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Effect of Working Memory Updating Training on Retrieving Symptoms of Children With Learning Disabilities

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Abstract

Working memory (WM) deficiency is a primary reason for the poor academic performance of children with learning disabilities (LDs). Studies have shown that the WM of typical children could be improved through training, and WM training contributes to improving their fluid intelligence and academic achievement. However, few studies have investigated WM training for children with LDs, and results have been inconsistent. The present study examined the long-term effects of WM updating training and whether it can mitigate LD symptoms. Fifty-four children with LDs were recruited and divided randomly into a training or control group. The training group underwent adaptive running WM training for 20 days. Before and after training, the 2 groups completed a 2-back task, a digit span task (forward and backward), Raven's *Standard Progressive Matrices* test, and a scholastic attainment test (Chinese and math). The tests were repeated 6 months later. The results showed that, as compared with the controls, the training group exhibited significant improvements in the digit backward span task, 2-back task, and Raven's *Standard Progressive Matrices*. The math scores of the training group improved significantly by 6 months after the training. The results of this study suggest that WM updating training could mitigate the cognitive deficits of LDs and improve the WM capacity, fluid intelligence, and math scores of children with LDs. Moreover, the training effects could be maintained for at least 6 months.

Keywords
learning disabilities, working memory updating training, fluid intelligence

Working memory (WM) plays a crucial role in the process of human cognition and reflects a person's ability to process and store information within a short time (Baddeley, 2000). It is closely related to the fluid intelligence (Engle, 2010; Fry & Hale, 2000; Kane & Engle, 2002; Mogle, Lovett, Stawski, & Sliwinski, 2008) and academic performance of children (Blankenship, O'Neill, Ross, & Bell, 2015; Bos, Ven, Kroesbergen, & Luit, 2013; Deschuyteneer, Vandierendonck, & Muyllaert, 2006; Dumontheil & Klingberg, 2012; Iglesias-Sarmiento, Carriedo-López, & Rodríguez-Rodríguez, 2014). The central executive system assists WM in encoding and retrieving information and in coordinating attention management. Updating ability is one of the central executive system aspects of WM (Miyake et al., 2000). It is associated with various advanced cognitive processes (Pelegrina, Capodieci, Carretti, & Cornoldi, 2015) and is the most relevant aspect to fluid intelligence in each component of the central executive system of WM (Engle, 2010; Friedman et al., 2006). WM updating represents the ability to monitor information and replace unrelated information with related information for a task at hand, and this process mainly involves the dorsal prefrontal cortex (Collette & Van der Linden, 2002). Moreover, updating is related to striatum, which is directly involved in the processing of WM (E. Dahlin, Neely, Larsson, Bäckman, & Nyberg, 2008; O'Reilly & Frank, 2006). Updating facilitates learning by allowing relevant information to get into WM and by preventing irrelevant information from interfering with it.

Approximately 10% to 15% of schoolchildren have learning disabilities (LDs; Hendriksen et al., 2007). Children with LDs have normal intelligence, but this is not reflected in their learning potential or academic achievement. Reading disorders and mathematics disorders are the most common type of LDs (Büttner & Hasselhorn, 2011;

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Fletcher, Morris, & Lyon, 2003). Studies have shown that although children with different types of LDs have different cognitive defects (Peng & Fuchs, 2016), they generally have WM deficits, which is a core problem of LDs (De Weerdt, Desoete, & Roeyers, 2013; Ho, Chan, Chung, Lee, & Tsang, 2007; Maehler & Schuchardt, 2009; Passolunghi & Pazzaglia, 2004). Moreover, such defects have a corresponding neural basis (Bigler, Lajiness-O'Neill, & Howes, 1998; Dool, Stelmack, & Rourke, 1993; Horowitz-Kraus, 2014; Horowitz-Kraus & Breznitz, 2009).

The deficiency of WM updating ability among children with LDs is clearly observable. Studies have suggested that children who experience difficulty in reading comprehension not only perform poorly in reading comprehension tasks but also perform worse than typical children do in problem-solving and updating tasks (Cornoldi, Drusi, Tencati, Giofrè, & Mirandola, 2012), especially in word-updating tasks (Pelegrina et al., 2015). Children with mathematics disorders perform as well as typical children do in word-updating tasks but worse in number-updating tasks (Iuculano, Moro, & Butterworth, 2011). However, some researchers have argued that only children with reading and mathematics difficulties exhibit WM updating defects (Peng, Congying, Beilei, & Sha, 2012; Peng, Sha, & Li, 2013). Compared with those of typical children, the WM updating ability defects of children with severe LDs may be one of the most notable reasons for their lower learning potential (Söderqvist, Nutley, Ottersen, Grill, & Klingberg, 2011). Evidence from the nervous system offers more compelling proof. Brain activity related to updating tasks exhibits abnormal patterns in children with LDs, meaning that their ability to monitor information is less developed versus that of typical children, and this ability might be impeded when they learn new knowledge and invoke old knowledge that may reduce their learning effectiveness.

