

Electrophysiological Evidence of Working Memory Updating Deficits in Children with Learning Disabilities*

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Abstract—Recent behavioral studies suggest that children with learning disabilities (LD) have difficulty in working memory (WM) updating. However, as behavioral performance represents the summed activity of multiple stages of processing, the temporal locus of the WM updating deficit remains unclear. Here, we used an event-related potential (ERP) paradigm to compare the temporal mechanisms of WM updating in 21 children with LD (aged between 10 and 12 years) and 21 age-matched controls while they performed the running memory task. Behavioral results showed that children with LD attained significantly lower accuracy when the task required updating. ERPs revealed that the occipital early P1 component and parietal late positive complex (LPC) amplitudes were lower in children with LD compared to controls when the task required children to remember a new stimulus. The LPC (1000-1500) amplitude correlated with the performance of academic and updating behavior. These results provide a novel electrophysiological evidence that children with LD have a specific impairment in early visual attention processing and lately WM updating.

Keywords—learning disability (LD); working memory updating; running memory task; event-related potentials (ERP)

I. INTRODUCTION

Children with learning disability (LD) have some cognitive and neuropsychological processing difficulties associated with learning literacy and math. Recently, accumulating literature has identified working memory deficits as closely associated with specific LD, such as reading disability [1], mathematical disability [2], ADHD [3], or combined reading and mathematics disability [4][5]. So, some researchers have concluded that working memory may be a core deficit in children with LD, especially an impaired ability to update relevant information from working memory as a hallmark of the learning disorder because working memory (WM) updating is considered to be a key component of working memory [6]. WM updating is the ability to simultaneously integrate new relevant information and suppress data that is no longer relevant (Friedman et al., 2006).

Although there is converging evidence suggesting apparent links between LD and dysfunctional WMU processes, the temporal locus of the updating deficit remains unclear. Keage et al studied the ERP indices of WM updating in AD/HD, they have found delayed latency and attenuated amplitude of N300 and P450 component in the child with AD/HD during a one-back working memory task [7]. Recently, Horowitz-Kraus [8] found individuals with dyslexia displayed decreased ERP components (N100, P300) compared to skilled readers in the “target-locked” conditions of the Wisconsin Card Sorting Test. Therefore, studying these ERP components in relation with the running memory task in children with LD could highlight neuronal processes underlying the updating function in LD.

In the current study, we attempted to use ERPs to pinpoint the impaired cognitive abilities in the running memory task and explore potential neural markers of WM updating deficit in children with LD. This WM task requires not only a phonological loop, but also an effective updating function [9]. As the number of required updates rises (as more digits are presented), the task becomes more difficult and requires a better updating function. In order to obtain a pure measure of updating ERP effects, a control task is generally required rule out phonological loop component. This is typically done to obtain difference waves, in which the waveforms observed during the control task are subtracted from those obtained during the experimental task.

ERP indices of the early discrimination (P1/N1), selection of material (P2), retrieval of relevant memories (N400), and late positive complex (LPC) will be assessed. A correlation analysis on ERP components and behavioral data collected during the task was conducted to find an ERP index sensitive to the WM updating function of children with LD.

II. METHODS

A. Participants

Twenty-one (12 boys, 9 girls) children with LD and 21 (11 boys, 10 girls) typically developing children were recruited from a public elementary school in Beijing. None of the children in the study attended special schools. All

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participants were in 5th ($n = 22$, age: 10.38 ± 0.57 years) or 6th grade ($n = 20$, age: 11.25 ± 0.55 years). All children with LD were tested with standardized math, reading, and spelling tests, treated and diagnosed by a recognized paraprofessional or in a specialized center.

B. The Running Memory Task

Participants performed the running memory task akin to that of Kiss et al [10], while the EEG was recorded. The task required subjects to process strings of items of unknown lengths (the length of which ranged from 3 to 9 digits), and then to remember the last 3 digits in those strings, regardless of how many total digits were presented in the string. Control tasks only required the temporary storage of items, without any need to update the presented information. Therefore, participants had to continuously update the contents of their WM. For example, if a fourth digit is presented (position 4), participants needed to delete the first digit of the 3 in their digit memory sets and add in the new one.

