

Determining Whether Tennis Benefits the Updating Function in Young Children: A Functional Near-Infrared Spectroscopy Study

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Abstract: This study aimed at investigating the behavioral and neuro-electrical impacts of a coordinative exercise intervention on the updating function of the working memory (WM) in young children. Children in the experimental group was tested on the 1-back working memory task before and after a coordinative exercise program that involved a 60 min session twice per week for eight weeks (totally 16 sessions), while the control group underwent routine classroom activities with the same WM tests. The results showed that the hit rates of performing the 1-back task increased significantly in the experimental group compared with that of the control group. The experimental group demonstrated a larger decrease in both reaction time and false alarm rates from pre-test to post-test than the control group. Physical fitness improved after exercise intervention in the experimental group. Neural adaptations due to the exercise training were evaluated using functional near-infrared spectroscopy (fNIRS) and the results indicated that the experimental group experienced a greater cortical oxygenated hemoglobin (Oxy-Hb) increase in the prefrontal area after the intervention than the control group. These results suggest that coordinative exercises are beneficial for improving WM as well as reaction time and physical fitness in young children.

Keywords: updating ability; coordinative exercise; working memory; fNIRS; young children

1. Introduction

Working memory (WM) involves three independent central executive function components: shifting, updating, and inhibition [1]. The updating function changes the storage in the WM as new information appears. Substantial evidence has established that the WM is associated with learning, inference, problem-solving, and intelligence [2]. One of the most popular experimental paradigms investigating the updating function is the “n-back” procedure. An n-back task involves asking the subjects to monitor the identity or location of a series of verbal or nonverbal stimuli [3].

Accumulating research has provided evidence linking the updating function of the WM with the fluid intelligence of school-age children [2]. Moreover, previous studies have shown that the updating function in WM influences children’s learning attainment. Mirandola et al. [4] found that children with a specific difficulty at comprehending written text were less competent in performing updating tasks. Iuculano et al. [5] showed that in comparison with normal children, children with mathematical learning difficulties have a relatively lower WM updating function.

It was found that the WM updating function is plastic, especially in early childhood. Tsujii et al. [6] demonstrated that the spatial WM is developed in children from five to seven years. Peng

et al. [7] used the n-back procedure to train WM of preschoolers for 14 days and reported that the experimental group significantly enhanced their WM but the control group did not. However, most of these interventional studies involving WM training did not investigate the role of exercise on WM, especially on WM updating ability in young children.

Aerobic exercises may be beneficial for both brain function and behavior performance of the WM in young children. Aerobic exercise refers to a type of exercise that provides energy through aerobic metabolism. The exercise duration lasts about 30 min or more and the exercise intensity is medium or above (60%–80% of the maximum heart rate value). Previous research has shown that acute aerobic exercises can shorten reaction time (RT) in the modified Sternberg WM task in young adults [8]. Acute moderate-intensity aerobic exercises were reported to also benefit preadolescent children's performance in the n-back task and enhance the neural basis of the WM [9]. Moreover, a longitudinal study has found that the level of extracurricular physical activity in four-year-old children can predict the performance of the 2-back task when they grow up to seven years old [10]. However, a meta-analysis with children aged 11–13 years reported no difference in the effect of various types of physical activities on cognition [11].

As an important type of exercise in early childhood, coordinative movements involving activations of multiple muscle groups refer to the motor-demanding exercise that involves activation of the cerebellum and motor control network and requires perceptual and high-level cognitive information processing [12]. Previous research has shown that the prefrontal cortex plays an important role in both cognitive functions [13,14] and motor coordination [15,16]. Moreover, the cerebellum affects the updating function of WM [17]. Parker et al. [18] suggested that the cerebellum influences the medial frontal networks in animal models, and it further supports the neuronal structures responsible for coordination as well as working memory. Due to the neuronal connections between the cerebellum and frontal cortex, it is reasonable to postulate that cognitive performance, especially WM, is influenced by coordinative exercises. Coordinative exercises involve complex motor movements for goal-directed behaviors. The focus of attention during these exercises keeps changing. Individuals have to update the motor information rapidly during coordinative exercise, for example, the forehand and backhand stroke practice in tennis.

It is important to determine the impact of coordinative exercises on the performance of the WM in young children as this type of exercise training may facilitate the development of their cognitive and neuromuscular systems. Because extensive research has shown that the prefrontal cortex (PFC) is an important component of the neural substrate for WM [3,19–22], this study examined the changes in the updating function of WM in kindergarten children after a long-term tennis exercise intervention and related functional neural adaptations in the frontal cortex during the 1-back task via functional near-infrared spectroscopy (fNIRS). fNIRS is a relatively new imaging technique for investigating cortical hemodynamic responses [23]. Because fNIRS is non-invasive, portable, and does not require a precise fixation of the body as in functional magnetic resonance imaging (fMRI), it is suitable for brain imaging studies on infants and children [24]. Using fNIRS, we were able to measure both oxygenated and deoxygenated hemoglobin changes in young children in natural settings, and the spatial sensitivity of fNIRS could help us obtain the spatial activation information in the young children's brain. We examined whether an eight-week coordinative tennis exercise training program would improve the updating function of WM and influence oxygen level in the hemoglobin index of fNIRS measurements in the frontal cortex elicited by the n-back test paradigm. We hypothesized that the coordinative exercise program would benefit the WM updating function in young children both behaviorally and neurophysiologically, in which the oxy-Hb signals in the PFC in the experimental group would increase after the coordinative exercise regime.