Studies have shown that individual WM is plastic. Evidence from typically developing children indicates that WM training can improve WM ability, fluid intelligence, and academic achievement (Jaeggi, Buschkuehl, Jonides, & Shah, 2011; Karbach, Strobach, & Schubert, 2015; Loosli, Buschkuehl, Perrig, & Jaeggi, 2012; Titz & Karbach, 2014; Zhao, Wang, Liu, & Zhou, 2011). Although previous studies have presented evidence on children with special needs, the results have been conflicting. Klingberg, Forssberg, and Westerberg (2002) were first to report WM training for children with attention-deficit/hyperactivity disorder, proving that WM capacity and fluid intelligence are plastic even for special-needs children with defective WM. Alloway (2012) implemented the Jungle Memory training program to train high school students with LDs and found that their WM, vocabulary, and math performance improved significantly. According to Alloway, Bibile, and Lau (2013), children with LDs can also benefit from an 8-week WM training program. In that study, the training program enhanced the fluid intelligence and spelling ability of children with LDs, and the effects were maintained 8 months after training. However, no significant improvement was observed in their mathematical performance. Other researchers suggested that adopting the Cogmed training program to train children exhibiting poor academic performance can improve their math and English performance but not their fluid intelligence (Holmes & Gathercole, 2014). However, even when the same training program is used for different people, the trend in the training effect is inconsistent. According to Holmes, Gathercole, and Dunning (2009), children with LDs who received WM training showed no immediate improvement in fluid intelligence or academic achievement, but a tracing test conducted 6 months after the training revealed improvements in verbal intelligence and reasoning ability. In research by Dahlin, children with LDs exhibited improved mathematical achievement immediately after WM training, but this effect was not observed in a follow-up test conducted 7 months later (K. I. E. Dahlin, 2013). However, no improvement was observed in fluid intelligence (K. I. E. Dahlin, 2010). These results suggest that some studies have shown WM training to be helpful in enhancing the WM of children with LDs and in improving their fluid intelligence and academic achievement. Such findings reflect both the near and far transfer of WM updating ability. However, the results of these studies have been inconsistent. On one hand, the findings may be the result of age differences of the participants. On the other, they reflect differences in training methods and measurement methods (Nutley & Söderqvist, 2017). Moreover, evidence supporting the long-term effects of WM training is insufficient.

Previous research was mostly concerned with the training of WM capacity for children with LDs but paid little attention to the training of WM central executive function, even though the central executive system is the core of WM. As an important part of the central executive system, updating plays a crucial role in learning and intelligence development, especially for children with LDs. Zhao and colleagues (2011) used adaptive running WM training tasks to train the updating ability of typical children and found that not only their updating abilities but also their fluid intelligence was improved (Wang, Zhou, & Shah, 2014). The effectiveness of their training was the improved presenting speed of the stimulation rather than improved memory. The faster the stimulus is, the higher requirements of the central executive system are. Results from normal adults showed further that the training contributed not only to improved updating ability but also to improvement in inhibition abilities (Zhao, Zhou, & Fu, 2013). Because children with LDs have impaired updating ability but normal levels of intelligence, the updating tasks helpful to typical children should also help children with LDs. WM updating training helps to improve these children's information monitoring ability, which facilitates processing new knowledge more

Table 1. Screening Information of Training Group and Control Group.

Group	Boys:girls, *n*	Age, years	SPM	PRS	AAT
Training (*n* = 26)	18:8	10.76 (1.08)	29.04 (6.19)	42.30 (8.54)	69.59 (13.81)
Control (*n* = 28)	19:9	10.06 (1.12)	30.06 (5.45)	40.26 (8.16)	68.65 (13.10)

Note. Values are presented as *M* (*SD*) unless noted otherwise. SPM = Raven's *Standard Progressive Matrices*; PRS = Pupil Rating Scale; AAT = Academic Adaptability Test.

effectively and inhibits the interference of unrelated old knowledge.

The present study examined whether WM updating training could enhance the WM abilities of children with LDs and improve their fluid intelligence and academic achievement. Moreover, to evaluate the long-term effects of WM updating training, we conducted a follow-up test 6 months after the training was completed.

Methods

Ethics Statement

The experiment was approved by the Institutional Review Board of the School of Psychology at Beijing Normal University. All participants signed an informed consent form before participating in the study.

Participants

We adopted a combined method that was based on the cutoff scores to select participants (Liu, Yao, Wang, & Zhou, 2014). The screening processes were as follows. (1) Children finished an Academic Adaptability Test (Zhou, 1991). The original scores were transformed to level scores, and children whose level scores were <2 were entered to the next screening step. (2) Head teachers of these children were required to fill out the revised *Pupil Rating Scale* (Myklebust, 1981; Salvesen & Undheim, 1994), which assessed the difficulty of the children's study. Children whose scores were <65 were selected to the next step. (3) The final exam results from the preceding semester were transformed into *Z* scores. Only children whose Chinese and math scores were <25th percentile were selected. (4) Finally, children completed the Raven's (2000) *Standard Progressive Matrices* (SPM) test. Standard scores were used, and children whose scores were >50th percentile were selected. (5) All the children had attention problems as reported from their teachers, but none of them were diagnosed with attention-deficit/hyperactivity disorder or other disabilities.

Fifty-four children with LDs were recruited from an elementary school in Beijing. At first, we divided the 54 students into two groups of 27 each. The two groups were equal according to the screening criteria. However, one participant from the training group fell ill after the pretest and missed the training for the first week. We reassigned this participant to the control group. So the training group comprised 26 children (18 boys, age: 10.76 ± 1.08 years), and the control group comprised 28 children (19 boys, age: 10.06 ± 1.12 years). No significant difference in age or other screening test results was observed between the two groups. Table 1 provides detailed information on the participants. The participants in the training group received computerized WM updating training for 20 days, which was practiced 5 days per week (approximately 45 min/day). The control group received no training. Parents of all the participants were informed about the safety of this experiment. All participants received a reward after completing the study.

