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Working-memory training improves developmental dyslexia in Chinese children★

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Abstract

Although plasticity in the neural system underlies working memory, and working memory can be improved by training, there is thus far no evidence that children with developmental dyslexia can benefit from working-memory training. In the present study, thirty dyslexic children aged 8–11 years were recruited from an elementary school in Wuhan, China. They received working-memory training, including training in visuospatial memory, verbal memory, and central executive tasks. The difficulty of the tasks was adjusted based on the performance of each subject, and the training sessions lasted 40 minutes per day, for 5 weeks. The results showed that working-memory training significantly enhanced performance on the nontrained working memory tasks such as the visuospatial, the verbal domains, and central executive tasks in children with developmental dyslexia. More importantly, the visual rhyming task and reading fluency task were also significantly improved by training. Progress on working memory measures was related to changes in reading skills. These experimental findings indicate that working memory is a pivotal factor in reading development among children with developmental dyslexia, and interventions to improve working memory may help dyslexic children to become more proficient in reading.

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Key Words

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Research Highlights

(1) Dyslexic children were trained on working memory tasks, including the visuospatial, verbal, and central executive domains.
(2) Working memory in children with developmental dyslexia can be improved through training.

INTRODUCTION

Developmental dyslexia is the most common learning disability, and is characterized by low reading abilities in children who have adequate intelligence, typical schooling, and sufficient sociocultural opportunities[1-2]. Many studies have shown that dyslexic children benefit from early intervention programs focusing on orthographic or morphological spelling treatments[3-4]. However, some children do not respond to such programs. These improvements are more difficult to achieve for fluency than for accuracy[5]. Numerous studies have examined whether dyslexia involves deficits in sub-systems of working memory, such as phonological loops, visuospatial sketchpads, and central executive functioning[6-9]. Furthermore, a multidisciplinary approach showed that a unifying theoretical framework for three working memory components may provide a system perspective for discussing past and present findings in a 12-year research program that point to heterogeneity in the neural basis and behavioral expression of dyslexia[10]. Recent studies found that children with attention-deficit/ hyperactivity disorder or with learning disabilities may experience beneficial effects from working-memory training[11-14].

Moreover, other recent data indicated working memory and literacy measures in adult dyslexic readers can be improved by working-memory training[15]. However, to date, there is no evidence that training on any other regimen yields increased working memory in children with developmental dyslexia. We hypothesized that working memory abilities in children with developmental dyslexia would improve following training, and these improvements would have a positive effect on the children's reading skills.

RESULTS

Quantitative analysis of experimental subjects and baseline data

Thirty developmentally dyslexic children were randomly divided into treatment group (11 males and 4 females, 10.2 ± 0.8 years old) and control group (10 males and 5 females, 10.9 ± 0.9 years old), with no significant difference in the age and gender between two groups ($P > 0.05$). The vocabulary test scores and intelligence quotient of children in treatment group were 2175 ± 309 words and 106 ± 7, while those in control group were 2 208 ± 319 words and 108 ± 5, respectively, with no significant differences ($P > 0.05$). Treatment group was engaged in training for 40 minutes a day and task difficulty was manipulated according to the completion of training. The control group was trained for 10 minutes a day, but the difficulty level was not interactively adjusted. All of them participated 5 weeks of training programs. Participant information is shown in Table 1.

