Academic Achievements in Children with ADHD in China: The Mediating Role of Executive Functions

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Abstract

Background: Attention-deficit/hyperactivity disorder (ADHD) is often accompanied by lower academic achievements related to executive dysfunction, but the correlations remain unclear. The current study aimed to elucidate to what extent executive functions affect academic achievements in pediatric ADHD.

Results: The results showed that mathematical achievements, reading comprehension achievements, subtraction and word semantics were all correlated with digit span and conversion. Reading comprehension achievements also had relationships with spatial span. In addition, reading comprehension achievements, subtraction and word semantics had negative relationships with the colour interference time and the semantic interference time. Furthermore, central executive function played significant mediating effects on mathematical achievements ($d_{\text{indirect effect}} = -0.04$, $P < 0.05$), subtraction ($d_{\text{indirect effect}} = -0.06$, $P = 0.01$) and word semantics ($d_{\text{indirect effect}} = -0.06$, $P < 0.05$). Inhibition played significant mediating effects on subtraction ($d_{\text{indirect effect}} = -0.03$, $P < 0.05$) and word semantics ($d_{\text{indirect effect}} = -0.06$, $P = 0.01$). Conversion had a significant mediating effect on word semantics ($d_{\text{indirect effect}} = -0.02$, $P = 0.01$).

Conclusions: The findings suggested that central executive function, inhibition and conversion may have more important mediating effects on academic achievements of children with ADHD than other components of executive functions. Targeted executive function training should be used to effectively improve the targeted academic achievements of children with ADHD.

1. Introduction

Attention-deficit/hyperactivity disorder (ADHD) is a childhood-onset neurodevelopmental disorder characterized by persistently inappropriate and impairing inattention, excessive activities and impulsiveness regardless of occasion that interferes with academic, occupational and social function[1–2]. Children with ADHD often have a higher incidence of failing grades and grade retention, often accompanied by lower academic scores[1]. Low academic achievement is often one of the important reasons for children with ADHD to visit clinical institutions[3]. Academic impairment is closely related to other social functions and often continues into adulthood, causing sustained impairment and reducing quality of life[2, 4]. Children with ADHD have been shown to exhibit lower mathematical and reading achievements[5–9]. More seriously, the prevalence of ADHD co-morbid with learning disorder (LD) ranges from 31%~45%, and the proportions of comorbidities with mathematical disabilities and reading disorders are 5%~30% and 15%~40%, respectively[10–11]. In addition, these problems cause great suffering and burden to the family and society, especially because of increases in related educational expenditure[12].

Barkley found that executive dysfunction was the central cognitive deficit in ADHD[13]. Extensive subsequent study has also suggested that executive dysfunction was an important endophenotype of ADHD[14]. To date, executive function (EF) is still an umbrella term that refers to a series of neurocognitive processes that supervise and control an individual's consciousness and behaviour to solve problems in an appropriate way to achieve a certain goal[15]. Generally, EFs include working memory, inhibitory function, shifting, planning and other cognitive functions[16]. Furthermore, working memory includes four sub-components: phonological loop, visuospatial sketchpad, central executive and episodic buffer[17–18]. The central executive system has been considered to be the most complex and important sub-component and can be divided into four distinct EFs: memory updating, inhibition, switching, and dual-task coordination[19–21]. Nigg et al. suggested that different sub-components of EF may have different effects on ADHD, and they pointed out that visual spatial working memory had the highest effect size ($d = 0.75 \sim 1.14$), followed by inhibition ($d = 0.61 \sim 0.94$), conversion ($d = 0.55 \sim 0.75$), and phonological working memory ($d = 0.4 \sim 0.5$)[22].

Furthermore, some reviews have systematically investigated the relationships between academic achievements and EFs in normal children. Regarding reading and EFs, Savage et al. found that working memory was more important than decoding, which was one of the relevant foundational reading skills for reading comprehension[23]. Subsequently, Peng et al. conducted a meta-analysis and found that the central executive of working memory was implicated in reading acquisition before 4th grade, and phonological working memory was more strongly related to later reading performance as readers gained additional experience beyond 4th grade[24]. Johann et al. studied 186 primary students and found that working memory and inhibition were related to reading speed and that cognitive flexibility was related to reading comprehension[25]. Similar results were found with

mathematics and EFs. Bull et al. found that low levels of working memory, switching and inhibition were related to mathematics[26]. Wei et al. found that spatial abilities (including spatial working memory) may play an important role in advanced mathematics for undergraduate college students[27].

Because of the executive dysfunction in ADHD and the possible relationships between academic achievements and EF, numerous studies have attempted to demonstrate that EF is closely associated with academic achievements in ADHD. Previous studies have indicated that EFs may play an important role in ADHD-related academic achievements, especially working memory and inhibition[9, 28–33]. Different components have been shown to not have equal influences on different kinds of academic achievements. However, the results regarding the extent to which the components of EF affected the academic achievements of ADHD have been inconsistent. Therefore, this study attempted to clarify the relationships of the components of EF with academic achievements in children with ADHD and further elucidate the degree to which each related component affected academic achievements in those with ADHD. We proposed the following research hypothesis: different sub-components of EF would have different effect sizes related to different academic achievements, and working memory, especially that associated with the central executive, may play the most important mediating roles in the academic achievements of children with ADHD.