Materials and Procedure

The two groups were required to complete digit forward recall and digit backward recall tasks, a 2-back task, Raven's SPM test, and academic tests (Chinese and math) to investigate the transfer effects of WM updating training for LDs. Six months after completing the training, all the participants repeated these tests except for the 2-back task. Figure 1 depicts the experimental procedure.

Training Tasks

Three versions of adaptive running memory training tasks were adopted in the study, which included three memory materials: animals, letters, and locations (Zhao et al., 2011). In the animals training task, different animals were presented on the center of computer screen sequentially. The number of animals randomly varied from 5 to 7, 9, and 11 in each trial. It is noteworthy that participants were not told how many animals would be presented in each trial and that they were required to remember the last three animals in a trial. Since participants could not predict the number of presented animals in each trail, they had to continuously update their memory items so that their WM updating abilities were trained. The other two training tasks were similar to the animals training task. Participants were required to report the last three letters in the alphabet training task and the last three locations of a cartoon in the location training task.

Each training task contained 30 trials that were separated into six blocks of five trials each. At the beginning of the training, the duration of each item was 1,750 ms. Duration time decreased by 100 ms in the next block if subjects correctly reported for three or more trials in the present block.

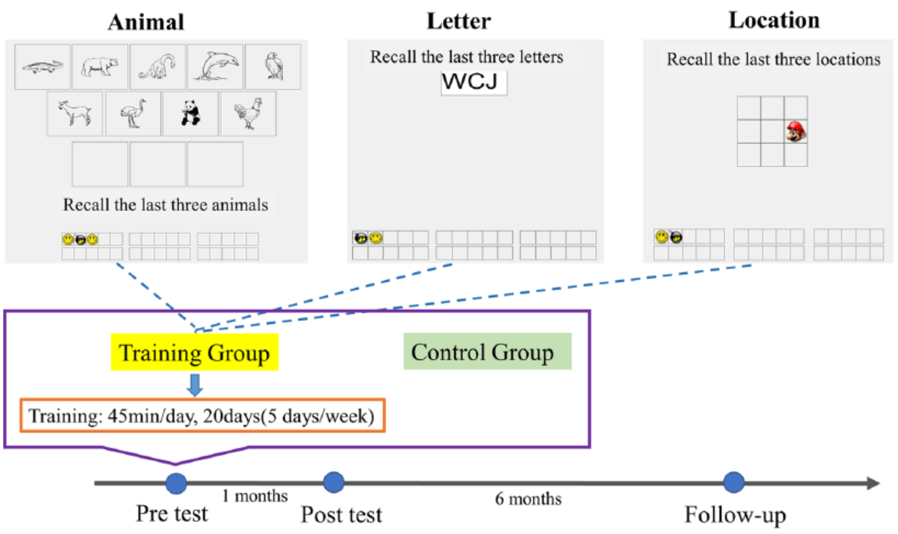

Figure 1. The whole experiment design in four parts: pretest, training, posttest, and follow-up test. Training tasks included three forms of the running memory task: *Animal Running Working Memory Task, Letter Running Working Memory Task*, and *Location Running Working Memory Task*. Digital forward recall and digital backward recall tasks, 2-back task, Raven's *Standard Progressive Matrices* test, and academic tests (Chinese and Math) were completed before training, after training immediately, and 6 months later (2-back task was not included in the follow-up test).

The duration time of the next day's training depended on the last block's duration time of the previous day.

Near Transfer Tests

Two-back task. The 2-back task was used to evaluate the near transfer of WM updating ability. In this task, the participants were shown a series of numbers ranging from 1 to 9. They were required to compare whether the current number matched the number that was shown two numbers prior. The task contained 84 trials; matching and mismatching conditions accounted for half of the trials. The reliability coefficient of 2-back task based on our sample was .78.

Digit span task. Following the digit span test in the *Wechsler Intelligence Test*, we used the digit forward and backward tasks to assess WM capacity. In the digit forward task, the numbers 1 to 9 were presented one by one (each number was presented for 1,000 ms). Participants began at Level 3, which required them to recall three numbers in the order in which they were presented. Each level contains three trials. If the participants had two or three correct answers at one level, they could go to the next level (e.g., Level 3 to Level 4). The test was stopped if the participants had no correct answers or had only one correct answer out of three trials at one level. The highest level in which each participant achieved two or three correct answers was taken as the digit forward capacity of that participant. The digit backward task required the participants to recall the number series in the opposite order. Digit forward recall tasks are considered to be a test of the phonological loop (Baddeley, 2000). Digit backward recall tasks include not only verbal representation and visual cognition but also spatial memory and attention processes (Larrabee & Kane, 1986). The reliability coefficients of digital forward task and backward task based on our sample were .81 and .89, respectively.

Far Transfer Tests

Raven's SPM test. We employed Raven's SPM test to evaluate the far transfer effect on fluid intelligence (Jaeggi et al., 2011; Zhao et al., 2011). The SPM test contains 60 items, with each correct answer receiving 1 point. Each item was presented on the computer screen, and the completion time was limited to 40 minutes. Based on our sample, the reliability coefficient of Raven's SPM test was .98.

Academic tests. Chinese and math scores were used as an index for academic achievement. There are no standard academic achievement tests in China. Midterm and final examinations are taken seriously by Chinese students. Test items are designed by teachers who teach the corresponding curriculum. The examinations test students' mastery of knowledge acquired in a semester.