Table 1 Characteristics of the participants

No.	Gender	Age (year)	Education (year)	Ethnicity	Vocabulary test scores (word)	Score of DCCC	Score of IQ
Treatment group							
1	Male	8	3	Han	1 994	74	99
2	Female	9	3	Han	1 847	75	110
3	Male	8	3	Han	1 937	78	194
4	Male	9	3	Han	1 944	79	101
5	Male	9	4	Han	2 018	80	108
6	Male	10	4	Han	2 051	73	103
7	Female	10	4	Han	2 204	75	108
8	Female	9	4	Han	2 144	78	102
9	Female	10	4	Han	2 237	79	97
10	Male	11	5	Han	2 318	80	92
11	Male	11	5	Han	2 585	83	100
12	Male	10	5	Han	2 620	80	103
13	Male	11	5	Han	2 486	85	115
14	Male	11	5	Han	2 585	74	94
15	Male	11	5	Han	2 274	77	108
Control group							
1	Female	9	3	Han	1 868	74	115
2	Female	8	3	Han	1 872	77	96
3	Male	9	3	Han	1 879	77	118
4	Female	8	3	Han	1 957	74	111
5	Male	9	3	Han	2 147	73	93
6	Male	9	3	Han	2 251	74	106
7	Female	10	4	Han	2 168	77	98
8	Male	10	4	Han	2 187	77	111
9	Male	9	4	Han	2 079	82	122
10	Male	10	4	Han	2 545	77	111
11	Female	11	5	Han	2 362	82	103
12	Male	10	5	Han	2 420	83	115
13	Male	11	5	Han	2 423	80	122
14	Male	11	5	Han	2 160	85	88
15	Male	10	5	Han	2 266	76	107

DCCC: Dyslexia Checklist for Chinese Children; IQ: intelligence quotient.

Working-memory training improved working memory in children with developmental dyslexia

There were no significant differences in baseline scores (T1) between the treatment group and the control group ($P > 0.05$).The effects of training in each group were tested by comparing the outcome scores after the training (T2) to the scores at T1. Performance on the four verbal working memory measures, the visuospatial working memory measure, and the central executive measure (time for completion of the Stroop task) was better at T2 than T1 in the treatment group ($P < 0.05$). Performance on two literacy measures (accuracy and reaction time in a visual rhyming task, $P < 0.05$; one-minute test of reading words, $P < 0.01$) was also better at T2 than T1 in the treatment group.

However, no significant differences were found for any measure in the control group ($P > 0.10$; Table 2).

Table 2 Task performance and effect sizes for the cognitive and literacy measures in the two groups

Item	Control group			Treatment group			Group difference (P)[a]	Effect sizes (d)[b]
	T1	T2	Training-related (t/P)	T1	T2	Training-related (t/P)		
Verbal working memory								
Digit span forward (scores)	9.47±1.88	9.60±1.80	–0.12/0.845	9.38±2.32	10.23±1.92	–2.67/0.020	0.459	0.40
Digit span backward (scores)	4.00±1.51	4.20±1.32	–0.39/0.702	4.08±1.61	5.00±1.58	–3.21/0.008	0.040	0.58
Word span task forward (scores)	9.86±2.03	10.07±1.79	–0.29/0.777	10.00±2.00	11.23±1.54	–2.48/0.029	0.065	0.69
Word span task backward (scores)	3.33±1.35	3.47±1.18	–0.23/0.776	3.15±1.41	4.46±1.61	–2.85/0.015	0.007	0.87
Visuospatial working memory								
Corsi span task (scores)	3.40±0.83	3.60±0.74	–0.69/0.490	3.40±1.24	4.87±0.83	–3.79/0.001	0.002	1.39
Central executive function								
Stroop task								
Accuracy (scores)	58.46±1.30	58.87±0.99	–0.94/0.352	58.33±1.63	58.87±0.99	–1.08/0.289	0.692	0.40
Time for completion (second)	106.86±17.36	104.75±15.66	0.35/0.729	105.31±19.73	91.72±16.30	2.06/0.049	0.018	0.75
Reading achivement								
Visual rhyming task								
Accuracy (scores)	35.77±1.11	38.38±1.59	–1.14/0.263	35.12±1.03	43.03±1.83	–2.11/0.044	0.040	0.77
Reaction time (ms)	1 108.16±139.78	1 045.02±104.71	1.39/0.173	1 127.63±181.10	934.69±158.34	3.11/0.004	0.010	1.13
One-minute tests of reading words (n)	65.63±10.30	67.86±8.28	–0.66/0.518	66.22±12.69	77.91±7.25	–3.09/0.005	0.001	1.13

