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Article

An fNIRS Study of Applicability of the Unity-Diversity Model of Executive Functions in Preschoolers

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Abstract: This study examined the relationship among the three domains of executive function (EF; cognitive shifting, inhibitory control, and working memory) to test the applicability of the unity-diversity model in preschoolers using both behavioral and fNIRS approaches. Altogether 58 Chinese preschoolers (34 boys, 24 girls, M_{age} = 5.86 years, *SD* = 0.53, Age range = 4.83-6.67 years) were administered the *Dimensional Card Change Sort* (DCCS), go/no-go, and missing scan task. Their brain activations in the prefrontal cortex during the tasks were examined using fNIRS. First, the behavioral results indicated that the missing scan task scores (working memory) correlated with the DCCS (cognitive shifting) and go/no-go tasks (inhibitory control). But the latter two did not correlate with each other. Second, the fNIRS results demonstrated that the prefrontal activations during the working memory task correlated with those in the same regions during the cognitive shifting and inhibitory control tasks. Still, the latter two did not correlate. The behavioral and neuroimaging evidence jointly indicates that the unity-diversity model of EF does apply to Chinese preschoolers.

Keywords: executive function; early childhood; fNIRS; working memory; cognitive shifting; inhibitory control

1. Introduction

Executive function (EF) includes a set of higher-order abilities to control one's actions and thoughts consciously [1,2] and is related to the prefrontal cortex, a region important for top-down control [3]. Therefore, EF has a protracted developmental trajectory that parallels the maturation of the frontal lobes, which develop speedily over the preschool period and continues to mature throughout adolescence and adulthood [4,5]. Many models of EF have emerged over the past decades, and the most prominent one is proposed by Akira Miyake and his colleagues [6,7], which emphasizes the unity and diversity of those executive processes. According to this model, there are some common executive processes (the unity of EF) and some unique to the specific EF components, including cognitive shifting, inhibitory control, and working memory (the diversity of EF). However, a recent meta-analysis of the existing studies could only confirm that in school-aged children (6 years or up), there were partially separable but partially overlapping executive processes at a neural level [8]. This conclusion indicated that the unity and diversity model of EF could only apply to school-aged children, leaving those preschoolers (ages 4-6) unexplored. To fill this gap, this study explored the unity and diversity of EF in the preschool years using both behavioral and neuroimaging evidence.

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1.1. Behavioral Study of the Three Components of EF

It is widely believed that EF consists of three components: (1) *shifting* or cognitive shifting: the ability to switch flexibly between tasks or mental states; (2) *inhibition* or inhibitory control: the ability to deliberately override dominant or prepotent responses; and (3) *updating* or working memory: the ability monitor and add/delete working-memory contents [7]. Using confirmatory factor analysis, the existing studies have suggested some continuity in the three-factor EF from school children to adults [9–11]. But studies on preschoolers have suggested a unitary [10–13] or a two-factor structure with inhibition and working memory as separate but correlated factors [14–16]. Moreover, the exact factor structure seems to vary over age and task (quantity and content), demonstrating mixed results [17]. And a systematic review of the unity and diversity of executive functions supported the increasing multidimensionality of executive functions over the course of development. Still, the findings suggested that it might derive from methodological differences between child and adult studies, such as the number of indicators used per construct in measurement models [18].

Despite the mixed findings on preschoolers, it is generally suggested that key EF components emerge during the first three years of life, which include some simple skills (i.e., holding information in mind) and will be integrated into the complex processes (inhibitory control, working memory, and cognitive shifting). This development is hierarchical and characterizes the maturation of EF abilities [19]. Thus, given the rapid growth of EF during early childhood (ages 4-6), it is critical to confirm whether the unity and diversity of EF apply to preschoolers to clarify conceptual and methodological ambiguity, guide future research, and inform early intervention [20].

1.2. The Neural Correlates of Executive Function

Advances in behavioral and neuroimaging approaching have provided evidence that EF is located not only in the prefrontal cortex (PFC) but also in areas of the frontoparietal network, such as the dorsolateral prefrontal cortex (DLPFC), ventrolateral prefrontal cortex (VLPFC), and posterior parietal cortex (PPC), as well as subcortical regions [21–24]. Regarding the neural basis of the three EF factors, the existing studies have also identified the brain areas activated during the respective tasks. First, for preschoolers' cognitive shifting, longitudinal studies on the prefrontal cortex activation have revealed that prefrontal cortex activation plays a vital role in successful switching during the dimensional card change sort (DCCS) task [25]. Furthermore, a mindfulness training study revealed that behavioral changes during the DCCS task are related to changes in the DLPFC [26]. Nevertheless, fMRI studies during the DCCS tasks have shown that the functional network of cognitive shifting is still developing after the preschool period: the LPFC might be significantly more connected with the inferior parietal cortex and subcortical regions in adults than in children [27]. Second, for children's inhibitory control, an fNIRS study showed an age-independent effect in the right PFC and an age-dependent effect in the left orbitofrontal cortex (lOFC) [28]. In addition, a comparative study revealed that children and adults might have different patterns: children had stronger parietal coherence in short-range functional connectivity in the right frontal and right parietal cortices, but adults showed long-range functional connectivity between bilateral frontal and parietal areas [29]. Third, for children's working memory, neuroimaging studies have shown that activation in the lateral prefrontal cortex, right premotor areas, caudal superior frontal sulcus, and right inferior prefrontal gyrus were detected during visuospatial working memory tasks [30–32]. Furthermore, the existing fNIRS studies revealed that preschoolers' prefrontal and parietal regions were activated during working memory tasks [33,34].

1.3. The Unity-Diversity Framework of Executive Function

Miyake and Friedman (2012) have reviewed the existing studies to comprehend the nature of individual differences in EF and its cognitive and biological foundations. Based on the review, they developed a new theoretical framework: the unity-diversity

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framework. This framework proposes that individual differences in EF show both unity (as there are some common executive processes) and diversity (as there are some processes unique to the specific EF components, such as cognitive shifting, inhibitory control, and working memory). Furthermore, they believe this framework reflects substantial genetic contributions and demonstrates developmental stability.