The final exam results from the preceding semester were used as the pretest scores. The results of midsemester exams (after the training was completed) were used as the posttest scores. Follow-up test scores were taken from the final

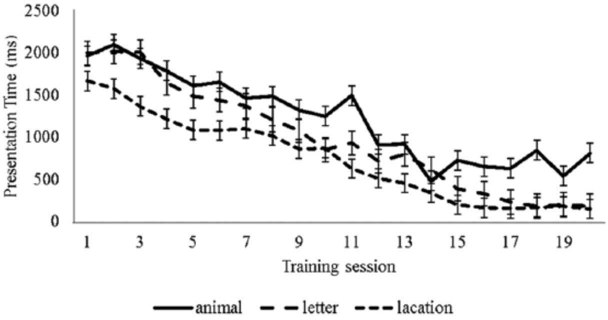

Figure 2. Training results of three training tasks across 20 days of training. Duration time of three training tasks decreased gradually, which means that the difficulty of the training improved and the updating ability of training group increased. Error bars represent standard errors.

Table 2. Independent-Samples *T* Test of Pretest Score in Training and Control Groups.

	Training (*n* = 26)	Control (*n* = 25)	*t*	*p*
Raven's SPM	29.04 (6.19)	31.04 (5.44)	–1.225	.227
Digit span task				
Forward	5.80 (1.09)	5.87 (1.39)	–0.185	.854
Backward	3.96 (1.04)	4.78 (1.88)	–1.917	.063
Exam				
Chinese	–0.84 (1.15)	–0.66 (1.11)	–0.561	.577
Math	–1.09 (1.23)	–0.55 (0.91)	–1.792	.079
Two-back task				
Accuracy	0.70 (0.08)	0.77 (0.08)	–3.043	.004**
Reaction time	1,091 (323)	961 (240)	1.628	.110

Note. Values are presented as *M* (*SD*) unless noted otherwise. Chinese exams mainly included reading comprehension (80%) and writing skills (20%). Math exams mainly included calculation (60%) and problem-solving skills (40%). SPM = *Standard Progressive Matrices*.
$^{**}p < .01$.

examination (6 months after the training was completed). The original scores were transformed into *Z* scores. In these three time points, Chinese exams mainly tested reading comprehension (80%) and writing skills (20%). Math exams mainly tested calculation (60%) and problem-solving skills (40%). The reliability coefficients of Chinese and math exams were .68 and .60, respectively.

Results

SPSS 22.0 was used for data aggregation and statistical analysis. The reaction time and accuracy in the 2-back task were investigated. For each participant, data for incorrect responses and nonresponses were excluded. Responses that were 2.5 standard deviations longer than the mean reaction time and those with reaction times <200 ms were also excluded. Data of three participants in the control group were excluded for low accuracy in the 2-back task. All of the children completed the training. The results from three training tasks are shown in Figure 2. Finally, the data of the training group (*n* = 26) and control group (*n* = 25) were analyzed.

Pretest

To test for differences in cognitive ability before training, the Raven's SPM test, the digit forward and digit backward tasks, and 2-back task were administered to both groups. In addition, we collected their standardized Chinese and math scores as indicators of academic performance. An independent-samples *t* test was conducted to test for between-groups differences, and the results revealed no significant difference between the training and control groups in their cognitive test scores or academic performance; however, the 2-back task accuracy scores differed significantly between the two groups (Table 2).

Posttest

Because two groups had significant differences in 2-back accuracy at pretest, to investigate the near transfer effect of WM updating training, a 2 × 2 (time [pretest and posttest] × group [training and control groups]) repeated measures analysis of covariance (ANCOVA) was performed on the

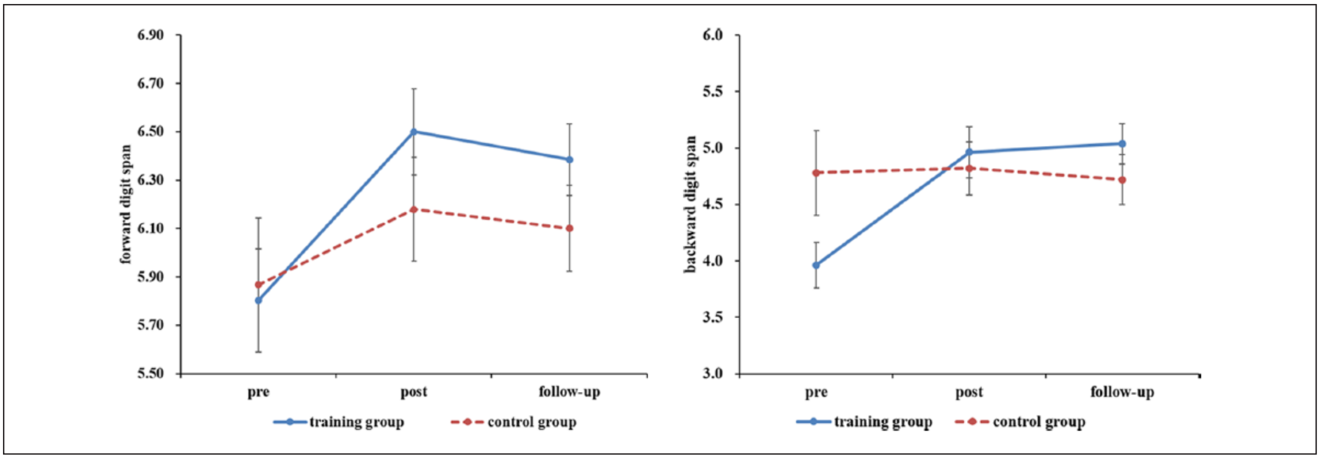

Figure 3. The left figure shows the pretest, posttest, and follow-up test scores of the digital forward span task of both groups, and on the right is the digital backward span task, in which the solid line represents the training group and the dotted line, the control group. Error bars represent standard errors.

digit forward and digit backward tasks. Accuracy of the 2-back task at pretest was the covariate.