2. Method

2.1 Participants

A total of 262 participants were recruited in our study, including 140 children with ADHD recruited from child psychiatric clinics of Peking University Sixth Hospital and 122 typically developing controls recruited from local primary and middle schools. All subjects and their guardians signed informed consent forms. This study was approved by the Medical Ethics Committee of Peking University Sixth Hospital.

ADHD group The inclusion criteria were as follows: (a) Children met the diagnostic criteria of the Diagnostic and Statistical Manual of Mental Disorders, 4th ed. (DSM-IV) and were diagnosed by a qualified child psychiatrist using the Clinical Diagnostic Interview Scale (CDIS). (b) The age range was 6–16 years old, and the sex was not restricted. (c) Children had an IQ > 70. (d) Subjects were not receiving medication treatment for ADHD. The exclusion criteria were as follows: (a) with the exception of LD, other childhood mental disorders such as schizophrenia, autism spectrum disorders (ASD), mental retardation, opposition defiant disorders (ODD), conduct disorder (CD), tic disorders (TD), mood disorder and anxiety disorder; (b) obvious physical and neurological diseases; and (c) use of any stimulants, atomoxetine, antipsychotics, antidepressants, mood stabilizers, etc.

TD group (typically developing children group) The inclusion criteria were as follows: (a) children did not meet the ADHD diagnostic criteria of the DSM-IV which was diagnosed by a qualified child psychiatrist using The Schedule for Affective Disorders and Schizophrenia for School Age Children-Present and Lifetime Version (K-SADS-PL); (b) the age range was 6–16 years old, and the sex was not restricted; and (c) children had an IQ ≥ 70. The exclusion criteria were as follows: (a) attention deficit, hyperactivity, or impulsivity item scores ≥ 4 on the ADHD-Rating Scale IV; (b) children had obvious mental, physical and neurological diseases.

2.2 Measures

2.2.1 Clinical Interview

The Clinical Diagnostic Interview Scale (CDIS) Qualified psychiatrists used this scale to interview parents of the children with ADHD for clinical symptom assessment. The Chinese version of the CDIS was used to classify ADHD and other conditions, including LD, ODD, CD, TD, anxiety disorders, and mood disorders. The Chinese version was translated and developed by our group based on the DSM-IV (APA, 1994) and has demonstrated adequate validity and reliability[34].

The Schedule for Affective Disorders and Schizophrenia for School Age Children-Present and Lifetime Version (K-SADS-PL) Qualified psychiatrists used this scale based on the DSM-IV to interview parents of normal children to assess the current and previous history of mental disorders in the children and adolescents. The K-SADS-PL was also used to classify ADHD and other

conditions, including ODD, CD, TD, anxiety disorders, mood disorders and psychiatric disorders. The *kappa* coefficient of this scale was above 93%, and the range of retest reliability coefficients for different mental disorders was 0.63 ~ 1.00[35].

2.2.2 IQ measurements

General Intelligence The Chinese revision of the Wechsler Intelligence Scale (C-WISC) was used to assess the general intelligence level of all subjects, which was standardized by Gong Yaoxian, to exclude children with intellectual disability. The scale had good reliability and validity[36].

Fluid Influence The Raven's progressive matrices task (R'SPM) was used to estimate fluid influence, which represents the abstract reasoning ability of children. The children were presented with an incomplete figure with six segments underneath it. The child had to identify the correct segment to complete the figure's regular pattern. The task was translated and revised by the China R'SPM-CR national group in 1989. The test is characterized by using geometric shapes, thereby preventing culture, race, and language restrictions, and was shown to be especially suitable for children and elderly individuals. The reliability was 0.95[37].

2.2.3 Executive function measurements

Phonological Working Memory The digit span test (WAIS-III) was used to assess the phonological working memory of the participants. It was a part of the C-WISC and included forward and backward order recall. Forward recall measures short-term memory, which mainly depends on the phonological loop, while backward recall involves the central executive system, which involves updating, reordering and processing information[36, 38–41]. Digits were presented at a 1 sec per digit rate, and the subjects needed to recall both trials of the same span length. The subjects needed to recite as many numbers as possible in forward or backward order according to the examiner. When repetitions of the same length were incorrect, the test stopped. The examiner recorded the highest number of digits and total scores that the subject can correctly recited. The higher the score was, the better the phonological working memory ability.

Visual-Spatial Working Memory The spatial span test (WMS-III) was used to estimate children's visual-spatial working memory. Children were given a test board with ten cubes, each of which had a number from 1 to 10 printed on the side facing the examiner. Each number sequence was performed twice. The subjects were asked to tap the same cube in the same and opposite sequence as the tester, and the evaluation index was the total score. The higher the score was, the better the visual-spatial working memory ability[42].