The existing neuroimaging studies have supported this unity-diversity model in school-aged children and adults. For example, meta-analyses of fMRI data found both separable executive processes (i.e., diversity; Lenartowicz et al., 2010) and a common activation indicative of an overarching EF network (i.e., unity; Herd et al., 2014; Niendam et al., 2012). The existence of a superordinate cognitive control network involving dorsolateral prefrontal, anterior cingulate, and parietal cortices that supports a broad range of executive functions is confirmed in healthy individuals aged 18–60 using quantitative meta-analytic methods [37]. Neuroimaging studies in school-aged children have generally focused on the emergence and maturation of specific EF processes and examined separately but suggested distinguishable developmental trajectories as indicated by age-related activation changes [38–41]. A recent meta-analysis confirmed that the school-aged children (ages 6-12) had partially separable but partially overlapping executive processes at a neural level, indicating that the unity and diversity model of EF applies to children of this age [8], with significant bilateral activation in fronto-parietal areas and regions of the supplementary motor area across suggesting common executive components. However, no neuroimaging studies have ever explored the applicability of this model to preschoolers (ages 4-6), leaving a research gap to be addressed by this study.

1.4. The Present Study

Preschoolers may activate the lateral prefrontal regions during EF tasks that tap their cognitive shifting, inhibitory control, and working memory. According to the unity-diversity model (Miyake & Friedman, 2012), the three executive processes might be highly correlated at the neural level, even during preschool years. As there has been no neuroimaging evidence to support the applicability of this unity-diversity model in preschoolers, this study is dedicated to examining the unity and diversity of EF in young children using both behavioral and neuroimaging approaches. In particular, the Dimensional Change Card Sort (DCCS; Zelazo, 2006) task will be used to measure cognitive shifting, the Go/No-Go task [43] to measure inhibitory control, and the missing scan task [44] to measure working memory. Meanwhile, the concentration changes of oxygenated hemoglobin (HbO) and deoxygenated hemoglobin (HbR) in the dorsolateral and ventrolateral prefrontal activations will be assessed using fNIRS. Specifically, this study set to examine the following hypotheses:

Hypothesis 1: There would be significant correlations between the behavioral performances in the three EF tasks;

Hypothesis 2: There would be significant correlations between the prefrontal activations in the three EF tasks.

Hypothesis 3: There would be significant differences in the prefrontal activations between the three EF tasks.

2. Materials and Methods

2.1. Participants

Altogether 62 right-handed Chinese preschoolers participated in this study. These participants had no known developmental disorders. Four participants were excluded from formal analysis due to failure to finish the tasks, resulting in a final sample of 58 children. Among these children, 34 were boy and 24 were girl, M_{age} = 5.86 years, SD = 0.53, Age range = 4.83-6.67 years.

2.2. Behavioral task

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The participants were invited to perform the three tasks to measure their cognitive shifting, inhibitory control, and working memory, respectively: DCCS, go/no-go, and missing scan task. All the tasks were computerized using Psychophysics Toolbox extensions and displayed on a 55.35cm*31.13cm Dell monitor.

2.2.1. Dimensional Change Card Sort Task

The DCCS task was initially developed by [42] and modified by Xie et al. (2022) to accommodate the block design of fNIRS, which was suitable for children aged 3 to 6 years old [45]. It was employed to measure cognitive shifting in this study. Two target cards with two dimensions (i.e., a red rabbit and a blue boat) were used as stimuli and displayed in the upper center of the screen. One test card (i.e., a blue rabbit or a red boat) would appear on the lower center of the screen, which matched the test cards on one dimension but not in the other (color or shape). The participants would perform three consecutive test blocks, and each block consisted of a pre-switch (25s) and post-switch phase (25s). A line of instruction in grey would appear on the bottom of the screen to remind the experimenter of the beginning or end of the task. In the pre-switch phase, they were instructed to sort the cards according to one rule (e.g., color), and in the post-switch phase, they were asked to sort the cards according to the second rule (e.g., shape). The rule order for the three blocks was fixed and applied to all the participants to control for learning effects: (1) color → shape; (2) shape → color; and (3) color → shape. The participants would point to the target card, and the experimenter would press the key to record the answers.

The aggregate number of correct responses in all the blocks was calculated as a measure to index total performance. However, the experimenter recorded participants' responses, and response time could not accurately reflect children's performance. Thus, the accuracy rate was calculated by dividing the correct trials by the total trials and was used for subsequent analysis. The task paradigm of DCCS is shown in Figure 1.

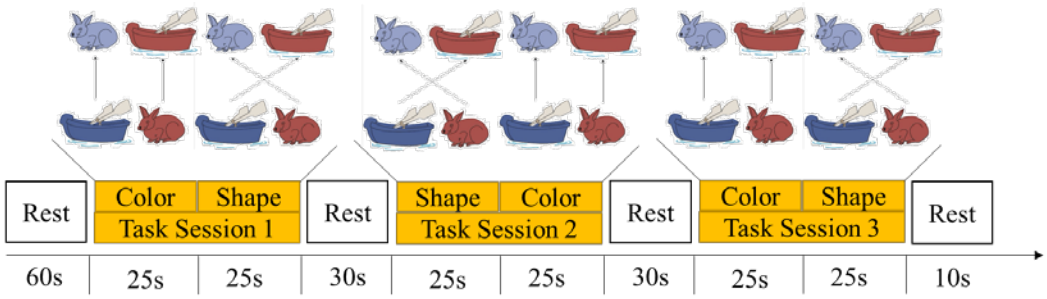

Figure 1. Task paradigm of DCCS Task.