2. Materials and Methods

2.1. Ethics Statement

This research was approved by the Ethical Committee of Beijing Normal University. Written informed consent was obtained from the parent or guardian of each child prior to his/her participation in the study.

2.2. Participants

We set the power value $1 - \beta = 0.80$ [25] and the effect size $f^2 = 0.25$, which is a medium effect size value [26], and we calculated the sample size using the G*Power software and got the estimated total sample size to be 24. We recruited 32 young children with parental consent. Some of them dropped out of the program during the long-term intervention, and some were too active to finish the working memory task. Finally, A total of 20 valid preschoolers (10 boys, $M_{\text{age}} = 72.3 \pm 2.74$ months; 10 girls, $M_{\text{age}} = 73.2 \pm 1.30$ months) attending kindergarten located in Beijing, China, participated in the study.

Before the exercise intervention, general health and physical fitness of the children were examined by a certified pediatric trainer. All participants were children with normal development and had no vascular-related diseases, movement disorders, mental illness, or other conditions that may affect their cognitive and motor performance prior to participation. The children were randomly assigned into either experimental or control groups (10 in each group, 5 boys in each group).

2.3. Procedure

2.3.1. Exercise Intervention Project

The intervention group received eight weeks of planned tennis games besides routine classroom activities in kindergarten. The 60 min planned tennis training comprised a 10 min warm-up, 40 min main training, and 10 min cooling-down. The main training included continuous jumping, shuttle run, jogging around a pile, and a toss exercise that all required coordination. Both the warm-up and cooling-down consisted of some static stretching activities. The intervention took place twice a week for eight weeks for a total of 16 sessions. The exercise intensity was quantified using a Polar exercise heart rate monitor (RS800CX PTE). According to the American College of Sports Medicine (ACSM) Resource Manual for Guidelines for Exercise Testing and Prescription [27], we set the moderate-intensity exercise at 60%–69% of the maximum heart rate. The program was implemented by four trained kinesiology graduate students with expertise in teaching tennis exercise to preschoolers and they were blind to the group assignment. The control group was a waitlist control group; children in this group underwent routine classroom activities organized by the teachers in kindergarten, which included free play, picture book reading, and subject teaching for sixty minutes. Each activity lasted for 20 min. During the free play section, children were allowed to play in the courtyard in the kindergarten supervised by two teachers. The emphasis of the free play was for enjoyment and safety, not a competition nor skill enhancement. During the book reading section, more than 100 books were exhibited on the bookshelf. Children could fetch any book he or she liked to read. During the subject teaching section, children were taking art, science, music, nature or moral classes, and so on according to the kindergarten's class schedule. The order of the activities was arranged by the teachers.

2.3.2. The 1-Back Task

This study used E-prime software to write the task paradigm. We considered a white square (Red Green Blue, RGB: 255, 255, 255) as a stimulus, and the background was black (RGB: 0, 0, 0). First, the children practiced five trials of the task. After practice, the formal test program began. The formal test comprised four blocks, 30 trials in each block with totally 120 trials. The hit rate of each block was 46.66%. All trials were presented randomly. As shown in Figure 1, at the beginning of each trial, a white fixation point (RGB: 255, 255, 255) was presented in the center of the screen for 1 s; the square

then randomly flashed along the four sides of the screen for 500 ms, followed by a screen that remained blank (RGB: 0, 0, 0) until the response. The subjects were required to judge whether the position of the current square was the same as that of the square presented before. If two successive squares appeared in the same position, the subjects pushed the “F” button. If not, they pushed the “J” button. The children were asked to take a 20-s rest after each block. The number of hits, correct rejection, false alarms, and misses, as well as response times, were recorded.

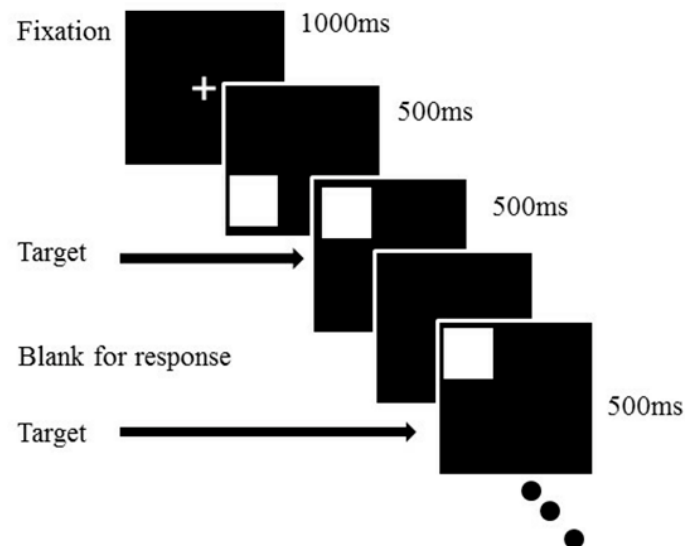


Figure 1. The flow path of the 1-back task. The subjects were required to judge whether the position of the current square was the same as that of the square presented before.

2.3.3. fNIRS Measurement

Converging evidence from neuroimaging in children, neuropsychological patients, and healthy adults indicates a supportive role of the left lateral prefrontal cortex (LPFC) in executive-control conditions on tasks in the memory and language domains [28–34]. The left lateral prefrontal cortex (LPFC) hemodynamic response was measured using a wearable and continuous-wave single-channel functional near-infrared spectroscopy (fNIRS; probe size: 58 × 28 × 6 mm; PortaLite, Artinis Medical System, The Netherlands).