Inhibition The Stroop Colour-Word Test was used to assess the inhibitory and impulse control abilities of all children. The test had four trials: (a) the child was asked to read 30 black Chinese characters, (b) to read the colour of the 30 colourful squares (red, green and yellow), (c) reading colourful Chinese characters, and (d) reading the colour of the colourful Chinese characters. They were asked to complete all trials as quickly and accurately as possible. The examiner recorded the time and errors during each trial. The scores for reading Chinese characters and naming the colour of the colourful squares reflected abilities of instant attention and fast reading. The results of reading the colourful characters and naming the colour of the colourful characters reflected inhibitory abilities. The colour interference time was the time to read the colourful characters minus the time to read the Chinese characters. The semantic interference time was the time to name the colour of colourful characters minus the time to name the colour of the colourful squares. The longer these two time measures were, the worse the inhibitory effect[43].

Conversion The trail making test (TMT) was used to assess the transfer function of children. The test included test A, which asked the child to connect the digits from 1-2-3 as quickly and accurately as possible, and test B, which asked the subjects to connect 1-A-2-B-3-C. The test B time minus test A time was the transfer time, which reflected the transfer function. The longer the time was, the worse the transfer function[44].

2.2.4 Academic achievement measures

The subjects completed the measurements of academic achievements on web-based applications in the "Online Psychological Experimental System (OPES)" (<http://www.dweipsy.com/lattice/>). In this study, we assessed performance in five tasks that took 48 min[45].

Mathematical Achievement Graded mathematical achievement was used to assess each child's best mathematical problem-solving achievement. The children were asked to solve as many items as possible within 18 min. The questions used in the test were edited based on semester-final examinations, including number knowledge, operations, simple arithmetic, word problems and geometry. The questions for each grade were randomly chosen and grouped into five sets and each included three questions. The participants were first given a set of questions from the first grade level. If the child correctly solved at least two questions from the set of three, the difficulty level was increased by one grade. If they gave incorrect answers for two questions in one set, the difficulty level remained at the same grade. If they gave incorrect answers for all three questions in one set or failed to solve all five sets of questions, the difficulty level dropped to a lower grade. The test was stopped when the time was up or if all five sets of questions in the first grade were answered. Thus, different participants could receive questions based on their math skills, which were mainly below their grade level. The final score was calculated as the sum of weighted scores in each grade, which was the number of correctly answered questions times the grade level (1–12). There were a total of 1,722 problems in the test database. The reliability was 0.92[46].

Reading comprehension Achievement Graded reading achievement was used to estimate one's highest level of Chinese reading comprehension achievement. The materials in the test were also edited based on semester-final examinations and consisted of language knowledge, comprehension and distinction. This test was designed as a standardized achievement test, and the child was asked to read and solve as many passages and problems as possible within 20 min. The method was similar to the graded mathematical achievement.

Computation Fluency Simple subtraction and complex subtraction were assessed, and the average score was used to reflect the computational fluency. Simple subtraction consisted of 92 problems. The largest minuend was 18, and the smallest minuend was 2 (i.e., $6 - 2$, $16 - 8$). The differences between two operands were always single-digit numbers. Each problem included two candidate answers. The false answer deviated from the true answer by plus or minus 3 (i.e., ± 1 , ± 2 , or ± 3). This was a time-limited (2 min) task. The split-half reliability of the test was 0.96. Complex subtraction consists of 95 problems, including double-digit numbers for both operands (i.e., $21 - 10$, $55 - 22$). Each problem included two candidate answers. The differences between the false answers and the true answers were 1 or 10 (i.e., ± 1 , ± 10)[47].

Reading Fluency Word semantics were used to evaluate Chinese reading fluency. Materials for the task were adapted from textbooks used in primary schools from first grade to ninth grade. It included 120 trials. In each trial, a sentence missing one word was presented in the middle of the computer screen. The participants were asked to complete the sentence by selecting one of 2 candidate words presented beneath the sentence by pressing the Q key or the P key. The stimulus remained on the screen until the participants responded. It was a 5-min time-limited task. The reliability of the test was 0.88[48].

3. Statistical Analysis

All analyses were conducted by IBM SPSS 22.0 and SPSS AMOS 22.0 software. The children's age, sex and fluid intelligence were considered covariates in all analyses. It should be noted that because IQ shares significant variance with working memory and if using it as a covariate, it would produce over-correct findings, so IQ was used only to exclude the children with intellectual disability in this study[49]. We chose fluid intelligence, which was the score from the R'SPM, as a covariate[50].

First, we used descriptive statistics to present clinical characteristics, including demographics, EFs and academic achievements. These statistics were compared between the ADHD group and the TD group using an independent *t*-test or multivariate analysis of covariance (MANOVA) for continuous variables and the chi-square test for categorical variables.