2.2.2. Go/No-Go Task

The go/no-go task was modified from Lahat et al.'s (2010) paradigm to measure children's inhibitory control, which has good validity and well-mapped neural bases (Wiebe, Sheffield, & Es, 2012). In each trial, an animal stimulus (cow, horse, tiger, or dog) was presented at the center of the screen. The participants were instructed to press the "space" key on the keyboard as soon as they saw each animal (go stimuli) except for the dog (no-go stimulus). They were told not to press when they saw the dog. In the practice session, there were four go trials and four no-go trials in the training session, where children will be reminded of the rules should they respond incorrectly. The task consisted of 30 go trials and 30 no-go trials divided into three task blocks, with 10 go trials and 10 no-go trials randomly distributed within each block. The participants would perform three consecutive test blocks with rest phases in between. The accuracy rate by dividing the correct trials by the total trials was used for subsequent analysis. The task paradigm of go/no-go is shown in Figure 2.

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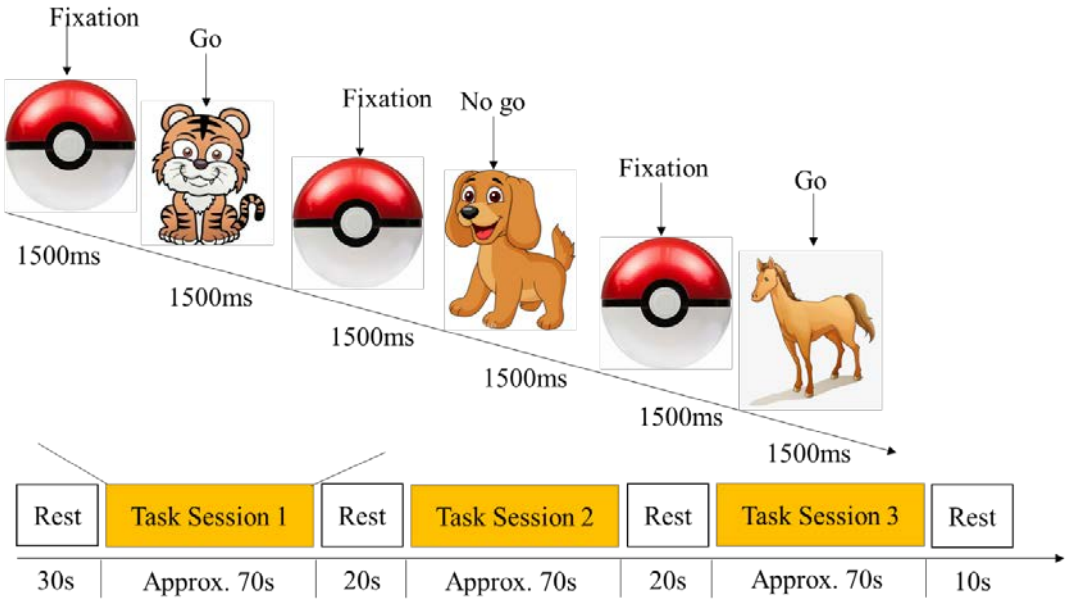

Figure 2. Task paradigm of Go/No-Go Task.

2.2.3. Missing Scan Task

The missing scan task was modified from Roman's task, which is suitable for measuring working memory capacity for preschoolers (ages 3- 6) [44]. It was adapted into a block to make it fit the fNIRS experiment paradigm in this study. A total of 30 animal figures were used as test stimuli, such as monkey, butterfly, duck, and pig. In each trial, four animals would appear on the screen for 10s, and the participants were instructed to name pictures of each animal to prevent the need to learn new vocabulary. Then, the four animals would disappear into a "house" for 3s. After that, three animals would re-appear on the screen, and the participants were instructed to verbally respond to the name of the missing animal in 6s before the next set of animals appeared on the screen. The experimenter would record the participants' responses using the keyboard. There were two trials in the practice session to ensure the participants understood the test rules, and there were five trials in each one of the test blocks. The participants would perform three consecutive test blocks with rest phases in between. The task paradigm of the missing scan is shown in Figure 3 (Figure 3).

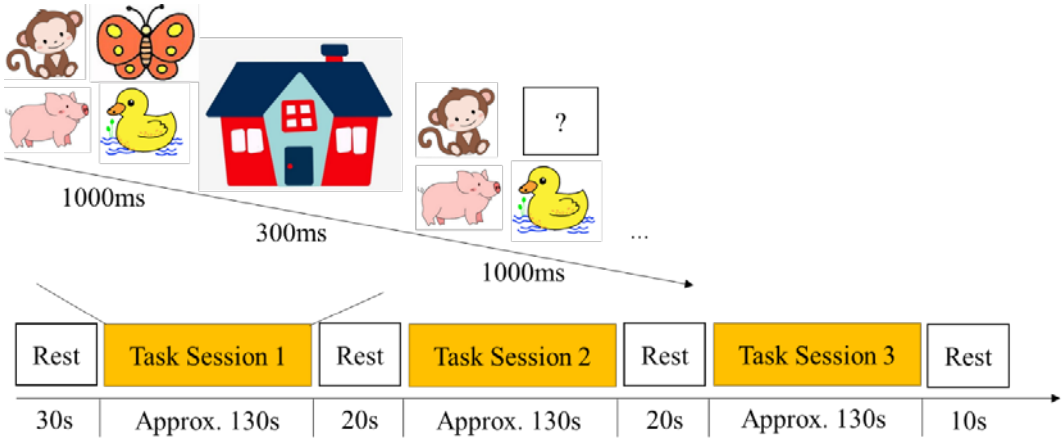

Figure 3. Task paradigm of Missing Scan Task.