The PortaLite device constantly emits light at 760 and 850 nm wavelengths between a transmitter and three aligned receivers (three independent channels), placed at 30, 35, and 40 mm from the transmitter. The measure of light attenuation is used to calculate the concentration changes in cortical oxygenated hemoglobin (oxy-Hb) and deoxygenated hemoglobin (deoxy-Hb) at the two wavelengths, allowing for theoretical penetration distances from 1.5 to 2 cm [35]. Light penetrates deeper for farther distances between the source and the detector. The sampling frequency of the system was 50 Hz. The PortaLite device is suitable for children [30].

In the current study, the transmitter and the three light sources were laterally attached to the left forehead and were tightly fixed in a customized headband, see Figure 2. The detection optode was positioned above the supra orbital ridge of the children’s left side [36]. The spatial position of Fp1 was marked by a 64-electrode electroencephalogram cap which is suitable and standard to preschool children, and the probe was positioned over the participant’s prefrontal cortex at Fp1 according to the International 10–20 system of electrode placement [37]. The optode had a slightly twisted joint in the middle, and therefore, it was adjustable to the curvature of the forehead. It was attached to the skin by double-sided tape to hold it firmly. The optode was wrapped with a dark opaque medical bandage to prevent signal contamination by ambient light.

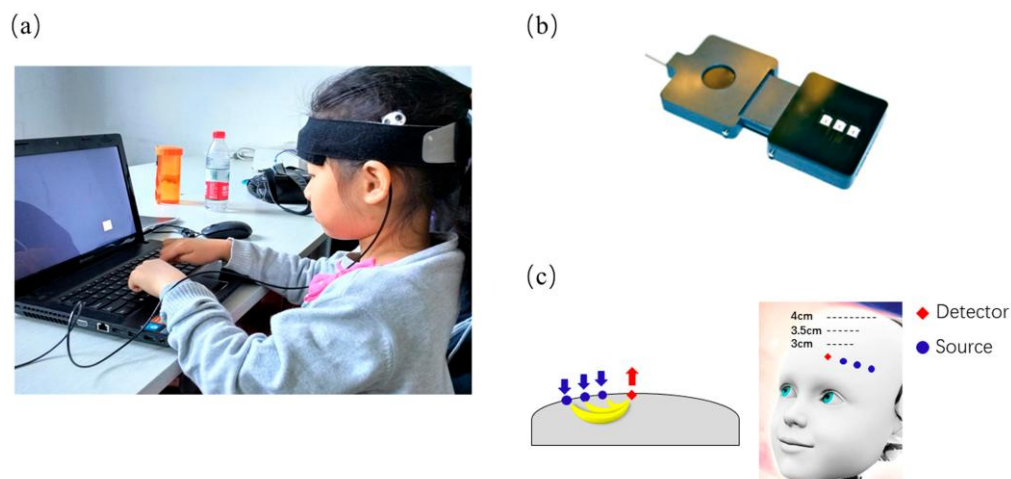


Figure 2. (a) Optode placement in our experiment. (b) A photograph of the wearable functional near-infrared spectroscopy (fNIRS) and (c) Schematic diagrams of the channels corresponding to multiple distances of 30, 35, and 40 mm between the sources and the detector.

2.4. Statistical Analysis

The fNIRS data were analyzed using commercially available software (Oxysoft, Artinis Medical SystemsTM, The Netherlands). A moving average window of 1 s was applied to the O₂Hb signals to filter out the noise of the heartbeat frequency. The fNIRS data were excluded from the analyses when the standard deviations of oxy-Hb during the pre-task period exceeded 0.035 [38]. For the fNIRS signals, the value at the start of the first trial was taken as zero. Changes of [O₂Hb] were calculated for approximately 105 s from this point. Therefore, the 1-back task period for each subject was divided into four time-segments of approximately 105 s each. To establish the hemodynamic and systemic responses to cognitive performance, the mean values of oxy-Hb for each subject were calculated for four time segments of 105 s. The signals were linearly detrended and were filtered using a band-pass filter with a cutoff frequency of 0.01~0.1 Hz. The time series was cubically interpolated at 1 Hz to obtain uniformly spaced time series for spectral and transfer function analysis.

The behavioral data were analyzed with the SPSS 20.0 software package. We considered the hit rates, false-alarm rates, d-primes, and RT of the 1-back task as the behavioral dependent variable and the oxy-Hb values as the neural dependent variable. The independent variables were time measurements (pre-test and post-test) and groups (the experimental group and control group). We used the repeated measures analysis of variance (Repeated ANOVA) to analyze the data. For RT across all tasks, trials with values more than 2.5 standard deviations above or below the individual mean and less than 100 ms were excluded before computing the overall mean and standard deviation.