C. ERP Recording and Analysis

ERP recording and analysis were conducted using SCAN4.3 system. ERPs were selectively averaged according to groups, task types (updating and control tasks), and updating positions (position 3 as the non-update position and positions 4 through 6 as update positions). Then, we obtained difference waves by subtracting the ERP waveforms observed during the control task from the experimental waveforms of LD group and control group. For ERP components, three-factor repeated measure ANOVAs were conducted on participant group type (LD group and control group), update position type (update position and non-update position), and electrode position (FPz, Fz, Cz, Pz and Oz).

III. RESULTS

A. Behavioral Results

Behavioral data of accuracy and response time on the task are presented in "Table I".

TABLE I. MEANS ACCURACY AND RESPONSE TIME OF LDS AND CONTROLS

	Accuracy (% \pm SD)			
	Non-update	Update once	Update twice	Update thrice
LDS	92.41 \pm 9.29	85.57 \pm 11.13	86.24 \pm 12.28	79.92 \pm 13.04
Controls	94.71 \pm 7.31	94.40 \pm 6.60	92.99 \pm 8.90	90.57 \pm 9.75
	Response time (ms \pm SD)			
	Non-update	Update once	Update twice	Update thrice
LDS	1097.15 \pm 272.84	1247.55 \pm 377.95	1256.53 \pm 402.43	1298.95 \pm 312.80
Controls	1088.83 \pm 330.45	1179.87 \pm 346.13	1167.00 \pm 309.48	1207.90 \pm 334.72

The LD children had significantly lower accuracy ($F_{(1, 39)} = 7.85$, $p = 0.008$, $\eta^2 = 0.17$) compared with controls. There was a significant interaction between updating times and group ($F_{(1, 117)} = 2.99$, $p = 0.03$, $\eta^2 = 0.07$). Simple effect

comparisons showed that there was no difference between the LD children and the control children under the non-update condition ($p = 0.38$). Under the update once, twice and thrice condition, the LD children's accuracy rate was significantly lower than that of the control children ($p < 0.05$).

In terms of response time, there was no significant interaction between updating condition and group ($F_{(1, 117)} = 0.83$, $p = 0.47$, $\eta^2 = 0.02$). There was no significant main effect of group ($F_{(1, 39)} = 0.42$, $p = 0.52$, $\eta^2 = 0.01$). There was a main effect of updating times ($F_{(3, 117)} = 10.71$, $p < 0.001$, $\eta^2 = 0.21$). Post hoc comparisons showed that response time in the no-update condition was significantly shorter than in the update once, update twice, and update thrice conditions ($p < 0.01$). There was no significant difference among the update once, update twice and update thrice conditions ($p > 0.05$).

B. ERP Results

Grand-average ERP difference waves and topographical map were shown in "Fig. 1" and "Fig. 2".

- P1/N1. For P1 and N1 components within 100-140 ms, result showed that interaction between update position type and electrode position was significant ($F(4, 140) = 4.61$, $p = 0.004$, $\eta^2 = 0.11$). Further analysis showed that N1 in Fz was more positive for update position than non-update position, which is N1's positive position effect; P1 in Oz was more negative for update position than non-update position, which is P1's negative position effect. Comparison of position effect of two groups in different electrode sites showed us that P1's negative position effect in Oz was discovered in LD group, but not in control group.
- P2. For P2 within 165 to 215 ms, result showed that interaction between update position type and electrode position was significant ($F(4, 140) = 3.525$, $p = 0.025$, $\eta^2 = 0.089$). Further analysis showed that in Pz, P2 was more negative for update position than non-update position, which is P2's negative position effect. Comparison of position effect of two groups in different electrode sites showed us that P2's negative position effect was discovered in LD group, but not in control group.
- N400. Within the 300 to 500 ms time window of N400, the interaction between update position and electrodes was significant ($F(4, 140) = 10.36$, $p < 0.001$, $\eta^2 = 0.23$). Simple effects analyses showed a positive position effect in Fz, where ERP waveforms were more positive for the update position than the non-update position. Pz and Oz showed a negative position effect in which ERP waveforms were more negative for the update position than the non-update position. The positive position effect in Fz and negative position effect in Pz were observed in both groups.