2.3. Functional Near-Infrared Spectroscopy Recordings

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A multichannel fNIRS system (Oxymon MK III, Artinis, The Netherlands) was used to measure the concentration changes of oxygenated hemoglobin (HbO) and deoxygenated hemoglobin (HbR) at wavelengths of 762 and 846 nm in the participants. Following the study design of previous studies on young children's EF [47,48], the fNIRS probe consisted of 30 optodes using a 3*10 light level stencil located in the forehead, which constituted 44 channels to cover the frontal area. Each channel consisted of one emitter and one detector optode, with a 2.5 cm distance. To ensure consistent light-level array positions for all participants, the lower middle of the array was positioned at the Fpz position, which is consistent with the 10-20 measurement system. Accordingly, the region of interest (ROI) was the left ventrolateral prefrontal cortex (VLPFC), right VLPFC, left dorsolateral prefrontal cortex (DLPFC), right DLPFC, left posterior superior frontal cortex (PSFC), right PSFC, left temporal cortex (TC), right TC, and medial prefrontal cortex (MPFC) (see Figure 4). Previous studies have shown that the frontal area was actively involved in EF [26,49]. The sampling rate was set at 50Hz for data acquisition. A differential path-length factor (DPF) value was calculated for each participant according to the formula (DPF = $4.99 + 0.0678*Age^{0.814}$) based on their age [50].

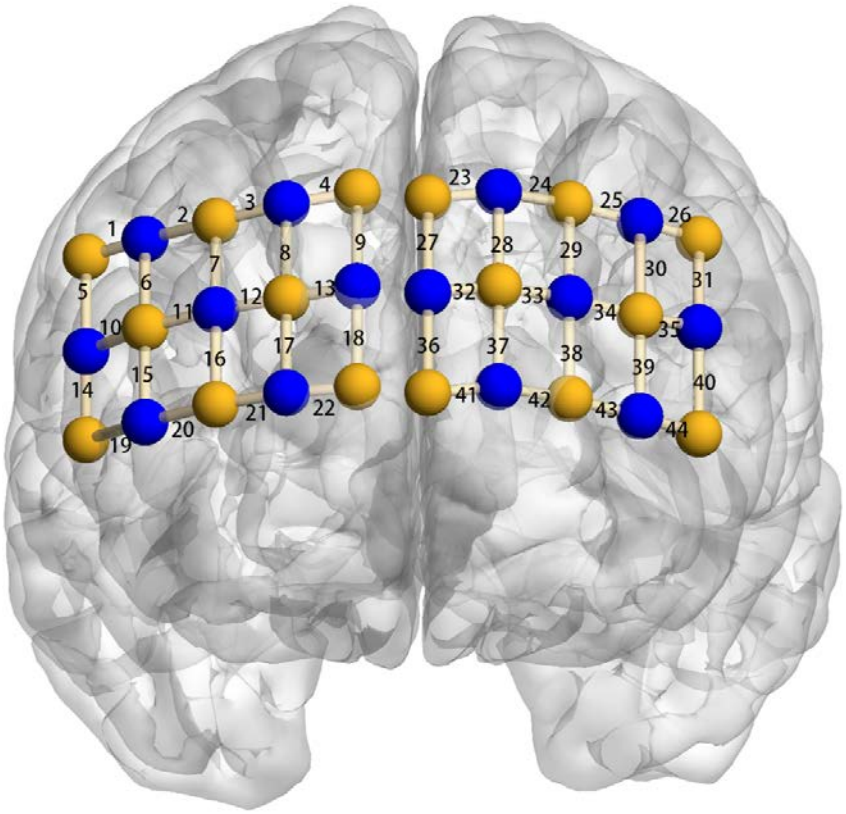

Figure 4. Localization of Regions of Interest. *Note.* Ventrolateral prefrontal cortex (VLPFC): channel 16, 17, 21, 22, 38, 41, 42, 43; dorsolateral prefrontal cortex (DLPFC): channel 3, 4, 7, 8, 9, 12, 13, 24, 25, 28, 29, 30, 33, 34; posterior superior frontal cortex (PSFC): channel 1, 2, 5, 6, 26, 31; left temporal cortex (TC): channel 10, 11, 14, 15, 19, 20, 35, 40, 44; medial prefrontal cortex (MPFC): channel 18, 23, 27, 32, 36, 37, 41.

2.4. Procedure

The study was conducted in accordance with the principles of the Declaration of Helsinki and approved by the University Ethics Committee of the first author. All the parents of the participating children provided written consent and were informed verbally of the research purpose and the safety of the fNIRS experiment. Each child was invited into a quiet room in the preschool to receive the EF tasks. An experienced NIRS technician

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placed the NIRS cap on the child while an experienced preschool teacher engaged in book-reading with the child.

2.5. Analytic Plan

First, participants' behavioral results were exported and analyzed in Matlab. Then, descriptive and correlational analyses were conducted to examine the relationship across the three tasks to examine Hypothesis 1.

Next, the fNIRS data were prepossessed. Due to higher sensitivity to changes in cerebral blood flow [51,52], higher signal-to-noise ratio [51], and retest reliability [53], we focused on the blood oxygen concentration (HbO). The HbO data were first visually inspected to assess the quality of the data. The channels with high-frequency signal interference caused by bad optical coupling between the optode and the scalp, as well as head movements, were removed before formal analysis [54]. Next, the NIRS-KIT software [55] was used to perform first-order baseline correction on the HbO. Accordingly, the DTTR algorithm was used to remove motion artifacts [56]. Slow drifts and high-frequency noises were reduced using the bandpass filter (third-order Butterworth filter) with cut-off frequencies of 0.01-0.09 Hz [57]. After that, the difference in the average changes in HbO during the corresponding rest and task phases in each task was used as the dependent variable in the following analyses. To increase the signal-to-noise ratio, the 44 channels were averaged into nine ROIs, where the time-series data were averaged within each ROI. Finally, the correlations of activations between the differences in average changes in HbO across tasks were assessed.

Finally, whether the activations in the ROIs differed across tasks was examined to examine Hypotheses 2 and 3. The difference in the average changes in HbO during the corresponding rest and task phases in each task was used as the dependent variable in this analysis. A 3x9 ANOVA was conducted with the three tasks and nine regions for HbO.

3. Results

3.1. Behavioral Results

The results of descriptive analysis and correlation analysis are shown in Table 1. The participant's performance in the missing scan task was correlated with their performance in DCCS (r = .26, p < .05) and go/no-go task (r = .53, p < .001). But the DCCS was not significantly correlated with the go/no-go task (r = .13, p > .05). Then, partial correlational analyses were conducted after controlling for children's age, and the performance in the missing scan correlated with the go/no-go task (r = .42, p < .01). Therefore, Hypothesis 1 is not supported by this study.