The range of scores in the digit span forward and digit span backward is 0–22 points, with higher scores indicating better verbal working memory. The range of scores in the word span task forward and word span task backward tasks is 0–18 points, with higher scores indicating better verbal working memory. The range of scores in the Corsi span task is 0–8 points, with higher scores indicating better visuospatial working memory. The range of accuracy scores in the Stroop task is 0–60 points, with higher scores indicating better central executive function. The range of accuracy scores in the visual rhyming task is 0–70 points, with higher scores indicating better reading skills.

Data are expressed as mean ± SD of fifteen participants in each group. [a] Training-related differences were compared between the treatment group and the control group; [b] effect sizes in the treatment group. Effect sizes were calculated using Cohen's effect size formula[16] (d), where an effect size of 0.20 is considered small, an effect of 0.50 medium, and an effect of 0.80 large. T1: Before training; T2: 5–6 weeks after training.

Training-related changes were compared between the treatment and control groups. This comparison revealed a significant treatment effect for two of four verbal working memory measures (digit span backward task, $P < 0.05$; word span backward task, $P < 0.01$), a visuospatial working memory measure (Corsi span task, $P < 0.01$), a central executive measure (time for completion of a Stroop task, $P < 0.05$), and two literacy measures (accuracy and reaction time in a visual rhyming task, $P < 0.05$; one-minute tests of reading words, $P < 0.01$; Table 2).

With regard to the cognitive measures and the two literacy measures, the results showed a significant effect of training on both visuospatial working memory and reading achievement tasks (Table 2).

Relationship between cognitive changes and reading skill changes following working memory training

The relationship between training-related changes in literacy and cognitive measures in the treatment group were analyzed (Table 3).

Table 3 Correlations between training-related changes in literacy measures and cognitive measures in the treatment group

Item	Accuracy on visual rhyming task	Reaction time on visual rhyming task	One-minute tests of reading words
Digit span backward	0.42	0.51	0.47
Word span task backward	0.68	0.49[a]	0.52
Corsi span task	0.56[b]	0.73[a]	0.59[b]
Time for completion of a Stroop task	0.48	0.55	0.72[b]

[a]$P < 0.05$, [b]$P < 0.01$.

Progress on word span backward scores was positively correlated with progress on accuracy in a visual rhyming task. Progress on the Corsi span task was positively correlated with progress on literacy measures (accuracy and reaction time in a visual rhyming task and one-minute tests of reading words). The time for completion of a Stroop task was positively related to progress on one-minute tests of reading words. Finally, differences in training-related changes in literacy and cognitive measures were regressed to T1 in the treatment group. The results showed that training-related changes in the Corsi span task and accuracy and reaction time in a visual rhyming task and one-minute tests of reading words were inversely predicted by performance at T1 (Table 4).

Table 4 Differences between post-training and baseline literacy measures and cognitive measures regressed to baseline performance in the treatment group

Assessment	*B*	*SE*	*β*	*t*	*P*
Digit span backward	–0.51	0.36	–1.38	–1.38	0.192
Word span task backward	–0.32	0.26	–0.33	–1.26	0.231
Corsi span task	–0.88	0.22	–0.80	–4.07	0.001
Time for completion of Stroop task	–0.79	0.39	–0.44	–2.08	0.049
Accuracy on visual rhyming task	–0.28	0.13	–0.52	–2.19	0.048
Reaction time on visual rhyming task	–0.40	0.18	0.55	–2.28	0.042
One-minute tests of reading words	–0.51	0.08	–0.87	–6.22	<0.001

In other words, children performing the worst at T1 improved the most at T2. None of the changes in other skills (T2–T1) regressed to T1 showed any significant difference.