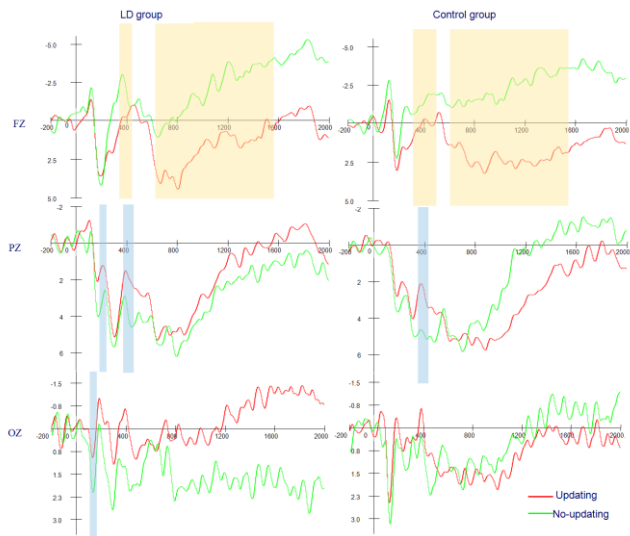


Fig. 1. ERP waveforms of LD children and control children time-locked to stimuli in update position and non-update position.

- **LPC.** Within the 500 to 1000 ms time window of LPC, the main effect of update position type was significant ($F(1, 35) = 8.50, p = 0.006, \eta^2 = 0.20$). ERP waveforms for the update position were more positive than those for the non-update position. The interaction between update position type and electrodes was significant ($F(4, 140) = 13.50, p < 0.001, \eta^2 = 0.28$). Simple effects analyses showed that ERP waveforms in FPz, Fz, and Cz were more positive for the update position than the non-update position, indicating a positive position effect in anterior regions that was observed for both groups.

Within the 1000 to 1500ms time window of LPC, the main effect of update position type was significant ($F(1, 35) = 25.30, p < 0.001, \eta^2 = 0.42$), and ERP waveforms for the update position were more positive than for the non-update position. The interaction between update position type and electrodes was also significant ($F(4, 140) = 17.75, p < 0.001, \eta^2 = 0.34$). Simple effects analyses showed that ERP waveforms in FPz, Fz, and Cz were more positive for the update position than the non-update position. The interaction among participant group type, update position type, and electrodes was marginally significant ($F(4, 140) = 2.62, p = 0.069, \eta^2 = 0.07$). Simple effects analyses showed that for the LD children, ERP waveforms in FPz, Fz, and Cz were more positive in the update position than the non-update position. ERP waveforms in Oz were more negative in the update position than the non-update position. For the control children, ERP waveforms in FPz, Fz, Cz, and Pz were more positive for the update position than the non-update position.

C. Correlations between ERP and Behavioral Data

Within the 300 to 500 ms time window of N400, a significant positive correlation between the position effect at Pz and math score was observed for the LD children ($r = 0.53, p = 0.019$), while the control children showed no such correlation. In the 1000 to 1500 ms time window of LPC, a

positive correlation between the position effect at Pz and response time was significant for the control children ($r = 0.58, p = 0.012$), while the LD children showed no such correlation.