Table 1. Mean (*SD*) of Accuracy in Each Task and their Correlations.

Task	M (SD)	1	2	3
1. DCCS	0.97(0.00)	-		
2. Go/No-Go	0.93(0.01)	0.13	-	
3. Missing Scan	0.62(0.05)	0.26*	0.53***	-

Note. * p < .05, *** p < .001.

3.2. The fNIRS Results

Results for the changes in HbO are depicted in Table 2. Next, correlations of the prefrontal activations in the nine ROIs across the three tasks were examined. The correlations between the DCCS and go/no-go tasks are depicted in Table 1. Results showed that for the tasks DCCS and go/no-go, there were no significant correlations in the same region (ps > .05), but there were significant correlations in the left VLPFC during DCCS and left DLPFC during go/no-go task (r(58) = -.30, p < .05), the left VLPFC during DCCS and left TC during

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go/no-go task (r(58) = -.28, p < .05), the left PSFC during DCCS and MFPC during go/no-go task (r(58) = .29, p < .05), and the leftTC during DCCS and MFPC during go/no-go task (r(58) = .30, p < .05). Results showed that for the tasks DCCS and missing scan, there were significant correlations in the same region of left VLPFC (r(58) = .28, p < .05) and right DLPFC (r(58) = .38, p < .001), as well as significant correlations in the left VLPFC during DCCS and right VLPFC during missing scan task (r(58) = .37, p < .05), the left VLPFC during DCCS and right DLPFC during missing scan task (r(58) = .32, p < .05), the right PSFC during DCCS and right DLPFC during missing scan task (r(58) = -.29, p < .05), and the right TC during DCCS and left DLPFC during missing scan task (r(58) = .29, p < .05). The results showed that there were significant correlations in the same region of left DLPFC (r(58) = .28, p < .05), as well as significant correlations in the left PSFC during go/no-go and right TC during missing scan task (r(58) = -.48, p < .01), the right PSFC during go/no-go and left PSFC during missing scan task (r(58) = 038, p < .05), the right PSFC during go/no-go and left TC during missing scan task (r(58) =.29, p < .05), and the MFPC during go/no-go and left PSFC during missing scan task (r(58) = .36, p < .05). Detailed results for the correlation statistics are shown in Appendix Tables A1-A3. Therefore, Hypothesis 2 is not supported by this study.

Table 2. Mean (*SD*) of Changes in HbO during The Task Phases after Subtracting Rest Phases.

ROI	DCCS	Go/No-Go	Missing Scan
left VLPFC	-0.02 (0.08)	-0.01 (0.04)	0.01 (0.06)
right VLPFC	0.01 (0.13)	0.03 (0.07)	-0.00 (0.01)
left DLPFC	0.00 (0.11)	-0.00 (015)	0.01 (0.03)
right DLPFC	-0.00 (0.12)	-0.06 (0.04)	0.03 (0.07)
left PSFC	-0.08 (0.18)	-0.03 (0.07)	0.06 (0.04)
right PSFC	-0.09 (0.13)	-0.07 (0.05)	-0.01 (0.05)
right TC	-0.05 (0.12)	-0.14 (0.05)	0.03 (0.03)
left TC	-0.03 (0.17)	-0.01 (0.01)	0.00 (0.04)
MFPC	-0.02 (0.13)	-0.01 (0.04)	0.02 (0.02)

Note. VLPFC = ventrolateral prefrontal cortex (VLPFC); DLPFC = dorsolateral prefrontal cortex (DLPFC); PSFC = posterior superior frontal cortex (PSFC); TC = temporal cortex (TC); MPFC = medial prefrontal cortex (MPFC).

Finally, the prefrontal activations across tasks were compared. Two-way ANOVA analyses on HbO data revealed a significant main effect of the task (F (2, 89) = 7.6, p = .001). Post-hoc analyses using the Bonferroni method revealed that the participants showed strong activation during the missing scan task compared to the DCCS task (p < .01). Prefrontal activation did not differ between the go/no-go and other tasks (ps > .05). No significant effect of regions (F (8, 89) = 1.88, p = .08) nor a significant interaction between task and regions (F (16, 89) = 1.6, p = .08) were found. Therefore, Hypothesis 3 is supported by this study.

4. Discussion

This is the first study to examine the applicability of the unity-diversity model of EF in Chinese preschoolers, using both behavioral and neuroimaging approaches. It provides behavioral evidence to support the correlation between working memory, cognitive shifting, and inhibitory control. And the fNIRS evidence proves that the prefrontal activations for working memory tasks correlate with those for cognitive shifting and inhibitory control. However, both behavioral and neuroimaging results do not demonstrate a significant correlation between cognitive shifting and inhibitory control. This section will discuss these findings and the limitations of this study.

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4.1. Working Memory as the Common Executive Process of EF

The results showed that the working memory task was correlated with the cognitive shifting and inhibitory control tasks behaviorally. Still, performance on the latter two tasks did not correlate. This finding indicated that working memory might serve as a "foundation" for successful performance in cognitive shifting and inhibitory control tasks, which require the children to maintain and manipulate the rules in mind. First, for the cognitive shifting task, even though memory demands were minimized by the experimenter reminding the participants of the current sorting criterion on each trial [58], they almost succeeded in the switching task (mean correct rate of 97%), it seems that cognitive shifting required working memory in addition to the ability to shift. This finding provides empirical evidence to support Garon's hypothesis [19,59].

Second, for the correlation between inhibition and working memory task, this finding provides empirical evidence to settle down the arguments about whether inhibition is separate from working memory (e.g., Davidson et al., 2006; Zanto et al., 2011), whether inhibition is a behavioral product of exercising working memory (e.g., Munakata et al., 2011), or that working memory and inhibition depend on the same limited-capacity system so that increasing the demand on either affects one's ability to do the other (e.g., Engle & Kane, 2004; Wais & Gazzaley, 2011). However, as they are significantly correlated, it is hard to cut the linkage between working memory and inhibitory control. Instead, improved working memory is associated with increased inhibition. This implies that working memory plays an important role in the whole EF process, and in other words, it might serve as the common executive process shared by all EF tasks. The following section will elaborate more on this.