3. Results

3.1. Behavioral Results

3.1.1. Physical Fitness Measures

Mean and standard deviation measures of physical fitness for the two groups are presented in Table 1. Results of repeated ANOVA of 2 (group: experimental group and control group) × 2 (time measurement: pre-test and post-test) for physical fitness are exhibited in Table 2. The interaction between group and time measurement was significant. The post hoc test showed that the aerobic fitness of the experimental group improved after intervention, but that of the control group did not, except the measure of “sit-and-reach”, see Table 3. The post hoc test results from the other direction are provided in Supplementary Table S1. (Supplementary Table S1 shows that the experimental group performed worse than the control group in the test of “10 m shuttle run” and “throw a tennis ball” at

pre-test, but no difference was found between the two groups in the other tests at pre-test.) Body Mass Index (BMI) in both the experimental and the control group decreased after eight weeks, $F(1, 18) = 8.37$, $p < 0.01$, $\eta_p^2 = 0.32$, but neither the group difference, $F(1, 18) = 0.52$, $p = 0.48$, nor the interaction between group and test time was significant, $F(1, 18) = 0.08$, $p = 0.78$.

Table 1. Means and standard deviations for two groups on measures of physical fitness, M (SD).

	Pre-Test		Post-Test	
	Control Group	Experimental Group	Control Group	Experimental Group
10 m shuttle run (s)	6.99 (0.54)	7.63 (0.73)	7.13 (0.60)	6.46 (0.33)
Standing broad jump (cm)	104.50 (9.62)	95.00 (11.43)	107.30 (8.62)	113.10 (8.14)
Throw a tennis ball (m)	6.03 (1.30)	4.16 (1.66)	6.30 (1.01)	7.30 (1.62)
Both legs jump in succession (s)	5.34 (0.54)	5.78 (0.90)	5.10 (0.41)	4.65 (0.50)
Balance beam (s)	4.81 (1.41)	5.95 (1.40)	4.43 (0.98)	3.96 (0.68)
Sit and reach (cm)	8.84 (3.71)	7.53 (4.07)	11.00 (3.29)	11.60 (2.49)
Body Mass Index (BMI, kg/m ²)	16.39 (1.74)	16.60 (2.76)	15.97 (1.80)	16.34 (2.86)

Table 2. Results of repeated ANOVA of 2 (group: experimental group and control group) $\times$ 2 (test time: pre-test and post-test) for six indexes of the physical fitness.

		<i>Df</i> ₁	<i>Df</i> ₂	<i>F</i>	η_p^2
10 m shuttle run	Group	1	18	13.49 ***	0.43
	Group $\times$ test time	1	18	22.00 ***	0.55
Standing broad jump	Group	1	18	20.64 ***	0.53
	Group $\times$ test time	1	18	11.06 **	0.38
Throw a tennis ball	Group	1	18	46.30 ***	0.72
	Group $\times$ test time	1	18	32.80 ***	0.65
Both legs jump in succession	Group	1	18	45.26 ***	0.72
	Group $\times$ test time	1	18	18.91 ***	0.51
Balance beam	Group	1	18	13.98 ***	0.58
	Group $\times$ test time	1	18	6.50 **	0.39
Sit and reach	Group	1	18	76.40 ***	0.81
	Group $\times$ test time	1	18	7.18 *	0.29

Note. * $p < 0.05$. ** $p < 0.01$. *** $p < 0.001$.

Table 3. Post hoc test results of repeated ANOVA of 2 (group: experimental group and control group) $\times$ 2 (test time: pre-test and post-test) for six indexes of the physical fitness.

		<i>Df</i> ₁	<i>Df</i> ₂	<i>F</i>	η_p^2
10 m shuttle run	Control group	1	18	0.52	
	Experimental group	1	18	34.98 ***	0.66
Standing broad jump	Control group	1	18	0.74	
	Experimental group	1	18	30.96 ***	0.63
Throw a tennis ball	Control group	1	18	0.58	
	Experimental group	1	18	78.52 ***	0.81
Both legs jump in succession	Control group	1	18	2.83	
	Experimental group	1	18	61.34 ***	0.77
Balance beam	Control group	1	18	1.27	
	Experimental group	1	18	35.58 ***	0.66
Sit and reach	Control group	1	18	18.37 ***	0.51
	Experimental group	1	18	65.21 ***	0.78

Note. * $p < 0.05$. ** $p < 0.01$. *** $p < 0.001$.

3.1.2. 1-Back Task Data

Hits

A 2 (group: experimental group, control group) $\times$ 2 (time measurement: pre-test, post-test) repeated ANOVA was conducted on the percent of hits. Table 4 shows the ANOVA summary table for all the dependent variables. The main effect of both time measurement and group was significant, and the interaction between time measurement and group was also significant, see Figure 3a. The post hoc analysis indicated that the experimental group had a higher percentage of hits in the post-test period ($89.04\% \pm 8.43\%$) than that of the pre-test period ($70.83\% \pm 16.22\%$), $F(1, 18) = 19.31, p < 0.001, \eta_p^2 = 0.56$, but the percentage of hits in the control group did not change significantly from the pre-test period ($84.75\% \pm 15.58\%$) to the post-test period ($89.27\% \pm 9.46\%$), $F(1, 18) = 0.95, p = 0.34$. The post hoc test also showed that there was no difference in the percentage of hits between the experimental group ($70.83\% \pm 16.22\%$) and the control group ($84.75\% \pm 15.58\%$) in the pre-test, $F(1, 18) = 3.39, p = 0.08$, and the difference was not significant between the experimental group ($89.04\% \pm 8.43\%$) and the control group ($89.27\% \pm 9.46\%$) in the post-test, $F(1, 18) = 0.003, p = 0.96$.

Table 4. Summary for ANOVAs performed on hits, false alarms, d-primes, and response times.