Second, partial correlation analyses between academic achievements and EFs were conducted based on sex, age and fluid intelligence as control variables.

Third, based on the mediation analysis of Hayes[51], we took ADHD diagnosis status as the independent variable (*X*), EFs as mediators (*M*), and the academic achievements as the dependent variables (*Y*) to establish the structural equation models (SEM) in SPSS AMOS 22.0 and to explore how the EFs affected the academic achievements of the children with ADHD. If the chi-square/degree of freedom (CMIN/DF) < 3, root mean square error of approximation (RMSEA) < 0.1, comparative fit index

(CFI) 0.9, goodness of fit index (GFI) 0.9 and normed fit index (NFI) 0.9, we thought the model was good[52]. Effect ratios (indirect effect divided by total effect) were calculated to estimate the proportion of each significant total effect that was attributable to the mediating pathway (indirect effect). Bootstrapping was used to establish the statistical significance of all total, direct, and indirect effects. Ninety-five percent confidence intervals (CIs) were selected[53].

All statistical tests were two-tailed. $P < 0.05$ was considered statistically significant.

4. Results

4.1 Demographic characteristics

There were no significant differences between the two groups in age or grade. The ADHD group had more boys than the TD group ($\chi^2 = 21.45$, $P < 0.001$). The levels of IQ ($t = -9.05$, $P < 0.001$) and R’SPM ($t = -5.01$, $P < 0.001$) in the ADHD group were lower than those in the TD group (see Table 1).

Table 1
Demographic characteristics of the ADHD group and TD group

	ADHD N = 140	TD N = 122	χ^2/t	P
N Male (%)	114 (81.40%)	67 (54.90%)	21.45	< 0.001
Age (year)	9.71 ± 2.24 ^a	9.37 ± 1.81 ^a	-0.11	0.92
Grade	3 (1, 9) ^b	3 (1, 8) ^b	0.80	0.42
IQ	102.6 ± 14.72 ^a	117 ± 10.70 ^a	-9.05	< 0.001
R’SPM	39.29 ± 10.13 ^a	45.25 ± 8.95 ^a	-5.01	< 0.001
Type of ADHD	ADHD-I, 90 ADHD-HI, 3 ADHD-C, 46	-	-	-
N comorbid with LD (%)	43 (30.71%)	-	-	-
<i>Note.</i> ADHD = attention-deficit/hyperactivity disorder, ADHD-I = ADHD predominantly inattention type, ADHD-HI = ADHD predominantly hyperactive impulsive type, ADHD-C = ADHD combined type, IQ = intelligence quotient, R’SPM = Raven’s progressive matrices task score, LD = learning disabilities, a = means ± standard deviations, b = median (minimum, maximum)				

4.2 Comparison of executive functions

The comparisons were conducted after controlling for the influences of age, sex and the R’SPM scores. We found no significant differences in the forward scores for digit span between the ADHD group and the TD group. Other EF indexes in the ADHD group were lower than those in the TD group (see Table 2).

Table 2
Executive function comparison between the ADHD group and the TD group

Executive functions (EF)	Index	ADHD N = 140	TD N = 122	F	P
Spatial span test (Visual spatial working memory)	Forward	6.0 (2.0, 12.0) ^b	8.0 (5.0, 14.0) ^b	29.79	< 0.001
	Backward	5.0 (0.0, 10.0) ^b	7.0 (2.0, 12.0) ^b	39.55	< 0.001
	Total scores	12.0 (4.0, 21.0) ^b	15.0 (7.0, 24.0) ^b	47.72	< 0.001
Digit span test (Phonological working memory)	Forward	8.0 (2.0, 11.0) ^b	8.0 (5.0, 12.0) ^b	1.84	0.18
	Backward	3.0 (2.0, 9.0) ^b	5.0 (2.0, 9.0) ^b	10.67	< 0.01
	Total scores	11.0 (5.0, 19.0) ^b	13.0 (8.0, 19.0) ^b	10.13	< 0.01
Trail making test (Conversion)	Conversion time (seconds)	144.7 ± 127.48 ^a	95.3 ± 81.1 ^a	5.35	0.02
Stroop colour-word test (Inhibition)	Semantic interference time (seconds)	30.3 ± 20.1 ^a	19.2 ± 9.7 ^a	7.80	0.01
	Colour interference time (seconds)	7.9 ± 10.5 ^a	4.3 ± 5.7 ^a	27.98	< 0.001
<i>Note.</i> Age, sex and R'SPM scores were used as covariates. a = means ± standard deviations, b = median (minimum, maximum)					

4.3 Comparison of academic achievements

Comparisons were also conducted after controlling for the influences of age, sex and R'SPM scores. All four academic achievements in the ADHD group were lower than those in the TD group, and all *P* values were less than 0.01 (see Table 3).