The ANCOVA results for the digit forward task showed that the main effect of time was significant, *F*(1, 48) = 6.52, *p* = .01, η_p^2 = 0.12; the posttest score (*M* = 6.34) was significantly higher than the pretest score (*M* = 5.84). The main effect of group was nonsignificant, *F*(1, 48) = 1.32, *p* = .26, as was the interaction between time and group, *F*(1, 48) = 0.10, *p* = .75.

The results for the digit backward task showed that the main effect of time was not significant, *F*(1, 48) = 0.04, *p* = .85. The main effect of group was nonsignificant, *F*(1, 48) = 0.44, *p* = .51. The interaction between time and group was significant, *F*(1, 48) = 10.22, *p* = .002, η_p^2 = 0.176. The mean comparisons showed that, in the training group, the posttest score (*M* = 4.96) was significantly higher than the pretest score (*M* = 3.96, *t* = 6.94, *p* < .001), whereas in the control group, the posttest score (*M* = 4.82) was not significantly different from the pretest score (*M* = 4.78; Figure 3).

Due to the pretest difference between two groups on the 2-back task, an independent *t* test was used to analyze the group difference of changes from pre- to posttest. Results showed that between pre- and posttest, there was no significant difference between the training group and the control group on 2-back reaction time, *t*(49) = −0.69, *p* = .49. However, there was a significant difference between the training and control groups on 2-back accuracy, for which the training group (*M* = 0.08) had significant improvement on accuracy while the control group (*M* = 0.02) did not, *t*(49) = 2.30, *p* = .02, *g* = 0.635.

To investigate the far transfer effect of WM updating training, a 2 × 2 (time [pretest and posttest] × group [training and control groups]) repeated measures ANCOVA was performed on the fluid intelligence, standardized Chinese score, and standardized math score. Accuracy of 2-back task at pretest was the covariate.

The ANCOVA results for Raven's SPM test showed that the main effect of time was not significant, *F*(1, 48) = 3.37, *p* = .07. The main effect of group was not significant, *F*(1, 49) = 0.02, *p* = .89. The interaction between time and group was significant, *F*(1, 48) = 15.86, *p* < .001, η_p^2 = 0.248. The mean comparisons showed that, for the training group, the posttest score (*M* = 32.42) was significantly higher than the pretest score (*M* = 29.04, *t* = 7.56, *p* < .001), whereas for the control group, the posttest score (*M* = 31.68) was not significantly different from the pretest score (*M* = 31.04; Figure 4).

The results for the standardized Chinese scores showed a nonsignificant main effect of time, *F*(1, 48) = 0.60, *p* = .44; a nonsignificant main effect of group, *F*(1, 48) = 0.77, *p* = .39; and a nonsignificant interaction between time and group, *F*(1, 48) = 0.67, *p* = .42. Similar results were obtained for the standardized math scores, with a nonsignificant main effect of time, *F*(1, 48) = 0.09, *p* = .76, a nonsignificant main effect of group, *F*(1, 48) = 0.27, *p* = .61, and a nonsignificant interaction between time and group, *F*(1, 48) = 0.64, *p* = .43.

According to the results, the WM ability of the children in the training group improved after 20 days of computerized adaptive WM updating training. Their performance in the backward task span and updating ability also improved. In addition, the Raven's SPM scores, which were regarded as an index for fluid intelligence, also improved significantly, but the training effect was not evidenced in their Chinese or mathematics achievement.

Follow-Up Test

To investigate the long-term effects of WM updating training, we readministered all of the tasks (except for the 2-back task) 6 months after the training. A 2 × 2 (time [pretest and