DISCUSSION

This study is the first to examine working-memory training in Chinese children with developmental dyslexia. The aim was to investigate whether working-memory training improves dyslexic children's working memory and reading skills. We found that intensive and adaptive computerized working-memory training gradually increased the amount of information that the subjects could keep in working memory. The results from the baseline and post-training tests in the treatment group were compared with the control group, which received a low-dose version of the training. This comparison showed that the training indeed enhanced the children's working memory. Increased performance was seen in nontrained verbal working memory tasks, visuospatial working memory tasks, and central executive tasks, showing that the training effects generalized to other capacities. A significant training effect was also seen for both the visual rhyming task and reading fluency task (one-minute tests of reading words), and the effect size was substantial. Thus, it is possible to use working-memory training to improve cognitive function, which is an important deficiency in Chinese children with developmental dyslexia. However, future studies are required to determine the persistence of these effects.

Our experimental findings of significant effects of working-memory training on non-trained working memory tasks within the spatial, verbal, and central executive domains are consistent with previous studies of working-memory training in children and adults. Additional interesting findings of the present study were the improvements on the digit span backward and word span backward task, which are consistent with transfer of the training[11, 13, 16-17]. However, a significant training effect was not seen for either the digit span forward task or the word span forward task. Several studies have demonstrated training effects on non-trained tests of verbal working memory, with the dependent measure of the mean number of points on both the forward and backward condition[13, 18]. Some studies showed that recalling digits or words in the inverse order of presentation is generally considered to involve both the phonological loop and the central executive[19-20], as the sequence spoken by the experimenter must be stored and reversed to produce the correct answer. However, another interpretation of the processes involved in these tasks has been proposed by Li *et al* [21-22], with a series of converging evidence suggesting that backward recall relies on visuospatial representation of the input material. In other words, recalling digits or words in the inverse order of presentation may use more processing resources of working memory than recall of forward presentations. As such, they are easier to individually assess. The results of this study demonstrate that comprehensive working-memory training was more effective for the digit span backward and word span backward task.

A significant training effect was also seen for both the visual rhyming task and reading fluency task. Correlation analyses of training-related changes between literacy measures and cognitive measures in the treatment group confirmed a positive relationship between improvements in reading skills and increased working memory capacity. These findings are in line with those of previous studies. For example, Shiran and colleagues[15] stressed the importance of working-memory training for reading skills. It has been reported that 6 weeks of working-memory training in adult dyslexic readers increased literacy measures, such as phonology measures, silent reading times, and one-minute tests of reading words and pseudowords. Consequently, improvements in reading skills are probably related to the fact that reading skills depend on working memory. In other words, trained working memory tasks and reading skills rely on the same cortical areas. Some imaging investigations[23-24] have revealed that the left dorsal lateral prefrontal cortex and premotor cortex, regions related to working memory, are relevant to Chinese reading.

As predicted, the weakest performers improved the most on the visuospatial working memory and central executive tasks and in their reading skills. This suggests that children performing at the lowest level may improve the most following training on visuospatial working memory tasks, central executive tasks, and reading skills. This supports the notion that the enlargement of working memory supply may contribute to reading effectiveness and focused reading. It is important to note that the effectiveness of the training was more pronounced among the lowest-level performers as they had more to gain in working memory and reading skills.

The present study indicates that training of working memory may be useful for children with development dyslexia. Our findings highlight the relationship between larger working memory capacities and better reading skills. Thus, this study has important practical implications in that children with Chinese development dyslexia may benefit from working-memory training. Because the use of behavioral measures to study working memory is limited, future research should investigate how effective remediation is associated with increased activation or normalization of brain functions in dyslexic children. It is clear that more research in this direction is warranted.

SUBJECTS AND METHODS

Design

A double-blind, paired designed study.

Time and setting

The training was conducted at one primary school in Wuhan, Hubei Province, China from May to June in 2011. Data collection and analysis were performed from January to September in 2011.