Table 3
Academic achievement comparison between the ADHD group and the TD group (means ± SD)

Academic achievements	ADHD N = 140	TD N = 122	F	P
Mathematical achievement	12.08 ± 9.14	16.01 ± 8.73	18.34	< 0.001
Reading comprehension achievement	13.72 ± 11.21	21.89 ± 9.68	35.99	< 0.001
Subtraction	18.76 ± 9.71	25.54 ± 9.02	28.54	< 0.001
Word semantic	17.11 ± 11.34	26.16 ± 10.26	34.69	< 0.001
<i>Note.</i> Age, sex and R'SPM scores were used as covariates.				

4.4 Partial correlations between executive function and academic achievements

After controlling for the influences of age, sex and the R'SPM scores, we could see purer correlations between academic achievements and EFs. All academic achievements had negative relationships with diagnosis status.

The mathematical achievement scores had positive correlations with the forward digit span scores ($r = 0.16$, $P < 0.01$) and the backward digit span scores ($r = 0.23$, $P < 0.01$) and had negative relationships with conversion times ($r = -0.08$, $P < 0.05$). The

reading comprehension achievement scores had positive relationships with the total spatial span scores ($r = 0.14$, $P < 0.05$), the forward digit span scores ($r = 0.21$, $P < 0.01$), and the backward digit span scores ($r = 0.16$, $P < 0.01$) and had negative relationships with conversion times ($r = -0.13$, $P < 0.05$), the colour interference times ($r = -0.13$, $P < 0.05$) and the semantic interference times ($r = -0.19$, $P < 0.01$). The subtraction scores had a positive relationship with the backward digit span scores ($r = 0.25$, $P < 0.01$) and had negative relationships with conversion times ($r = -0.16$, $P < 0.01$), the colour interference times ($r = -0.16$, $P < 0.05$) and the semantic interference times ($r = -0.20$, $P < 0.01$). The semantic word scores had positive relationships with the forward digit span scores ($r = 0.18$, $P < 0.01$) and the backward digit span scores ($r = 0.21$, $P < 0.01$). It had negative relationships with conversion times ($r = -0.29$, $P < 0.01$), colour interference times ($r = -0.29$, $P < 0.05$) and semantic interference times ($r = -0.19$, $P < 0.01$) (see Table 4).

Table 4
Partial correlations between executive functions and academic achievements

	1	2	3	4	5	6	7	8	9	10	11	12
1 ADHD diagnosis status (ADHD = 1, TD = 0)	-											
2 Spatial span test-total scores	-0.40**	-										
3 Forward digit span	-0.08	0.11	-									
4 Backward digit span	-0.20**	0.09	0.16**	-								
5 Digital span test-total scores	-0.20**	0.14*	0.74**	0.78**	-							
6 Conversion time (s)	0.14*	-0.17**	-0.09	-0.09	-0.11	-						
7 Colour interference time (s)	0.17**	-0.10	-0.05	-0.09	-0.11	0.16**	-					
8 Semantic interference time (s)	0.31**	-0.14*	-0.06	-0.07	-0.08	0.12*	0.12	-				
9 Mathematical achievement	-0.26**	0.07	0.16**	0.23**	0.26**	-0.03	-0.13	-0.08*	-			
10 Reading comprehension achievement	-0.35**	0.14*	0.21**	0.16**	0.25**	-0.09	-0.13*	-0.19**	0.51**	-		
11 Subtraction	-0.32**	0.09	0.11	0.25**	0.23**	-0.16*	-0.16*	-0.20**	0.43**	0.39**	-	
12 Word semantic	-0.35**	0.10	0.18**	0.21**	0.26**	-0.16*	-0.29**	-0.19**	0.39**	0.50**	0.46**	-
<i>Note.</i> Age, sex and the scores of R'SPM were controlled for. The spatial span test-forward and spatial span test-backward were unrelated to all kinds of academic achievements. * $P < 0.05$. ** $P < 0.01$												

4.5 Mediation analysis

Based on the partial correlation results, we considered ADHD diagnosis status (ADHD = 1, TD = 0) as the independent variable (X), the EFs that significantly related to four kinds of achievements as mediators (M), and the academic achievements as the

dependent variates (Y) to establish SEMs and to analyse the independent contribution of each mediator on different academic achievements. All analyses were conducted after controlling for age, sex and R'SPM scores.

In the mediation pathway between ADHD status and mathematical achievements, forward and backward digit spans (Path 1–1) and semantic interference (Path 1–2) were mediators. In path 1–1, the total effect of an ADHD diagnosis on mathematical achievement was $d=-0.19$ ($P=0.01$). The ADHD diagnosis status exerted significant direct effects on backward digit span ($d=-0.29$, $P=0.02$) and mathematical achievements ($d=-0.14$, $P<0.01$) but not on forward digit span. The two mediators together explained 26% of the total effect (d indirect effect $=-0.05$, $P=0.03$). However, only backward digit span significantly moderated the effect of diagnostic status on mathematical achievements ($d=-0.04$, $P<0.05$), which was partial mediation, and the effect ratio was 21% (see Fig. 1). However, in Path 1–2, the semantic interference did not have any mediating effects (see Fig. 2).

