Future studies should optimize the tasks used in the active control group to avoid potential influence of the confounding variables. The properties of training procedures, including the number of training sessions, the duration for each training session, and modes (i.e., computerized verse paper-and-pencil tasks) did not keep consistent between two attention trainings and the non-attention training, which might exert influence on the final conclusion. In future studies, the abovementioned properties should be balanced between training and control groups so as to improve the reliability of the results. 2) In the current study, children from Grade 3 to Grade 6 were engaged, who may be the readers of different developmental stages. Moreover, the distributions of participants in different grades were not fully matched between TD and DD groups. Then, the age/grade effect on reading abilities should be concerned especially in the condition of using the same list of characters in the reading test for children from different grades in the future. Also, future studies may further examine the effectiveness of the VAS-related training in participants from other age/grade ranges. 3) The child participants in the present study generally started to learn English as the second language from Grade 1. Since the language properties such as orthographic depth and writing system have been found to modulate the relationship between VAS and reading (Bosse et al., 2007; Zhao et al., 2019; Zoubrinetzky et al., 2019), the language background of participants (e.g., English proficiency) should be taken into consideration in the future study. 4) The small sample size (especially at the follow-up stage) might limit the statistic power to detect training effects and retention effects. So, the current results on the VAS-related training on reading should be treated cautiously. Future studies should enlarge sample sizes to further ensure the VAS-reading relation and use more effective methods to reduce the attrition rate of participants.

Despite these limitations, this study is among the first to provide evidence for the effectiveness of cognitive training that targets BotU and TopD attentional skills regarding VAS under the TVA framework on VAS subcomponents and reading fluency in Chinese children with DD and suggests that it is necessary to ensure the cognitive processes involved in the training programs of DD to understand the potential mechanism of relevant training benefits and to further optimize the intervention programs. This study can facilitate our understanding of the detailed mechanism underlying the association between visual attentional components and reading fluency in Chinese children with DD and inform practice by confirming the effectiveness of training programs focusing on BotU and TopD attentional components.

Conclusions

Within the TVA framework, this study designed two types of attentional training programs for Chinese children with DD: the BotU and TopD attentional trainings. The intervention effects, including direct training, transfer, and retention effects, were systematically examined and compared between the two types of training. We found that the BotU training improved both of the within-category and between-category VAS subcomponents and further led to a tendency of improvement in sentence reading accuracy; meanwhile, the TopD training contributed to enhancing character reading speed possibly through the improvement in spatial attention.

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Data Availability All data is available when contacting the corresponding authors.

Declarations

Conflict of interest The authors declare no competing interests.

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