4.2. Applicability of The Unity-Diversity Model

First, the fNIRS results were similar to the behavioral results in this study: there was a medium correlation in the prefrontal activation between the working memory and cognitive shifting task and between the working memory and inhibitory control task. This finding corroborates the meta-analysis using activation-likelihood estimation, which found the existence of partially separable but partially overlapping processes in children over 6 years [8]. The current study has further extended this finding by demonstrating that there are both unity (working memory as the common executive process) and diversity (shifting does not correlate with inhibition) of EF in Chinese preschoolers (ages 4-6). Furthermore, there is growing evidence from neuroimaging studies suggesting a core network responsible for maintaining task sets, such as holding-in-mind, which seems to emerge early in life and is the prototype of working memory [65]. Therefore, the behavioral and neuroimaging evidence jointly proved the unity part of the unity-diversity model in preschoolers.

Second, this study also assessed whether the prefrontal activations differed across the shifting, inhibition, and updating tasks. The fNIRS results showed that preschoolers showed strong activation during the working memory task compared to the cognitive shifting task, indicating that the lateral prefrontal regions may be involved differently in the shifting and working memory tasks. Still, the relative recruitment of those brain regions may differ across different executive tasks [49]. Furthermore, such difference might also stem from different levels of cognitive challenge stemming from the two tasks, with almost all the participants performing successfully in the shifting task (mean correct rate 97%) but only more than half performing well in the updating task (mean correct rate 62%). Future studies shall design different behavioral tasks to examine the neural correlates during these three executive processes. In addition, a non-significant relationship was found between cognitive shifting and inhibitory control, indicating that the two factors might be dissociable in the preschool years. This finding is generally consistent with a recent behavioral study, which found that the one-factor model was not statistically better (though an adequate model fit) than the two-factor model consisting of two distinguishable factors [20]. Thus, although the present study did not use confirmatory factor

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analysis because of the limited number of EF tasks, the results are similar to the previous evidence. Therefore, these findings jointly proved the diversity part of the unity-diversity model of EF.

5. Conclusions

This study has examined the relationship among the three domains (cognitive shifting, inhibitory control, and working memory) of EF to test the applicability of the unity-diversity model in preschoolers, using both behavioral and neural approaches. The behavioral results indicated that working memory correlated with cognitive shifting and inhibitory control, but the latter two did not correlate with each other. And the fNIRS results demonstrated that the prefrontal activations during the working memory task correlated with those during the cognitive shifting and inhibitory control. Still, the latter two tasks did not correlate with each other. These findings jointly indicated that there were both unity (working memory as the common process) and diversity (shifting and inhibitory are separate) in preschoolers' EF, supporting the unity-diversity model of EF proposed by Miyake and Friedman [6].

However, this study has some noticeable limitations. First, due to the limited time that preschoolers could participate in this fNIRS study, there was only one task for each of the EF processes, which might not comprehensively measure the target variables. Furthermore, the three tasks were performed in a fixed order, which might affect the performance of the participants should they be randomized. Second, this study assessed only the lateral prefrontal regions with fNIRS. Other regions, such as the parietal regions, may also contribute to the executive process in a different manner. Future studies should include more regions if the fNIRS instrument has more channels (i.e., 32 X 32). Finally, the number of participants of different age are small, not enough to detect the age effect or pattern of executive function. Despite the limitations, this study contributes to the debate on the unity and diversity of the three constructs of executive function at both behavioral and neural levels in young children.

Supplementary Materials: The following supporting information can be downloaded at: www.mdpi.com/xxx/s1, Table A1: Comparison of HbO Activations in Different Regions between DCCS and Go/No-Go Task; Table A2: Comparison of HbO Activations in Different Regions between DCCS and Missing Scan Task; Table A3: Comparison of HbO Activations in Different Regions between Go/No-Go and Missing Scan Task.

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Appendix A

Table A1. Comparison of HbO Activations in Different Regions between DCCS and Go/No-Go Task.

ROI (DCCS)	ROI (Go/No-Go)	r	p
left VLPFC	left VLPFC	0.01	0.96
left VLPFC	right VLPFC	-0.16	0.24
left VLPFC	left DLPFC	**-0.30**	**0.02**
left VLPFC	right DLPFC	0.04	0.78
left VLPFC	left PSFC	0.07	0.63
left VLPFC	right PSFC	0.21	0.14
left VLPFC	right TC	-0.22	0.11
left VLPFC	left TC	0.05	0.70
left VLPFC	MFPC	-0.06	0.67
right VLPFC	left VLPFC	-0.14	0.31
right VLPFC	right VLPFC	-0.13	0.35
right VLPFC	left DLPFC	-0.09	0.51
right VLPFC	right DLPFC	-0.15	0.28
right VLPFC	left PSFC	-0.15	0.33
right VLPFC	right PSFC	0.04	0.77
right VLPFC	right TC	-0.03	0.84
right VLPFC	left TC	-0.19	0.16
right VLPFC	MFPC	-0.08	0.53
left DLPFC	left VLPFC	-0.01	0.92
left DLPFC	right VLPFC	**-0.34**	**0.01**
left DLPFC	left DLPFC	-0.02	0.91
left DLPFC	right DLPFC	-0.16	0.24
left DLPFC	left PSFC	-0.18	0.22
left DLPFC	right PSFC	0.01	0.93
left DLPFC	right TC	-0.13	0.34
left DLPFC	left TC	**-0.28**	**0.04**
left DLPFC	MFPC	-0.19	0.15
right DLPFC	left VLPFC	0.10	0.49
right DLPFC	right VLPFC	-0.06	0.65
right DLPFC	left DLPFC	-0.18	0.19
right DLPFC	right DLPFC	-0.06	0.64
right DLPFC	left PSFC	0.07	0.66
right DLPFC	right PSFC	0.16	0.29
right DLPFC	right TC	-0.20	0.15
right DLPFC	left TC	-0.12	0.38
right DLPFC	MFPC	-0.03	0.81
left PSFC	left VLPFC	0.18	0.24
left PSFC	right VLPFC	0.11	0.49
left PSFC	left DLPFC	0.05	0.75