In the pathway between ADHD status and reading comprehension achievements, forward and backward digit span (Path 2–1), colour and semantic interference (Path 2–2), and total spatial span (Path 2–3) were mediators. In the three paths above, none of the mediators played mediating roles in reading comprehension achievements (see Fig. 3-Fig. 5).

In the pathway with subtraction, backward digit span (Path 3–1), colour and semantic interference (Path 3–2), and conversion (Path 3–3) were mediators. In Path 3–1, the total effect of diagnostic status was $d=-0.31$ ($P=0.02$), and ADHD status had a significant direct effect on backward digit span ($d=-0.29$, $P=0.02$). Backward digit span significantly moderated the effect of diagnostic status on subtraction ($d=-0.06$, $P=0.01$), and the effect ratio was 19% (see Fig. 6). In Path 3–2, the total effect of an ADHD diagnosis on mathematical achievement was $d=-0.29$ ($P=0.01$). ADHD diagnosis status exerted significant direct effects on colour interference ($d=0.32$, $P=0.01$) and subtraction ($d=-0.24$, $P<0.01$) but not on the semantic interference. The two mediators together explained 17% of the total effect (d indirect effect $=-0.05$, $P=0.02$). However, only colour interference significantly moderated the effect of diagnostic status on mathematical achievement ($d=-0.03$, $P<0.05$), which was partial mediation, and the effect ratio was 10% (see Fig. 7). In Path 3–3, conversion did not have any mediating effects (see Fig. 8).

In the pathway with word semantics, forward and backward digit span (Path 4–1), colour and semantic interference (Path 4–2), and conversion (Path 4–3) were mediators. In Path 4–1, the total effect of an ADHD diagnosis on word semantics was $d=-0.34$ ($P=0.02$). ADHD diagnosis status exerted significant direct effects on backward digit span only ($d=-0.29$, $P=0.02$). The two mediators together explained 15% of the total effect (d indirect effect $=-0.05$, $P=0.01$). However, only backward digit span significantly moderated the effect of diagnostic status on word semantics ($d=-0.06$, $P<0.05$), which was partial mediation, and the effect ratio was 12% (see Fig. 9). In Path 4–2, the total effect of an ADHD diagnosis on mathematical achievement was $d=-0.32$ ($P=0.01$). ADHD diagnosis status exerted significant direct effects on colour interference times ($d=0.21$, $P=0.01$) but not on semantic interference times. The two mediators together explained 19% of the total effect (d indirect effect $=-0.06$, $P=0.01$). However, only colour interference significantly moderated the effect of diagnostic status on mathematical achievement ($d=-0.04$, $P<0.05$), which was partial mediation, and the effect ratio was 12% (see Fig. 10). In Path 4–3, the conversion had a significant mediating effect (d indirect effect $=-0.02$, $P=0.01$), and the effect ratio was 6% (see Fig. 11).

5. Discussion

5.1 Executive functions and academic achievements in children with ADHD

To the best of our knowledge, the academic achievements and EFs of children with ADHD are lower than those of typically developing children, even without accounting for the effects of age, sex, fluid intelligence and comorbidities. Many previous studies have verified that the EFs of children with ADHD are lower and that executive dysfunction could be the core disorder of ADHD[14, 54–55]. Similar to Re AM et al.'s findings, children with ADHD showed worse applied mathematical problem solving, which consisted of number knowledge, simple arithmetic, word problems and geometry; children with ADHD solved fewer problems and made more errors[56]. Sella et al. also found that children with ADHD had lower scores in simple arithmetic, such as taking more time to estimate sums of two-digit addition problems and providing poorer estimates than normal controls[6][6]. Reading comprehension and word semantics of children with ADHD were also lower than those of normal children, which was

the same as observed with English reading comprehension and vocabulary. Martinussen et al. found that youth with ADHD scored significantly lower than the comparison youth on a standardized measure of reading comprehension, word reading and expressive vocabulary[9]. Stern et al. used expository text from a contemporary history book from high school, and each text had ten comprehension questions. They also found that children with ADHD performed worse than normal controls[57].

Different EFs, including phonological working memory, visual spatial working memory, conversion and inhibitory function, had different relationships with academic achievements. Numerous studies have found that cognitive impairment is related to academic achievements in those with ADHD; similarly, we found parallel results. Similar to the study of Martinussen et al. who found that children with ADHD who had lower reading comprehension also exhibited more EF difficulties, as reported by the teacher[9]. Compared with reading fluency, EFs (including working memory, attention and suppression) made a significant contribution to reading comprehension[58]. Furthermore, our study indicated that academic achievements were significantly associated with working memory. This supports many studies that verified that working memory was closely related to math and reading[59]. Previous studies found that working memory was an important predictor of mathematical problem solving[60–61]. Nevertheless, the results were different regarding the relationships between phonological working memory/visual-spatial working memory and academic achievements. Our study found that all kinds of academic achievements were related to phonological working memory, and only reading comprehension was also associated with visual spatial working memory. This supported the results of Rennie B et al., who found that phonological working memory was the dominant factor regarding academic achievements[28, 33]. Rogers et al. also found that phonological working memory was more strongly associated with ADHD adolescents' achievement in reading and mathematics than visual spatial working memory[31]. The results suggested that the academic achievements of children with ADHD may depend on acoustic information encoding more than visual encoding.