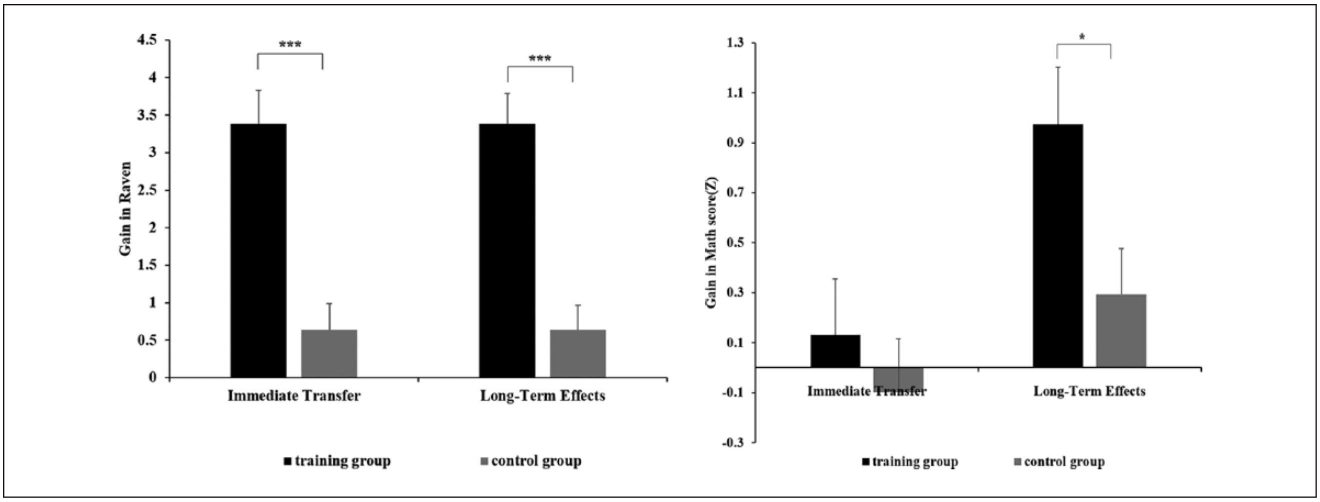

Figure 4. The far transfer effect of working memory update training on fluid intelligence and mathematics achievement. The left figure shows the Raven additive value in pretest and follow-up test of the two groups, where immediate transfer represents the difference between the pre- and posttest and where long-term effects represent the difference between the pretest and follow-up test. Black bars represent the training group; the gray bars, the control group. Error bars represent standard errors. $^{*}p < .05$. $^{***}p < .001$.

follow-up test] × group [training and control groups]) repeated measures ANCOVA was performed, and accuracy of 2-back task at pretest was the covariate.

The ANCOVA results for the digit forward task showed that the main effect of time was not significant, $F(1, 48) = 2.53$, $p = .12$. The main effect of group was nonsignificant, $F(1, 48) = 2.02$, $p = .16$, as was the interaction between time and group, $F(1, 48) = 0.50$, $p = .48$.

The results for the digit backward task showed that the main effect of time was not significant, $F(1, 48) = 0.32$, $p = .58$. The main effect of group was nonsignificant, $F(1, 48) = 0.26$, $p = .62$. The interaction between time and group was significant, $F(1, 48) = 15.99$, $p < .001$, $\eta_p^2 = 0.250$. The mean comparisons showed that, in the training group, the follow-up score ($M = 5.04$) was significantly higher than the pretest score ($M = 3.96$, $t = 7.98$, $p < .001$), whereas in the control group, the follow-up score ($M = 4.72$) was not significantly different from the pretest score ($M = 4.78$).

The ANCOVA results for Raven's SPM test showed that the main effect of time was not significant, $F(1, 48) = 1.64$, $p = .21$. The main effect of group was not significant, $F(1, 48) = 0.01$, $p = .92$. The interaction between time and group was significant, $F(1, 48) = 19.78$, $p < .001$, $\eta_p^2 = 0.292$. The mean comparisons showed that, in the training group, the follow-up score ($M = 32.27$) was significantly higher than the pretest score ($M = 29.04$, $t = 7.97$, $p < .001$), whereas in the control group, the follow-up score ($M = 31.60$) was not significantly different from the pretest score ($M = 31.04$).

The results for the standardized Chinese scores showed a nonsignificant main effect of time, $F(1, 48) = 0.61$, $p = .44$, a nonsignificant main effect of group, $F(1, 48) = 0.09$, $p = .77$, and a nonsignificant interaction between time and group, $F(1, 48) = 1.69$, $p = .20$. The results of the standardized math scores showed a nonsignificant main effect of time, $F(1, 48) = 0.01$, $p = .95$, nonsignificant main effect of group, $F(1, 48) = 0.06$, $p = .81$, but a significant interaction between time and group, $F(1, 48) = 5.11$, $p = .02$, $\eta_p^2 = 0.096$. The mean comparisons showed that in the training group, the follow-up score ($M = –0.12$) was significantly higher than the pretest score ($M = –1.09$, t = 4.27, $p < .001$), whereas in the control group, the follow-up score ($M = –0.26$) was not significantly different from the pretest score ($M = –0.55$).

The differences in all the tasks showed that the WM updating training improved the fluid intelligence, WM updating ability, and WM capacity of the training group. Even 6 months after the training, the effects were maintained. The math performance of the training group did not significantly improve immediately after the training, but a significant improvement was observed at the 6-month follow-up tests, indicating that the WM updating training might have a delayed effect in improving the academic performance of children with LDs.

Discussion

In the context of children with LDs, the present study analyzed the influence of computerized adaptive WM updating training to test for improvements in fluid intelligence, academic achievement, and WM. The research results show that 20 days of WM updating training not only improved the children's updating capability and WM capacity (near transfer) but also significantly improved their fluid intelligence (far transfer). In addition, the training group still benefited from the training 6 months after completion, as evidenced by the follow-up test results. Although the math achievement of the training group did not improve immediately after the training, their math performance 6 months after the training was markedly higher than that of the children in the control group, indicating a delayed training effect.

The near and far transfer effects of WM training have always been the focus of researchers in this field. In the present study, the 2-back, digit forward recall, and digit backward recall tasks were employed to test for near transfer effects. The 2-back task is a classic task for evaluating WM updating ability. *Updating* refers to the process of changing and revising the contents of WM (Collette & Van der Linden, 2002). Our training improved the participants' performance of the 2-back task, which was similar to a memory task. In 2-back task, participants were required to judge whether the present number was the same as two previous numbers. This means that participants have to remember the last three numbers continuously so that they can make correct judgement required by the training task. Because of the similarities in task requirements, the 2-back task and the training task may rely on the same brain region so that improvement in the training task contributed to the improvement in the 2-back task. In contrast to other studies that have adopted the *n*-back task to improve WM performance (Büttner & Hasselhorn, 2011; Jaeggi, Buschkuehl, Jonides, & Perrig, 2008; Jaeggi et al., 2011), the present study employed running WM updating tasks as training tasks targeting updating capability. The improvement in 2-back task performance is more appropriate for demonstrating the improvement of updating ability instead of a practice effect. Such training could improve the WM updating capability of children with LDs.