Source	Hits			False Alarms			D-Prime			Response Times		
	<i>F</i>	<i>df</i>	η_p^2	<i>F</i>	<i>df</i>	η_p^2	<i>F</i>	<i>df</i>	η_p^2	<i>F</i>	<i>df</i>	η_p^2
Group	4.85 *	1, 18	0.23	1.70	1, 18	–	1.02	1, 18	–	0.14	1, 853	–
Test time	13.36 **	1, 18	0.46	12.59 **	1, 18	0.44	3.19	1, 18	–	203.90 ***	1, 853	0.19
Group $\times$ test time	1.80	1, 18	–	4.50 *	1, 18	0.22	0.04	1, 18	–	7.44 ***	1, 853	0.01

Note. * $p < 0.05$. ** $p < 0.01$. *** $p < 0.001$.

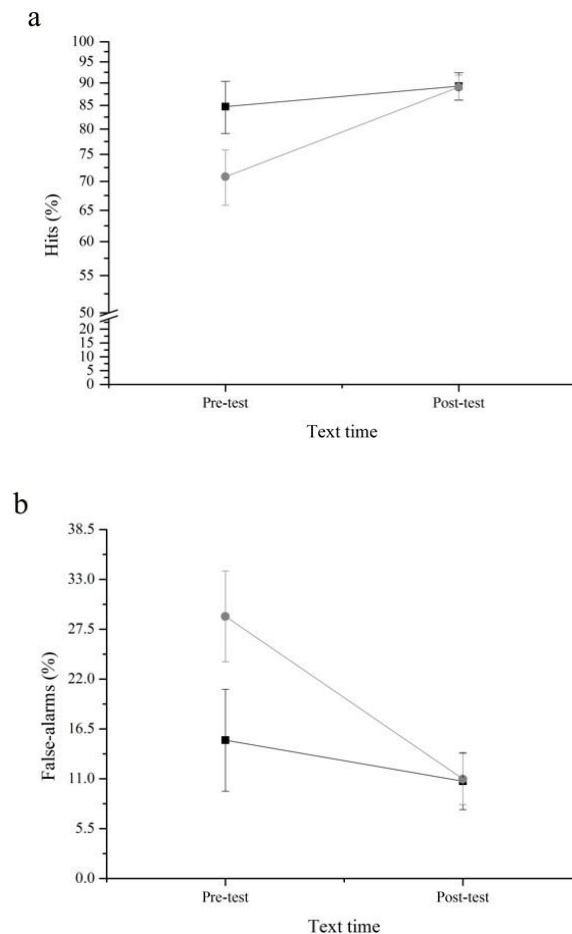


Figure 3. Cont.

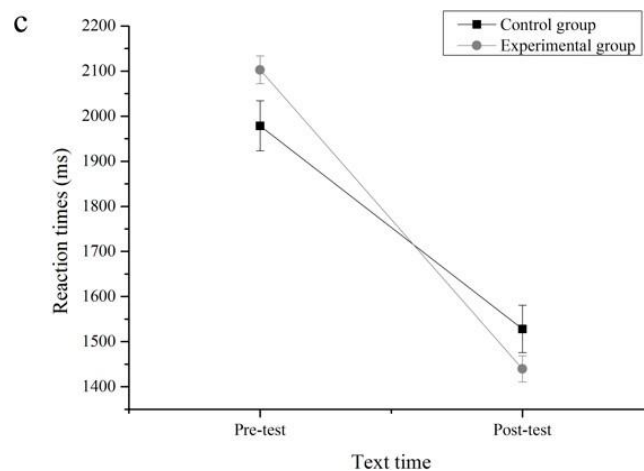


Figure 3. (a) Interaction of group (control group, experimental group) and test time (pre-test, post-test) in the percentage of hits. (b) Interaction of group (control group, experimental group) and test time (pre-test, post-test) in the percentage of false alarms. (c) Interaction of group (control group, experimental group) and test time (pre-test, post-test) in reaction times. Data are mean $\pm$ standard error (SE).

False Alarms

A 2 (group: experimental group, control group) $\times$ 2 (time measurement: pre-test, post-test) repeated ANOVA was conducted on the percentage of false alarms, see Table 4. The main effect of both time measurement and group was significant, and the interaction between group and time measurement was marginally significant. As shown in Figure 3b, the post hoc analysis indicated that the experimental group had a smaller percentage of false alarms in the post-test period ($10.96\% \pm 8.42\%$) than that of the pre-test period ($28.91\% \pm 16.57\%$), $F(1, 18) = 18.08, p < 0.01, \eta_p^2 = 0.53$, but the percentage of false alarms in the control group did not change significantly from the pre-test period ($15.24\% \pm 15.58\%$) to the post-test period ($10.73\% \pm 9.46\%$), $F(1, 18) = 0.92, p = 0.35$. The post hoc test from the other direction showed that there was no difference of the percentage of false alarms between the experimental group ($28.91\% \pm 16.57\%$) and the control group ($15.24\% \pm 15.58\%$) in the pre-test, $F(1, 18) = 3.18, p = 0.09$, and the difference was not significant between the experimental group ($10.96\% \pm 8.42\%$) and the control group ($10.73\% \pm 9.46\%$) in the post-test, $F(1, 18) = 0.003, p = 0.96$.