What calls for special attention is that the relationships between inhibition and academic achievements were truly inconsistent based on existing studies. In our study, all kinds of academic achievements were significantly associated with inhibitory effects. Response inhibition contributed significant predictive power to reading, even when excluding the influences of age and IQ[33]. Passolunghi et al. used the go/no-go task to assess inhibition in those with ADHD and found that cognitive inhibition may explain impairments in arithmetic problem solving[28]. Jesse et al. found that response inhibition (measured by colour-word interference) had no relation with math and reading of children with the combined type of ADHD (ADHD-C) and influenced only written expression ability[29]. Those differences may relate to selected objects and measurement instruments, but those differences suggest that the cognitive mechanisms involved in different types of ADHD may need further exploration.

We also found that conversion was associated with reading comprehension, computational fluency and reading fluency. However, research on the relationships between conversion (or shift or cognitive flexibility) and academic achievements is rare. Sjovallet al. used the Navon-like task to estimate the conversion function and found that it also had a significant relation with mathematical and reading achievements[32]. In this aspect, more studies are needed.

5.2 Mediating effects of executive functions on academic achievements in children with ADHD

In our study, only phonological working memory, especially the central executive, played a significant mediating effect in the pathway from ADHD status to problem-solving mathematical achievements, computational fluency and reading fluency. Inhibition also had a mediating effect on reading fluency.

5.2.1 Problem solving-related academic achievements

Consistent with previous studies, this research indicated that phonological working memory plays an important partial mediating effect in the path from ADHD status to mathematical problem-solving achievements. Furthermore, the central executive, which is a core part of phonological working memory, exerted a significant mediating effect on math, rather than the phonological loop, which is another part of phonological working memory. Frideman also found that central executive processes exerted a significant full mediating effect on ADHD-C-related applied mathematical problem solving, and the effect ratio was 60%, but neither the phonological loop nor visual spatial working memory was a mediator[62]. A meta-analysis of reading comprehension with working memory also indicated that the domain-general central executive of working memory is implicated in early reading

acquisition, and verbal working memory is more strongly implicated in later reading performance as readers gain more experience with reading[63]. The central executive also affected children's arithmetic strategy use in general students[21].

However, there was no similar finding in Chinese reading comprehension. In contrast to our results, Friedman had the same discovery that central executive processes mediated reading comprehension in boys with the ADHD-C type, whereas phonological short-term memory and visual-spatial short-term memory did not[64]. Rogers et al. took inattention symptoms as an independent variate in a path analysis and found that phonological working memory played a partial mediating effect on reading comprehension[31]. Savage R. et al. found that central processing predicted reading ability[65]. Swanson et al. also had the same finding in normal children[60]. The possible reason was that Chinese and English reading comprehension in children with ADHD may use different cognitive processes. However, more research should be carried out to find more evidence.

We did not find that visual spatial working memory played a role in problem solving-related academic achievements, and a similar finding was found in normal children. Van de et al. showed that as grade level progressed, the predictive value of visual-spatial working memory for individual differences in the level of mathematics performance decreased, while the predictive value of verbal working memory increased[66]. This suggested that phonological working memory and visual spatial working memory separately play different roles in ADHD-related problem solving. Similarly, we found that conversion and inhibition did not play mediating roles in ADHD-related problem solving-related academic achievements. Rogers et al. also did not find that inhibition and conversion play mediating roles in ADHD-related math and reading[31]. Sjöwalet al. also had the same finding[32]. However, we cannot ignore that they have significant associations with academic achievements.

5.2.2 Fluency-related academic achievements

This study also found that the central executive and inhibition played partial mediating effects on computation and reading fluency and that conversion also played a mediating effect on reading fluency in the children with ADHD. Similar to a previous study, Rennie et al. found after two years that working memory explained 61% of the variance in the computational fluency of ADHD children, and response inhibition also significantly contributed[33]. Jacobson et al. found that working memory was a significant predictor of oral reading fluency[67]. Reading fluency involves accuracy and the speed of reading[68]. The study of Kelly B. Cartwright et al. found that cognitive flexibility contributed to reading fluency over automatic decoding and other cognitive processes[69]. The study of Raya Meiri et al. also found that phonological working memory (measured by digit span) and inhibition (measured by the Stroop test) were positively correlated with reading and arithmetic fluency compared with nonfluency tasks in children with reading disorders[70]. Studies on the relationship between computational fluency and EF are rare. Clearly, additional studies should be conducted.