However, similar to the results reported by Sandberg, Rönnlund, Nyberg, and Stigsdotter-Neely (2014), the transfer effect of 2-back was observed in the accuracy scores instead of the reaction times; by contrast, Zhao et al. (2013) administered similar training tasks to adults, and they exhibited shorter reaction times rather than improvements in accuracy. A possible explanation for these differences is that, for adults, the 2-back task is comparatively easy; consequently, there is a ceiling effect. This might imply that the near transfer effect of WM updating training in adults could be more obvious in improved reaction times in the 2-back task, which means that the speed at which stimuli are processed is faster. Children with LDs whose WM updating ability was impaired performed mainly at the low accuracy level (Cornoldi et al., 2012; Pelegrina et al., 2015). The training improved their accuracy rather than shortening their reaction times, indicating that training could improve their memory of and judgment about external stimuli instead of accelerating their processing speed. Katz, Jaeggi, Buschkuehl, Stegman, and Shah (2014) conducted a 3-day updating training program for typical children and found that neither their accuracy nor reaction times improved in the 2-back task. Combined with our results, this indicates that the training effect would not occur until a certain amount of time after completing the training.

In the present study, the digit span task was used to evaluate WM capacity. The results show that the training group demonstrated a near transfer effect in the digit backward recall task but not the digit forward recall task. The training effect was still evident in the follow-up test conducted 6 months later, which demonstrates that the improvement in WM capacity is long lasting (Hovik, Saunes, Aarlien, & Egeland, 2013). Numerous researchers have suggested that training enhances backward memory span in digit recall tasks. Such evidence has been obtained not only for healthy adults (Westerberg & Klingberg, 2007), elderly adults (Shatil, Mikulecka, Bellotti, & Bureš, 2014), and typically developing children (St. Clair-Thompson, Stevens, Hunt, & Bolder, 2010) but also for special-needs children (Alloway & Alloway, 2009; Gray et al., 2012; Klingberg et al., 2005). The present study adopted WM updating training, which is not designed to improve WM capacity; however, the results reveal (1) that the WM capacity of the training group improved after the training, confirming the critical influence of updating ability on WM, and (2) that training of the central execution function could benefit the storage function of WM.

In addition, the participants' forward memory performance showed no significant improvement, whereas the opposite is true for their backward memory performance, which implies that the training program employed in the present study was aimed at improving WM capacity instead of short-term memory capacity. Researchers have argued that digit forward and backward recall tasks involve different psychological processes. Specifically, in digit forward recall tasks, children are merely required to use verbal coding to temporarily memorize a digit string (Rudel & Denckla, 1974). Therefore, digit forward recall tasks are considered to be a test of the phonological loop (Baddeley, 2000). However, digit backward recall tasks pose a greater challenge for central executive function because they invoke additional processes for temporarily storing information (Groeger, Field, & Hammond, 1999), including not only verbal representation and visual cognition but also spatial memory and attention processes (Larrabee & Kane, 1986). Evidence in neuroscience research has shown that the dorsolateral prefrontal cortex in both cerebral hemispheres is more active in the digit backward task than in the forward task. In particular, the degree of activation of the right dorsolateral prefrontal cortex is strongly associated with digit backward task scores, which indicates that visuospatial processing and central executive function are involved in this task (Hoshi et al., 2000). Researchers had shown that enhanced WM capacity can facilitate the acquisition of new knowledge and skills for children with LDs (Cowan & Alloway, 2008; L. Swanson & Alloway, 2012). From the analysis conducted in the present study, the improvement in the digit backward recall task might contribute to the daily learning of LDs.

Fluid intelligence was an essential indicator for the far transfer effect in our study. Compared with the control group, the training group exhibited significant improvement in its fluid intelligence after training, and that was also observed 6 months after completing the training. This result shows that the WM updating training exerted a far transfer effect (Alloway & Alloway, 2009; Klingberg et al., 2002) and a long-term effect (Alloway et al., 2013; Jaeggi et al., 2011). Because WM is the foundation for developing children's fluid intelligence (Chen & Li, 2007; Giofrè, Mammarella, & Cornoldi, 2013), children with LDs exhibit abnormal activity in cerebral areas related to WM updating function (Ashkenazi, Black, Abrams, Hoeft, & Menon, 2013), which impedes the development of their fluid intelligence. In this study, the intelligence of children with LDs was within the normal range. In contrast to studies reporting that children did not exhibit improvement in fluid intelligence (Dahlin, 2010), the present research observed an improvement in the participants' fluid intelligence as a result of the WM updating training. This might confirm the close relationship between WM updating ability and fluid intelligence (Chen & Li, 2007; Friedman et al., 2006); moreover, this might indicate that the fluid intelligence of children with LDs features the same plasticity as that of typically children (Zhao et al., 2011). This may be due to two reasons. First, the cerebral areas responsible for updating function and fluid intelligence partially overlap in the prefrontal area (Jung & Haier, 2007; Owen, McMillan, Laird, & Bullmore, 2005); WM updating training might decrease the abnormal activity in this area, thereby promoting the development of related cerebral areas in the prefrontal area of children with LDs, thus improving their fluid intelligence. Second, it might be attributable to the prefrontal area associated with children's attentional control, which is another factor attesting the significant correlation between WM and fluid intelligence (Halford, Cowan, & Andrews, 2007) because both of them depend on attentional control ability (Conway & Getz, 2010; Engle, 2010). The attentional control capability of children with LDs is less developed than that of their typically developing peers (Hendriksen et al., 2007; Meister et al., 2001). Because the difficulty of the training tasks implemented in this study was increased by shortening the time for stimulus presentation, the participants had to concentrate intensely on the task so that they could accurately and quickly process and memorize the targets. Therefore, training WM updating ability might promote the development of attentional control of children with LDs and thus improve their fluid intelligence (Jaeggi et al., 2008). Moreover, location running WM task might be helpful to improve the visual processing related to the Raven's matrix test.