Subjects

The participants were third- or fifth-graders (aged 8–11 years) from one primary school in Wuhan, China. This primary school is located in an urban community of average-level socioeconomic status in Wuhan, China.

Diagnosis criteria

All the dyslexic children were diagnosed according to criterions defined by the International Statistical Classification of Diseases and Related Health Problems (Tenth Revision, ICD-10), issued by World Health Organization[25].

Inclusion criteria

Several inclusion criteria were used to ensure that all participants: (1) Vocabulary test scores were at least 1.5 standard deviations lower than children in the same grade, as assessed by the Character Recognition Measure and Assessment Scale for Primary School Children[26]. (2) The score on the Dyslexia Checklist for Chinese Children was 2 standard deviations higher than the mean score[27]. (3) The children had normal nonverbal Raven intelligence quotients (intelligence quotient ≥ 85). (4) The children were physically healthy and had no history of neurological disease, head injuries, or psychiatric disorders. (5) Informed consent was obtained from each subject and their parents before initiating testing.

Methods

Procedure

During the week prior to the onset of training, the participants completed a set of assessments in working memory performance and reading achievement. Reading-related skills in the control group were measured within the same time interval as the treatment group. The format of the training was customized for each individual. All children completed two sessions of assessments within the same time intervals: (1) pre-test (T1), (2) post-test 5–6 weeks (T2).

The children in the treatment group engaged in training on a variety of working memory tasks using a computerized game environment. This training was conducted for approximately 40 minutes a day in the school over a period of 5 weeks. Children completed 100–150 trials every day. The time to complete each trial was reduced by 10% when the accuracy of the child in the treatment group increased by one fifth in each task. At the end of each day of exercises, children were allowed to choose a small tangible reinforcement from items such as sports or action figure cards, colored pencils, or a cartoon exercise book. Consistent with Torkel Klingberg’s experimental design[11], the control group was trained with a “placebo” or “low-dose” computer program, which was similar to the treatment program except its difficulty level was not interactively adjusted and daily training amounted to less than 10 minutes per day.

Training program

All training programs were written in the C programming language.

Visuospatial working memory task: The task involved the immediate serial recall of visuospatial information. Children were presented with six matrixes at 5 cm × 5 cm, with 3–5 colored squares in various positions (two matrixes for each of the three, four, or five square conditions). After the matrix had been removed, the child was asked to remember the positions of the colored squares and to point them out on an identical blank matrix[21, 28].

Visual verbal working memory tasks: For the training task, we used a similar paradigm to the one described by Miller *et al* [29]. The tasks in this paradigm are designed to reveal the nature of the working memory codes individuals rely on when asked to temporarily retain written words. Characters are selected from textbooks used in grades one to five. The average frequency of the characters was 17.64 per million, and the average number of strokes was 8.21. The participants were shown sequences of unrelated single target words, one after another on a computer screen. Immediately thereafter, they were asked to memorize a sequence of the first three target characters. Five Chinese characters were presented sequentially and displayed in a set order followed by a blank interstimuli presentation interval. The probe was three characters in the middle of the computer display. Only when both the orthography and order matched the three target characters was the subject supposed to press their index finger to indicate “yes” (A key of computer keyboard), otherwise, they were supposed to press their middle finger to indicate “no” (L key of computer keyboard). The tasks fell under a phonological condition designed to track reliance on a phonological memory strategy (Figure 1A), a visual condition designed to track reliance on a visual-perception-based memory strategy (Figure 1B), and a control condition (Figure 1C). In the phonological condition, the fourth characters resembled the target words phonologically, and were visually similar to those in the visual condition. The fifth characters were the distracter characters, and had no shared semantic, categorical, or linguistic features with the target words in any condition. Each condition was based upon 50 trails.