It should be noted that some studies have found that timing function deficits were an independent impairment domain and should receive more attention[59, 71–72]. In the present study, the evaluation tools for academic achievements were all time-limited tasks that could better assess the actual level of achievement of the children with ADHD. Second, this study was the first to analyse academic achievements from two dimensions: problem solving-related academic achievements (mathematical achievements and reading comprehension) and fluency-related academic achievements (subtraction and word semantics). We found that the central executive played a significant mediating effect on mathematical achievements, computational fluency and reading fluency but not on reading comprehension. As stated above, the central executive can be divided into four distinct EFs: memory updating, inhibition, switching, and dual-task coordination[19–21]. These results suggested that mathematical achievements, computational fluency and reading fluency may depend on all four functions; however, reading comprehension requires a more complex cognitive process. This aspect also needs more research.

6. Limitations And Future Directions

First, to analyse the relationships between EFs and academic achievements in children with ADHD, we recruited only children with pure ADHD and ADHD co-morbid with learning disorders. However, ADHD children with other comorbidities (e.g., ODD, CD, mood disorder, and OCD) make up a large proportion of this population, and these children may have more complex and serious problems regarding academic achievements. To reflect the actual state of ADHD-related academic achievements, we should include children with pure ADHD and those with comorbidities. Second, because of the limited sample size of different types of

ADHD, especially the hyperactive/impulsive type (ADHD-HI), we did not analyse the mechanisms across different ADHD types. Third, because cognitive mechanisms underlying academic achievements are complex, it is similarly complex same ADHD-related academic achievements. Fourth, the correlation coefficients and effect sizes between academic achievements and EFs in our study were weak, and we found only that EFs played a partial mediating role in the path of ADHD-related academic achievements. Therefore, in addition to exploring EFs, we also need to find relationships between other cognitive processes, such as phonological awareness and rapid naming.

7. Conclusions

In conclusion, the current study indicated that ADHD-related lower academic achievements were significantly associated with poorer EFs. EFs, especially phonological working memory, partially mediated the path from ADHD to academic achievements. Furthermore, function of the central executive, which is the prominent sub-component of phonological working memory, was strongly associated with mathematical achievement, computational fluency and reading fluency. Inhibition and conversion also mediated computation fluency and reading fluency. The efficacy of existing treatments, including medication, psychotherapy and comprehensive therapy, to improve academic achievements is not yet clear[73]. Cognitive function training (especially working memory training) has been widely carried out. Some have indicated that a period (usually a few weeks) of working memory training for children with ADHD could improve the level of academic achievements[74–75], but the duration of efficacy was not clear. These results suggested that individual targeted interventions towards subsystems of working memory, conversion and inhibition may benefit ADHD-related academic achievements.

Abbreviations

ADHD: Attention-deficit/hyperactivity disorder

EF: Executive function

LD: Learning disorder

DSM-IV: the Diagnostic and Statistical Manual of Mental Disorders, 4th ed.

CDIS: the Clinical Diagnostic Interview Scale

ASD: Autism spectrum disorders

ODD: Opposition defiant disorders

CD: Conduct disorder

TD: Tic disorders

K-SADS-PL: The Schedule for Affective Disorders and Schizophrenia for School Age Children-Present and Lifetime Version

C-WISC: The Chinese revision of the Wechsler Intelligence Scale

R'SPM: The Raven's progressive matrices task

TMT: Trail making test

OPES: Online Psychological Experimental System

MNOVA: Multivariate analysis of covariance

CMIN/DF: Chi-square/degree of freedom

RMSEA: Root mean square error of approximation

CFI: Comparative fit index

GFI: Goodness of fit index

NFI: Normed fit index

CIs: Confidence intervals

ADHD-C: Combined type of ADHD

ADHD-HI: Hyperactive/impulsive type of ADHD

Declarations

Ethics approval and consent to participate

All subjects and their guardians signed informed consent forms. This study was approved by the Medical Ethics Committee of Peking University Sixth Hospital. And the study was conducted in compliance with the Declaration of Helsinki.

Consent for Publication

All authors consent to publication of the study.

Availability of data and material

The datasets generated and/or analysed during the current study are not publicly available but are available from the corresponding author on reasonable request.

Competing interests

All authors declare that they have no competing interests.

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Author contributions

All authors contributed to the study idea and design. Data collection was performed by Min Dong, Lu Liu, Haimei Li, Yufeng Wang, Xinlin Zhou, and Qiujiu Qian, and analyses were conducted by Min Dong. The first draft of the manuscript was written by Min Dong. Xinlin Zhou and Qiujiu Qian commented on the different versions of the manuscript. All authors read and approved the final manuscript.

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Figures

Figure 1

Path 1-1

Figure 2

Path 1-2

Figure 3

Path 2-1

Figure 4

Path 2-2

Figure 5

Path 2-3

Figure 6

Path 3-1

Figure 7

Path 3-2

Figure 8

Path 3-3

Figure 9

Path 4-1

Figure 10

Path 4-2

Figure 11

Path 4-3