Another important finding of this research is that, in contrast to that of the control group, the mathematical performance of the training group improved significantly in the follow-up test. Unlike other studies that have determined that WM training improves mathematical performance immediately after training (e.g., Alloway et al., 2013; K. I. E. Dahlin, 2013; Witt, 2011), the present study detected such improvement only in the follow-up test, demonstrating a delayed training effect, which is similar to a finding reported by Holmes et al. (2009). Such a difference might be due to the difference between test tasks. In the present study, school math test scores, which were used as an index for mathematics achievement, were of higher ecological validity; this indicates the mastery of new knowledge acquired through prior learning. In agreement with some previous studies, the effects of WM updating training become significant when the training lasts for at least 20 days (Wang et al., 2014). The present research adopted the results of final examinations from the previous term (for the pretest scores), the results of a midterm test held 20 days after the training was completed (for the posttest scores), and the results of the final exam that was held 6 months after the training (for the follow-up test scores). The posttest math performance indicated that during the training period, the training effect had not yet occurred. However, after 20 days of WM updating training, the WM ability and fluid intelligence of the children in the training group had improved significantly. In addition, their attentional control improved, which is conducive to their maintaining focus during class and acquiring or applying knowledge more flexibly (Holmes et al., 2009). Therefore, the training group exhibited a significant improvement in math achievement in the follow-up test but not in the posttest. The follow-up test was conducted 6 months after the training had been completed; however, this does not imply that the influence of WM updating training on children's mathematical performance can be detected only after 6 months. Conversely, the training might have come into effect before the follow-up test. Adopting an academic performance test with higher ecological validity could more accurately indicate the influence of WM updating training on the daily academic performance of children with LDs.

In contrast to cognitive strategy training that benefits math performance (Krawec, Huang, Montague, Kressler, & De Alba, 2013), WM updating training is aimed at training the updating ability of children with LDs. However, it is very likely that updating training may improve not only children's ability of updating but also their efficiency in using it as a cognitive strategy. The strategy use in cognitive training may be one explanation for the transfer effect (Peng & Fuchs, 2017). However, the training group's improvement in mathematical performance after training indicated that this training program, to some extent, alleviated its deficits in WM updating ability so that its mathematics learning ability could be enhanced. Mathematics is a subject involving calculation, problem solving, and so on. Mathematical problem solving involves complex processes that require students to not only work out the results but also understand the question, gather available information, visualize the problem (and maintain the visualization), and then develop a viable solution (Montague, Warger, & Morgan, 2000). In this process, WM plays an irreplaceable role. Because different components of WM have different functions, the phonological loop is responsible for maintaining an intermediate result or subject; the visuospatial sketchpad is responsible for visualizing the problem and its solutions; and the central executive system is responsible for planning, selecting strategies, arranging activities, and tracking the operation results (DeStefano & LeFevre, 2004). The WM updating training used in the present research comprised verbal and visuospatial materials. In addition, the tasks exerted high demand on central executive function. Adequate training was applied for different components of WM; consequently, the children may have developed their ability to encode and maintain useful information and to visualize abstract concepts while solving math problems. Moreover, the central executive system regulates and allocates cognitive resources in a more effective manner. Consequently, the cognitive disorders generated by deficits in WM could be alleviated, and mathematical performance could be promoted.

We did not find any group differences in learning Chinese. Results of this study were different from those of K. I. E. Dahlin (2010), who carried out 5 weeks of WM training targeting reading and found improvement in reading comprehension. Evidences have shown that reading comprehension has strong relationship with WM (e.g., Cain, Oakhill, & Bryant, 2004; H. L. Swanson, Howard, & Sáez, 2006). Phonological loop and central executive deficits might both lead to dyslexia (de Jong, 2006). The different results that we found may be due to the difference in the test material and training task. Our Chinese test included reading comprehension and writing work. WM training may not improve writing skills. Moreover, our training contained only one task that was relevant to phonological loop, and the training material contained letters rather than Chinese characters. It is possible that the training improved the participants' sensitivity to English letters but not Chinese characters. Whether the training will improve English proficiency will be an interesting future research question.

Conclusion

Our research suggests that WM updating training benefits children with LDs in terms of their updating ability, WM capacity, fluid intelligence, and mathematics achievement. Results demonstrated that the WM and fluid intelligence of children with LDs featured the same plasticity observed in typically developing children. Moreover, their deficits in learning could be mitigated by training their WM updating ability. Future studies in this area should consider designing other training methods for children with different types of LD according to the characteristic of their cognitive deficits (Peng & Fuchs, 2016) to maximize the training effect. Additionally, selecting training tasks that children find more interesting could motivate them more and thus might be helpful in enhancing the training effects (Deveau, Jaeggi, Zordan, Phung, & Seitz, 2014; Shute, Ventura, & Ke, 2015). Moreover, we used three training tasks and three memory materials that may improve not only updating ability but other cognitive abilities, such as visual processing.

Declaration of Conflicting Interests

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