Central executive tasks: An inhibiting task is an often used version of the task used in this study[30]. Participants are required to give a fast left- or right-hand response to a central target arrow during presentation of congruent flanker (*i.e.*, target arrow and flankers associated with the same response) or incongruent flanker (*i.e.*, target arrow and flankers associated with different responses) arrows. No responses were required for non-target, octagon figures presented instead of the target. The flanker arrows were presented before the target arrow. The participants received 150 trials consisted of 50 congruent flankers, 50 incongruent flankers, and 50 octagon figures.

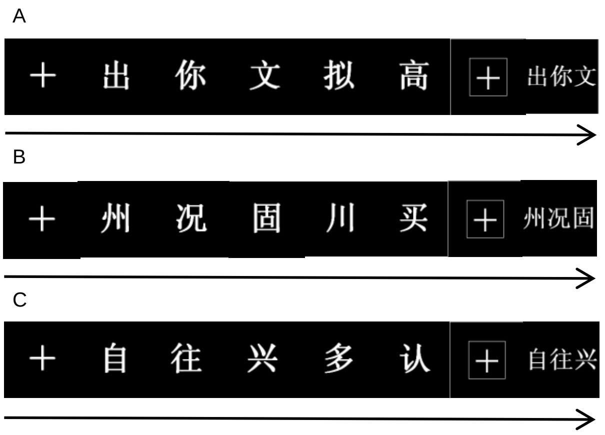

Figure 1 Visual verbal working memory tasks.

"+" suggests the new trail stimulus sequence; ⊞ suggests the next required to judge. Arrows indicate the reading order.

(A) Phonological condition. (B) Visual condition. (C) Control condition.

Tests for the evaluation of the training

The study was a double-blind study where children, parents, and the psychologist administrating the baseline and post-training tests were blinded to the version of the computer program the children had practiced, and to the expected effects of the two versions. All training was completed in a quiet room in the school, in small groups of five children supervised by a training aide who was a paid research associate. Evaluation included nontrained working memory measures and reading achievement.

Working memory measures:
(1) Verbal working memory:
(a) Digit span task
The digit span task is one of the tasks most often used to measure verbal working memory. It is part of the Wechsler Intelligence Scale for children, including the digit span forward task and the digit span backward task. In the first part, the digits are repeated in the same order as presented. In the second part, the child is asked to repeat the digits in the reverse order. The score corresponds to the maximum length of the item set recalled in the correct order of presentation.

(b) Word span task
For the purpose of measuring children's verbal working memory for words instead of numbers, a word span test was used[31-32]. It consisted of a series of frequently occurring Chinese words. Administration of the task and the scoring method were similar to those used for the Digit Span Subtest from the Wechsler Intelligence Scale for children.

(2) Visuospatial working memory:
Corsi span task
This is a well-known task, very frequently used to measure short-term memory for spatial sequential information[11, 13, 33]. In addition, the task is considered to involve the encoding of visual stimuli, the retention of information over time, and response selection, prior to overt response execution[34]. From two up to nine lamps were presented sequentially in a 3 × 3 grid. These lamps were illuminated successively, and each child was asked to recall the correct order by clicking the appropriate location with the computer mouse. The number of Lamps in the sequence was successively increased until the subject missed two trials in a row. The score was the maximum number of lamps remembered.

(3) Central executive function:
Stroop task
The Stroop task was used as a test of response central executive. Words describing colors were printed with ink in a color that was incongruent with the word. For example, the word "green" printed in yellow ink. The subjects were asked to name the ink color for each word. The time and accuracy for reading all 60 items was noted[35].

(4) Reading achievement:
(a) Phonological task
Phonological awareness was measured by the children's accuracy and mean reaction time on correct responses on the visual rhyming task. The visual rhyming task we used was similar to the paradigm described by Grossi *et al* [36]. It contained 35 pairs of rhyming words and 35 pairs of nonrhyming words. Subjects needed to decide whether two sequentially presented written words rhymed or not. Each pair matching the average frequency of the characters and the average number of strokes selected from the textbooks used in grades one to five. The maximum score was 70.