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left PSFC	right DLPFC	0.02	0.90
left PSFC	left PSFC	0.23	0.13
left PSFC	right PSFC	0.12	0.43
left PSFC	right TC	-0.01	0.97
left PSFC	left TC	0.11	0.45
left PSFC	MFPC	0.29	0.05
right PSFC	left VLPFC	0.05	0.75
right PSFC	right VLPFC	0.08	0.59
right PSFC	left DLPFC	-0.26	0.06
right PSFC	right DLPFC	-0.10	0.52
right PSFC	left PSFC	-0.24	0.12
right PSFC	right PSFC	0.24	0.10
right PSFC	right TC	-0.09	0.52
right PSFC	left TC	-0.06	0.67
right PSFC	MFPC	0.03	0.84
right TC	left VLPFC	0.08	0.57
right TC	right VLPFC	0.05	0.73
right TC	left DLPFC	-0.05	0.70
right TC	right DLPFC	0.02	0.87
right TC	left PSFC	-0.24	0.11
right TC	right PSFC	-0.13	0.37
right TC	right TC	-0.07	0.58
right TC	left TC	0.12	0.38
right TC	MFPC	0.04	0.77
left TC	left VLPFC	0.11	0.43
left TC	right VLPFC	0.12	0.38
left TC	left DLPFC	0.24	0.07
left TC	right DLPFC	-0.09	0.49
left TC	left PSFC	0.07	0.67
left TC	right PSFC	0.23	0.11
left TC	right TC	0.09	0.52
left TC	left TC	0.19	0.16
left TC	MFPC	**0.30**	**0.02**
MFPC	left VLPFC	-0.01	0.92
MFPC	right VLPFC	-0.14	0.28
MFPC	left DLPFC	-0.20	0.14
MFPC	right DLPFC	-0.02	0.88
MFPC	left PSFC	-0.15	0.33
MFPC	right PSFC	0.06	0.67
MFPC	right TC	-0.25	0.06
MFPC	left TC	-0.17	0.20
MFPC	MFPC	-0.11	0.43

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Note. Bold indicates significant results. VLPFC = ventrolateral prefrontal cortex (VLPFC); DLPFC = dorsolateral prefrontal cortex (DLPFC); PSFC = posterior superior frontal cortex (PSFC); TC = temporal cortex (TC); MPFC = medial prefrontal cortex (MPFC).

Table A2. Comparison of HbO Activations in Different Regions between DCCS and Missing Scan Task.

ROI (DCCS)	ROI (Missing Scan)	r	p
left VLPFC	left VLPFC	**0.28**	**0.03**
left VLPFC	right VLPFC	**0.37**	**0.01**
left VLPFC	left DLPFC	0.05	0.70
left VLPFC	right DLPFC	**0.32**	**0.02**
left VLPFC	left PSFC	0.18	0.23
left VLPFC	right PSFC	0.19	0.19
left VLPFC	right TC	-0.21	0.11
left VLPFC	left TC	0.12	0.39
left VLPFC	MFPC	0.13	0.33
right VLPFC	left VLPFC	-0.09	0.53
right VLPFC	right VLPFC	0.13	0.34
right VLPFC	left DLPFC	-0.11	0.41
right VLPFC	right DLPFC	0.24	0.07
right VLPFC	left PSFC	0.01	0.95
right VLPFC	right PSFC	0.06	0.70
right VLPFC	right TC	0.09	0.50
right VLPFC	left TC	0.20	0.13
right VLPFC	MFPC	0.09	0.49
left DLPFC	left VLPFC	0.07	0.59
left DLPFC	right VLPFC	0.20	0.14
left DLPFC	left DLPFC	0.12	0.38
left DLPFC	right DLPFC	0.21	0.14
left DLPFC	left PSFC	0.16	0.28
left DLPFC	right PSFC	0.12	0.40
left DLPFC	right TC	0.01	0.97
left DLPFC	left TC	0.14	0.30
left DLPFC	MFPC	-0.15	0.28
right DLPFC	left VLPFC	0.07	0.60
right DLPFC	right VLPFC	0.20	0.14
right DLPFC	left DLPFC	-0.23	0.09
right DLPFC	right DLPFC	**0.38**	**0.00**
right DLPFC	left PSFC	0.18	0.24
right DLPFC	right PSFC	0.25	0.09
right DLPFC	right TC	-0.02	0.86
right DLPFC	left TC	0.16	0.23
right DLPFC	MFPC	0.13	0.33
left PSFC	left VLPFC	-0.03	0.82

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left PSFC	right VLPFC	-0.13	0.38
left PSFC	left DLPFC	0.21	0.16
left PSFC	right DLPFC	0.11	0.48
left PSFC	left PSFC	0.29	0.05
left PSFC	right PSFC	-0.17	0.27
left PSFC	right TC	-0.20	0.19
left PSFC	left TC	0.17	0.27
left PSFC	MFPC	-0.01	0.96
right PSFC	left VLPFC	-0.15	0.29
right PSFC	right VLPFC	-0.10	0.50
right PSFC	left DLPFC	-0.11	0.46
right PSFC	right DLPFC	**-0.29**	**0.05**
right PSFC	left PSFC	0.16	0.31
right PSFC	right PSFC	0.08	0.56
right PSFC	right TC	0.17	0.25
right PSFC	left TC	0.24	0.09
right PSFC	MFPC	0.11	0.45
right TC	left VLPFC	0.09	0.49
right TC	right VLPFC	0.03	0.81
right TC	left DLPFC	**0.29**	**0.03**
right TC	right DLPFC	-0.11	0.44
right TC	left PSFC	-0.02	0.92
right TC	right PSFC	0.02	0.91
right TC	right TC	0.12	0.36
right TC	left TC	0.13	0.32
right TC	MFPC	0.04	0.75
left TC	left VLPFC	0.08	0.58
left TC	right VLPFC	0.03	0.81
left TC	left DLPFC	0.00	0.97
left TC	right DLPFC	0.04	0.77
left TC	left PSFC	0.24	0.11
left TC	right PSFC	-0.12	0.42
left TC	right TC	-0.16	0.22
left TC	left TC	0.24	0.07
left TC	MFPC	0.25	0.06
MFPC	left VLPFC	-0.05	0.70
MFPC	right VLPFC	-0.01	0.95
MFPC	left DLPFC	-0.13	0.33
MFPC	right DLPFC	0.15	0.26
MFPC	left PSFC	0.10	0.53
MFPC	right PSFC	-0.01	0.96
MFPC	right TC	0.03	0.80
MFPC	left TC	0.09	0.51