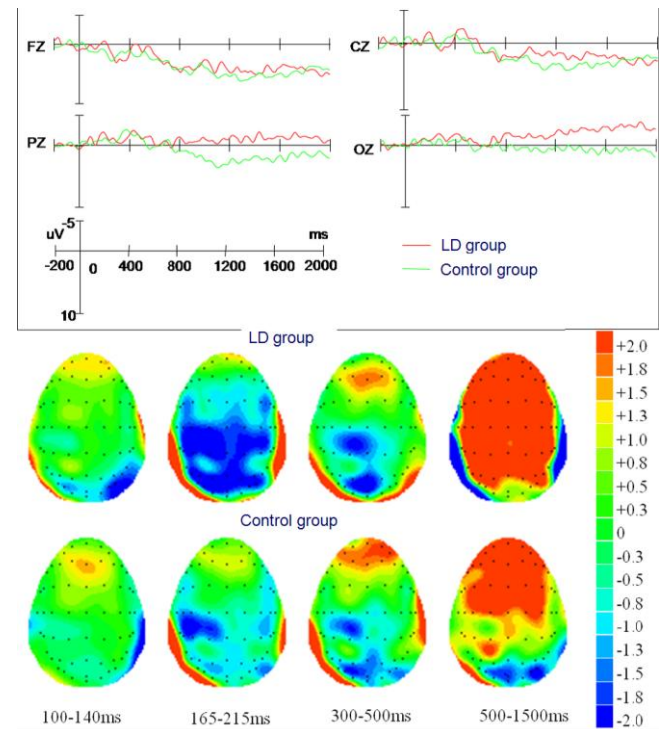


Fig. 2. Top: ERP difference waveforms of LD children and control children (update position minus non-update position). Bottom: topographical map of ERP difference waves (update position minus non-update position) of LD children and control children.

IV. CONCLUSION

In the present study, we investigated behavioral and electrophysiological indices of WMU function in children with LD. The behavioral results revealed that children with LD performed more errors than typically developing children in the updating conditions. Since no updating function was involved in the zero update condition, participants only needed to store and remember the 3 digits presented, while an updating function is required when more than 3 digits are presented. Thus, our results indicate a specific difference in updating, but not storage, between the LD and controls. This is consistent with previous studies [10][11].

Our ERP results suggest that a negative position effect during the early stage of processing (P1, P2), in which the LD children's waveforms over central parietal regions were more negative for update position than control children. The P1 is presumed to reflect early attention processing, the more a participant's attention is directed toward an upcoming target, the larger the amplitude of the P1 response to the target should be. Children with LD may have a passive attention toward an updating target. Our results also showed no difference in the ERPs within the 300- to 500-ms time window between the 2 groups.

The scalp topography of the LPC is shown that differences exist between the two groups. After 500 ms, the control children showed a positive position effect over anterior and posterior regions, while the LD children only showed a positive position effect over anterior and central regions, and a negative position effect over posterior regions.

Consistent with neurobiological basis of math (MD), reading (RD), and comorbid math and reading disability (MD+RD)[12], children with LD are characterized by limited abnormalities of LPC for memory updating involving posterior brain regions including parietotemporal and occipitotemporal area. Previous studies showed that the posterior parietal cortex maintains or shifts internal attention among the representations of items in WM [13]. Jonides et al [14] studies showed that the posterior parietal cortex plays not only a role in the storage but also in the proactive interference of verbal information in working memory. Therefore, typically developing children can shift between multiple representations of items, while children with LD showed deficits in representation shifting or proactive interference resolution. This could mean that the LD children performed worse than the control children at discarding the first digit in memory sets, suggesting that they may have difficulty in the suppression of old digits. Moreover, the LPC of children with LD is more located in anterior brain regions, which may be owing to the compensatory mechanisms of frontal brain areas in children with LD [12].

As for the relations among LPC, academic and behavior performance, some potential meaningful associations were found. In the 1000- to 1500-ms time window, the position effect at Pz and response time was significantly correlated for the control children but not the LD children. This suggests that a position effect within this time window may reflect functions related to information integration. Information integration is a comprehensive ability that is related to response time. It is a relatively predictive neurological index, which can be widely utilized research in diagnosis, assessment, and intervention training[15]. Within the 1000- to 1500-ms time window, the control children showed a positive position effect over parietal regions, while the LD children showed a positive position effect only over prefrontal, frontal, and central regions. This could explain why the LD children did not show any such correlation.

There is converging evidence that early intervention might prevent or remedy the onset of LD [16][17]. Our results suggest that LPC might be as neurophysiological index of WM training-related changes in LD brain function and see if they were linked to clinical improvement.

To conclude, the present study provides evidence that children with LD have deficit in early attentional processes, they cannot recognize the new digit well. Furthermore, children with LD are characterized by limited abnormalities of late positive complex in posterior regions, which were related to suppressing the old digit and WM updating. Future studies with larger samples should account for the heterogeneity of LD by including subgroups in order to shed more light onto the neural correlates of the cognitive dysfunction in LD.

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