(b) One-minute tests of reading words
This task were similar to Li and colleague's reading ability task[37]. 100 Chinese characters in the test were selected from textbooks that were used in primary schools for first to third graders, divided into 10 rows and 10 columns. Children were asked to read the characters aloud as quickly and accurately as possible within 1 min. Accuracy and reading fluency were scored.

Statistical analysis

Performance on non-trained working memory tasks and the two literacy measures is provided as mean ± SD.

Paired-samples *t*-tests were conducted to evaluate group differences. Effect sizes were calculated using Cohen's effect size formula[38] (*d*), where an effect size of 0.20 is considered small, an effect of 0.50 medium, and an effect of 0.80 large. Furthermore, we conducted correlation analyses and regression analyses to determine the training effects. SPSS version 13.0 for windows software (SPSS, Chicago, IL, USA) was used for statistical analysis.

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REFERENCES

[1] Schlaggar BL, McCandliss BD. Development of neural systems for reading. Annu Rev Neurosci. 2007;30: 475-503.
[2] Zhu D, Wang J, Wu H. Working memory function in Chinese dyslexic children: a near-infrared spectroscopy study. J Huazhong Univ Sci Technolog Med Sci. 2012; 32(1):141-145.
[3] Eden GF, Jones KM, Cappell K, et al. Neural changes following remediation in adult developmental dyslexia. Neuron. 2004;44(3):411-422.
[4] Spironelli C, Penolazzi B, Vio C, et al. Cortical reorganization in dyslexic children after phonological training: evidence from early evoked potentials. Brain. 2010;133(11):3385-3395.
[5] Al Otaiba S, Fuchs D. Who are the young children for whom best practices in reading are ineffective? An experimental and longitudinal study. J Learn Disabil. 2006; 39(5):414-431.
[6] Beneventi H, Tønnessen FE, Ersland L. Dyslexic children show short-term memory deficits in phonological storage and serial rehearsal: an fMRI study. Int J Neurosci. 2009; 119(11):2017-2043.
[7] Wang JJ, Bi HY, Gao LQ, et al. The visual magnocellular pathway in Chinese-speaking children with developmental dyslexia. Neuropsychologia. 2010;48(12):3627-3633.
[8] Cohen-Mimran R, Sapir S. Deficits in working memory in young adults with reading disabilities. J Commun Disord. 2007;40(2):168-183.
[9] Zhu DM, Wang J, Wu HR. Switch dysfunction in developmental dyslexia: a study with Chinese children. Zhongguo Ertong Baojian Zazhi. 2011;19(3):207-209.
[10] Berninger VW, Raskind W, Richards T, et al. A multidisciplinary approach to understanding developmental dyslexia within working-memory architecture: genotypes, phenotypes, brain, and instruction. Dev Neuropsychol. 2008;33(6):707-744.
[11] Klingberg T, Forssberg H, Westerberg H. Training of working memory in children with ADHD. J Clin Exp Neuropsychol. 2002;24(6):781-791.
[12] Klingberg T, Fernell E, Olesen PJ, et al. Computerized training of working memory in children with ADHD--a randomized, controlled trial. J Am Acad Child Adolesc Psychiatry. 2005;44(2):177-186.
[13] Holmes J, Gathercole SE, Dunning DL. Adaptive training leads to sustained enhancement of poor working memory in children. Dev Sci. 2009;12(4):F9-15.
[14] Klingberg T. Training and plasticity of working memory. Trends Cogn Sci. 2010;14(7):317-324.
[15] Shiran A, Breznitz Z. The effect of cognitive training on recall range and speed of information processing in the working memory of dyslexic and skilled readers. J Neurolinguistics. 2011;24(5):524-537.
[16] Jaeggi SM, Buschkuehl M, Jonides J, et al. Improving fluid intelligence with training on working memory. Proc Natl Acad Sci U S A. 2008;105(19):6829-6833.
[17] Dahlin KI. Effects of working memory training on reading in children with special needs. Read Writ. 2011;24(4): 479-491.
[18] Thorell LB. Do delay aversion and executive function deficits make distinct contributions to the functional impact of ADHD symptoms? A study of early academic skill deficits. J Child Psychol Psychiatry. 2007;48(11): 1061-1070.
[19] Gathercole SE, Pickering SJ. Assessment of working memory in six and seven year-old children. J Educ Psychol. 2000;92(2):377-390.