D-Prime

D-prime was estimated as $d' = Z_{\text{Hits}} - Z_{\text{False alarms}}$. To avoid d' being undetermined when the hit or the false alarm rate was equal to 0 or 1, the fourth method proposed by Stanislaw and Todorov [39] was conducted. Specifically, scores equal to 1 were replaced by $(n - 0.5)/n$ and scores equal to 0 were replaced by $0.5/n$, with n representing the number of signal and noise trials. A 2 (group: experimental group, control group) $\times$ 2 (time measurement: pre-test, post-test) repeated ANOVA was conducted on these values, similar to the previous analyses, see Table 4. The ANOVA revealed no significant effect on group, $F(1, 18) = 1.02, p = 0.33$, time measurement, $F(1, 18) = 3.19, p = 0.09$, or the interaction between the two variables, $F(1, 18) = 0.04, p = 0.85$.

Reaction Times

Only the RT of the correct trials was analyzed (399 incorrect trials, 29.17%). The normality test (Kolmogorov–Smirnov test) showed that the reaction time scores neither in the pre-test ($d = 0.12, df = 858, p < 0.001$) nor in the post-test period ($d = 0.13, df = 858, p < 0.001$) obeyed the normal distribution, and the q–q diagram was checked for further confirmation. The scores of reaction time were normalized, and 47 trials with values more than 2.5 standard deviations above or below overall the mean were excluded. A 2 (group: experimental group, control group) $\times$ 2 (test time:

pre-test, post-test) repeated ANOVA was conducted after the exclusion, see Table 4. The main effect of the time measurement was significant, but no significant difference was found between the groups. The interaction between the two variables was significant, see Figure 3c. The post hoc test showed that there was no group difference (control group: 1978.67 ± 950.35 ms, experimental group: 2102.86 ± 1245.97 ms) of RT in the pre-test, $F(1, 853) = 2.64, p = 0.11$, and that the RT in the experimental group (1439.62 ± 646.02 ms) was significantly shorter than that in the control group (1528.22 ± 538.72 ms) in the post-test, $F(1, 853) = 4.39, p < 0.05, \eta_p^2 = 0.01$.

3.2. fNIRS Results

Figure 4 shows the courses over time of the mean fNIRS signals that were measured during the 20 s pre-task baseline period and the 105 s 1-back tasks. Figure 5 displays the mean values of oxy-Hb for each of the four 105 s time segments in the 1-back task. The repeated ANOVA of 2 (group: experimental group, control group) $\times$ 2 (time measurement: pre-test, post-test) $\times$ 4 (time segment: 1, 2, 3, 4) revealed the following main effects to be (marginally) significant: time measurement, $F(1, 15) = 8.12, p = 0.012, \eta_p^2 = 0.35$, and time segment, $F(3, 45) = 2.56, p = 0.067, \eta_p^2 = 0.15$. The interaction of time measurement and group was also significant, $F(1, 15) = 14.46, p = 0.002, \eta_p^2 = 0.49$. No other effects or interactions reached significance.

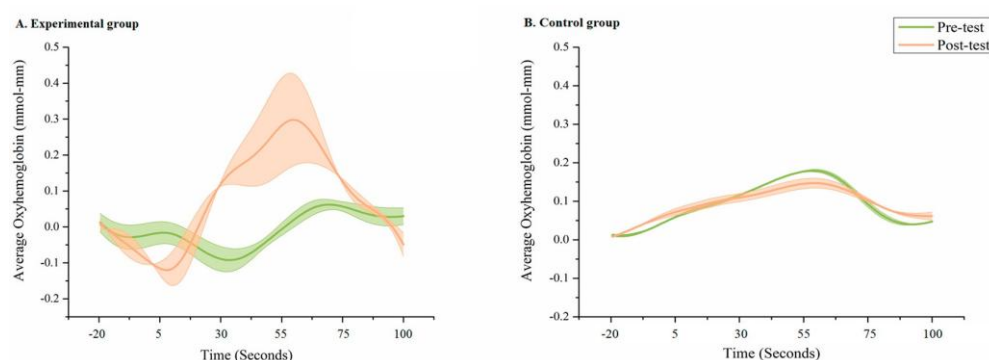


Figure 4. The courses over time of the mean oxy-Hb signals in the left lateral frontal lobe that were measured during the 20 s pre-task baseline period and the 105 s 1-back tasks. The fNIRS signals of four task blocks were averaged at the same sampling point along 125 s (totally 6250 sampling points) to obtain the time series figure for improving the signal-to-noise ratio (SNR).

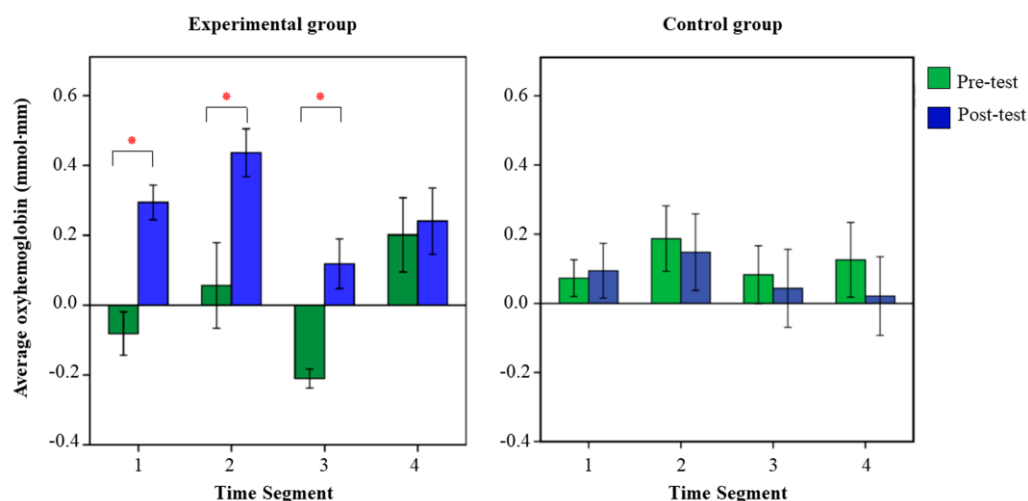


Figure 5. The mean values of oxy-Hb for each of the four 105 s time segments in the 1-back task.