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MFPC	MFPC	0.03	0.82

Note. Bold indicates significant results. VLPFC = ventrolateral prefrontal cortex (VLPFC); DLPFC = dorsolateral prefrontal cortex (DLPFC); PSFC = posterior superior frontal cortex (PSFC); TC = temporal cortex (TC); MPFC = medial prefrontal cortex (MPFC).

Table A3. Comparison of HbO Activations in Different Regions between Go/No-Go and Missing Scan Task.

ROI (Go/No-Go)	ROI (Missing Scan)	r	p
left VLPFC	left VLPFC	0.08	0.56
left VLPFC	right VLPFC	0.09	0.52
left VLPFC	left DLPFC	0.05	0.73
left VLPFC	right DLPFC	0.14	0.32
left VLPFC	left PSFC	0.26	0.08
left VLPFC	right PSFC	-0.09	0.53
left VLPFC	right TC	0.04	0.75
left VLPFC	left TC	0.07	0.62
left VLPFC	MFPC	0.09	0.52
right VLPFC	left VLPFC	-0.15	0.28
right VLPFC	right VLPFC	0.14	0.29
right VLPFC	left DLPFC	-0.04	0.79
right VLPFC	right DLPFC	-0.17	0.21
right VLPFC	left PSFC	0.28	0.07
right VLPFC	right PSFC	-0.09	0.56
right VLPFC	right TC	0.11	0.41
right VLPFC	left TC	0.16	0.23
right VLPFC	MFPC	0.25	0.07
left DLPFC	left VLPFC	0.00	0.99
left DLPFC	right VLPFC	-0.24	0.08
left DLPFC	left DLPFC	**0.33**	**0.01**
left DLPFC	right DLPFC	-0.06	0.69
left DLPFC	left PSFC	0.06	0.68
left DLPFC	right PSFC	0.10	0.47
left DLPFC	right TC	-0.01	0.96
left DLPFC	left TC	0.10	0.45
left DLPFC	MFPC	-0.17	0.21
right DLPFC	left VLPFC	-0.18	0.18
right DLPFC	right VLPFC	0.07	0.60
right DLPFC	left DLPFC	-0.07	0.63
right DLPFC	right DLPFC	0.05	0.69
right DLPFC	left PSFC	-0.03	0.87
right DLPFC	right PSFC	-0.26	0.07
right DLPFC	right TC	-0.07	0.61
right DLPFC	left TC	-0.11	0.42

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right DLPFC	MFPC	0.01	0.96
left PSFC	left VLPFC	0.03	0.87
left PSFC	right VLPFC	-0.10	0.50
left PSFC	left DLPFC	0.08	0.58
left PSFC	right DLPFC	0.07	0.65
left PSFC	left PSFC	-0.20	0.19
left PSFC	right PSFC	-0.05	0.77
left PSFC	right TC	**-0.48**	**0.00**
left PSFC	left TC	-0.20	0.19
left PSFC	MFPC	-0.15	0.31
right PSFC	left VLPFC	0.00	0.97
right PSFC	right VLPFC	0.04	0.78
right PSFC	left DLPFC	-0.06	0.66
right PSFC	right DLPFC	-0.07	0.64
right PSFC	left PSFC	**0.38**	**0.01**
right PSFC	right PSFC	0.02	0.89
right PSFC	right TC	0.05	0.72
right PSFC	left TC	**0.29**	**0.04**
right PSFC	MFPC	0.00	1.00
right TC	left VLPFC	-0.17	0.20
right TC	right VLPFC	0.09	0.52
right TC	left DLPFC	-0.10	0.45
right TC	right DLPFC	0.01	0.93
right TC	left PSFC	-0.16	0.29
right TC	right PSFC	-0.20	0.15
right TC	right TC	0.07	0.60
right TC	left TC	-0.15	0.25
right TC	MFPC	-0.07	0.62
left TC	left VLPFC	-0.00	0.99
left TC	right VLPFC	-0.01	0.96
left TC	left DLPFC	-0.01	0.93
left TC	right DLPFC	-0.06	0.64
left TC	left PSFC	0.15	0.30
left TC	right PSFC	-0.05	0.71
left TC	right TC	-0.23	0.08
left TC	left TC	0.13	0.31
left TC	MFPC	0.22	0.10
MFPC	left VLPFC	-0.16	0.23
MFPC	right VLPFC	0.00	1.00
MFPC	left DLPFC	-0.04	0.76
MFPC	right DLPFC	0.01	0.94
MFPC	left PSFC	**0.36**	**0.01**
MFPC	right PSFC	-0.20	0.17

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MFPC	right TC	0.11	0.40
MFPC	left TC	0.16	0.24
MFPC	MFPC	0.23	0.09

Note. Bold indicates significant results. VLPFC = ventrolateral prefrontal cortex (VLPFC); DLPFC = dorsolateral prefrontal cortex (DLPFC); PSFC = posterior superior frontal cortex (PSFC); TC = temporal cortex (TC); MPFC = medial prefrontal cortex (MPFC).

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