[20] Morra S. Issues in working memory measurement: testing for M capacity. Int J Behav Dev. 1994;17(1):143-159.
[21] Li SC, Lewandowsky S. Forward and backward recall: Different retrieval processes. J Exp Psychol Learn Mem Cogn. 1995;21(4):837-847.
[22] D'Amico A, Guarnera M. Exploring working memory in children with low arithmetical achievement. Learn Individ Differ. 2005;15(3):189-202.
[23] Siok WT, Perfetti CA, Jin Z, et al. Biological abnormality of impaired reading is constrained by culture. Nature. 2004; 431(7004):71-76.
[24] Siok WT, Niu Z, Jin Z, et al. A structural-functional basis for dyslexia in the cortex of Chinese readers. Proc Natl Acad Sci U S A. 2008;105(14):5561-5566.
[25] World Trade Organization. International Classification of Diseases (ICD-10). Beijing: People's Medical Publishing House.1993.
[26] Wang, XL, Tao BP. Chinese Character Recognition Test Battery and Assessment Scale for Primary School Children. Shanghai: Shanghai Education Press. 1993.
[27] Wu HR, Song RR, Yao B. The establishment of dyslexia checklist for chinese children. Zhongguo Xuexiao Weisheng. 2006;7(3):189-190.
[28] Luo Y, Wang J, Wu HR. Correlation between visual-spatial working memory and chinese language cognition of children with developmental dyslexia. Zhongguo Ertong Baojian Zazhi. 2011;19(10):881-883.
[29] Miller P, Kupfermann A. The role of visual and phonological representations in the processing of written words by readers with diagnosed dyslexia: evidence from a working memory task. Ann Dyslexia. 2009;59(1):12-33.
[30] Wild-Wall N, Oades RD, Schmidt-Wessels M, et al. Neural activity associated with executive functions in adolescents with attention-deficit/hyperactivity disorder (ADHD). Int J Psychophysiol. 2009;74(1):19-27.
[31] Thorell LB. Do delay aversion and executive function deficits make distinct contributions to the functional impact of ADHD symptoms? A study of early academic skill deficits. J Child Psychol Psychiatry. 2007;48(11): 1061-1070.
[32] Gau SS, Shang CY. Executive functions as endophenotypes in ADHD: evidence from the Cambridge Neuropsychological Test Battery (CANTAB). J Child Psychol Psychiatry. 2010;51(7):838-849.
[33] Olesen PJ, Westerberg H, Klingberg T. Increased prefrontal and parietal activity after training of working memory. Nat Neurosci. 2004;7(1):75-79.
[34] Fischer MH. Probing spatial working memory with the Corsi Blocks task. Brain Cogn. 2001;45(2):143-154.
[35] Bench CJ, Frith CD, Grasby PM, et al. Investigations of the functional anatomy of attention using the Stroop test. Neuropsychologia. 1993;31(9):907-922.
[36] Grossi G, Coch D, Coffey-Corina S, et al. Phonological processing in visual rhyming: a developmental ERP study. J Cogn Neurosci. 2001;13(5):610-625.
[37] Tan LH, Spinks JA, Eden GF, et al. Reading depends on writing, in Chinese. Proc Natl Acad Sci U S A. 2005; 102(24):8781-8785.
[38] Cohen J. Statistical Power Analysis for the Behavioral Sciences. New York: Academic Press. 1988.

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