To examine these interactions, the experimental group and the control group in oxy-Hb values were analyzed by separate ANOVAs, see Table 5. For the experimental group, both the main effects of time measurement and of time segment were significant, $F(1, 7) = 50.54, p < 0.001, \eta_p^2 = 0.88, F(3, 21) = 3.98, p < 0.05, \eta_p^2 = 0.36$. The time measurement and time segment interaction was not significant, $F(3, 21) = 2.21, p = 0.12$, mainly due to the pre- vs. post-test significant differences for 1st, 2nd, and 3rd time segments, $F(1, 7) = 17.27, p < 0.01, \eta_p^2 = 0.71, F(1, 7) = 9.54, p < 0.05, \eta_p^2 = 0.58, F(1, 7) = 18.68, p < 0.01, \eta_p^2 = 0.73$. Although there was no significant difference between pre- and post-test conditions in mean oxy-Hb values for the 4th time segment, $F(1, 7) = 0.12, p = 0.74$, the similar trend was reflected in Figure 4.

Table 5. The values of oxy-Hb for each of the four 90 s time segments in the 1-back task, M (SD).

	Time Segments 1		Time Segments 2		Time Segments 3		Time Segments 4	
	Pre-Test	Post-Test	Pre-Test	Post-Test	Pre-Test	Post-Test	Pre-Test	Post-Test
Experimental group	-0.08 (0.05)	0.29 (0.07)	0.05 (0.11)	0.43 (0.09)	-0.21 (0.06)	0.12 (0.10)	0.20 (0.11)	0.24 (0.10)
Control group	0.07 (0.05)	0.09 (0.06)	0.18 (0.10)	0.14 (0.09)	0.08 (0.06)	0.04 (0.09)	0.12 (0.10)	0.02 (0.10)

For the control group, in contrast, the main effects of time measurement and of time segment were not significant, $F(1, 8) = 0.32, p = 0.58, F(3, 24) = 0.37, p = 0.75$, as was the time measurement and time segment interaction, $F(3, 24) = 0.19, p = 0.88$. Further analyses revealed that there were no significant pre- vs. post-test differences for the four time segments, $ps > 0.05$.

The mean values of oxy-Hb in both pre-test and post-test were normalized, and the difference value from pre-test to post-test was calculated as $\delta Z_{\text{oxy-Hb}} = Z_{\text{post oxy-Hb}} - Z_{\text{pre oxy-Hb}}$. δZ_{hit} and $\delta Z_{\text{false-alarm}}$ were calculated in the same way. Then, the correlation analysis was conducted. A positive correlation was observed between δZ_{hit} and $\delta Z_{\text{oxy-Hb}}, r(17) = 0.58, p < 0.05$, and a negative correlation was found between $\delta Z_{\text{false-alarm}}$ and $\delta Z_{\text{oxy-Hb}}, r(17) = -0.56, p < 0.05$. This result indicated the consistency of behavioral and neural changes.

4. Discussion

This study aimed to examine the effect of an 8-week coordinative tennis exercise training on the updating aspect of the working memory (WM) performance in young children in both behavioral and neurophysiological domains.

The behavioral results showed that the hit rate of performing the 1-back task by the experimental group increased after the intervention. At the same time, the experimental group gained a smaller percentage of false alarms after the exercise, but neither the hit rate nor the false alarm rate changed much in the control group. Both the experimental group and the control group gained faster RT after the exercise, and the improvement was more significant in the experimental group than it was in the control group.

These findings suggest that the eight-week tennis game program facilitated improvement in the updating function of the WM. The result is consistent with that of prior research examining the relationship between physical exercise and WM of adolescents and adults. Ludyga et al. [40] used the Sternberg task to examine working memory maintenance. During this task, the adolescents were called upon to remember a set of letters and indicate whether a probe matches one of the previous memory set items. It was concluded that performing a combination of aerobic and coordinative exercises daily elicits benefits for WM maintenance of adolescents aged 12–15 years. Koutsandréou et al. [41] utilized a letter digit span task to measure WM capacity, and they underwent the WM task before and after an afterschool coordinative exercise regimen. The study suggested that WM capacity of the 9- to 10-year-old children benefited from the coordinative exercise program. Mcmorris et al. [42] reported that acute, intermediate-intensity exercises have a strong beneficial effect on the speed of response in

the WM tasks in adults. Moreover, the result is similar to those of studies investigating the effect of acute exercises on the executive function in normal children [43].

To our knowledge, much of the literature on the relationship between exercise and working memory pays particular attention to the aerobic exercise and the capacity or maintenance of WM. There is a relatively small body of literature that is concerned with the coordinative exercise and updating function of WM. In addition, only few empirical studies investigated the issue in preschool children. The present findings may add some evidence to the exercise-related WM improvement in young children. However, these findings are contrary to that of Woost et al. [44], who found no evidence for a longitudinal additive effect of sequential physical and spatial training on cognitive performance. A possible explanation for this contrary finding might be that they used an intelligence structure test to assess the cognitive performance associated with the hippocampus, and the participants in that research were young, homogeneously well-educated adults.

The reason for the improvement in the updating function of the intervention group may be that during the coordinated exercise training process, the children were asked to do shuttle runs, forehand-backhand hits, and run around a mark, etc. These practices require children to update an action rapidly and frequently. For example, the children had to run from the right to left of the mark when running around it and this type of activity requires them to make quick adjustments and could be beneficial for the updating ability in the spatial WM.

The fNIRS results obtained herein showed that in comparison with the control group, the experimental group demonstrated a large hemoglobin concentration increase in the prefrontal cortex from the pre-test to post-test. In accordance with the present results, Yanagisawa et al. [45] observed oxy-Hb signal increases associated with the Stroop interference in the left dorsolateral prefrontal cortex (DLPFC) after a bout of moderate exercise. They postulated that the increased level of wakefulness caused by acute moderate exercise may be the reason for increased activation of the left DLPFC in cognitive performance. Suda et al. [46] also found that fatigue and sleepiness may lead to decreased LPFC activation, although such effects in WM have yet to be explored. Furthermore, Hyodo et al. [47] revealed that older participants with higher aerobic fitness exhibited a higher oxy-Hb signal amplitude in the dorsolateral PFC when performing a color-word Stroop task, which indicated that high aerobic fitness is associated with increased oxygen supply to the dorsolateral PFC.

Another possible reason for these results may partly be explained by the psychomotor efficiency theory. After exercises, the physiological system of the human body usually manifests itself in minimizing the amount of energy consumed to complete the maximum workload; that is, the effectiveness of the various systems of the body is improved. The oxy-Hb signal climbed in the prefrontal cortex indicated that the neural resources were more concentrated in the cognitive task after eight weeks of coordinative exercise training. Specifically, less attentional demand and less cognitive interference with motor planning and execution were needed when performing a task [48], which supports the view that coordinative exercises benefit the allocation of attention resources and stimulate the evaluation speed [49], as well as enhance the activation in the PFC [16].

Given that frontal brain electrical activity can predict working memory performance at age 4–12 years [50], it is possible that coordinative exercises may alter the prefrontal cortex, which in turn influences its function. In this study, since the physical fitness of the experimental group improved after the proposed exercise, coordinative exercises may affect the updating ability of the WM in young children via the improvement of physical fitness. Indeed, previous studies showed that aerobic fitness training increased hippocampal volume in elderly humans, which is correlated with better spatial memory performance [51,52]. Furthermore, Thomas et al. [53] suggested that the hippocampal volume is modulated by aerobic exercise throughout the lifespan. The mediating role of physical fitness can be tested by the structural equation model based on a large sample size in the future.

Another possible explanation for this relationship between the coordinative exercises and the updating function of WM might be that both these variables were involved in the cerebellum. Accumulative evidence has shown that the cerebellum plays an important role in WM. Baier et al. [54]

utilized an adapted Corsi-block task to investigate visual WM in patients with cerebellar ischemic stroke, and they suggested that the cerebellum controls the incoming visual WM information. Other studies [17,54] used a 3-back task to measure the WM of adults and found that the reaction speed in the task is linked to structural variation in both motor and cognitive subregions of the cerebellum. Much remains to be done in determining the role of the cerebellum in the relationship between the coordinative exercises and WM.

5. Limitations and Prospects

This study found that a coordinative exercise training program improved the prefrontal cortex function and the updating ability of the WM in young children. We believe this study has useful information for helping children and their parents choose extramural sports activities, and researchers in the field to design their future work. However, the limitations of the study should be recognized.

First, the sample size of the present study was limited. We calculated the sample size before intervention, but the uncontrollable factor was that some young children dropped out of the program during the long-term intervention. Although the effect size of most results was acceptable, these results must be interpreted with caution due to the small sample size, and the conclusions should be validated on larger data sets. Second, it is worth noting that only three channels were used herein. The number and positioning of the optodes may have limited the findings. Owen et al. [3] indicated that several cortical regions were activated robustly during the n-back task. This possibility needs to be investigated in the future. Third, a large variance in the hit rates of both groups in the pre-test may prevent group differences from being considered significant. This variance may be caused by the individual difference in young children's self-control ability and attention stability during the task [55]. This possibility could also be reflected in the long reaction times in young children. It should be testified by examining children who were slightly older in order to observe whether there were performance differences between the two groups in the hit rates a few years later when responses were more stable.

Additionally, this study focused on the visual WM of young children. The materials used in the 1-back task were squares. Future research should attempt to use vocal or auditory materials to explore the relationship between coordinative exercises and auditory WM. Finally, most previous studies were focused on the relationship between different types of exercises and the entirety of the WM in children. Future research is necessary to deliver some empirical evidence for aspects that are actually being affected.

Supplementary Materials: The following is available online at <http://www.mdpi.com/2076-3417/10/1/407/s1>, Table S1: Post hoc test results of repeated ANOVA of 2 (group: experimental group and control group) $\times$ 2 (test time: pre-test and post-test) for six indexes of the physical fitness.

Author Contributions: Y.L. analyzed behavioral experiment results and wrote the paper, and Z.W. carried out experiments. G.H.Y. reviewed and revised the paper, and C.J. designed the experiment and analyzed the fNIRS data. All authors have read and agreed to the published version of the manuscript.

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