Vigilance, Inhibitory Control and Regional Cerebral Blood Oxygenation in the PFC - Differences in ADHD Types of Presentations

Sebastian Skalski[1] *and Paweł Dobrakowski*[2]

[1] Polish Academy of Sciences, Institute of Psychology, Warsaw, Poland

[2] Humanitas University, Institute of Psychology, Sosnowiec, Poland

ABSTRACT

It is commonly believed that proven abnormalities in the structure and functioning of the prefrontal lobes affect cognitive deficits in children with ADHD. The purpose of the current study was to assess vigilance, inhibitory control, and regional cerebral blood oxygenation (rCBO2) in the prefrontal cortex (PFC) of children with ADHD. The study included 150 children with ADHD and 51 typically developing (TD) children aged 9-12 years. Children with ADHD showed a deficit in vigilance (assessed by the shortened version of the Mackworth clock task), inhibitory control (the Stroop task), different rCBO2 patterns in the PFC, as well as lower cortical activation during cognitive tasks. These differences are discussed in the context of the types of ADHD presentations.

KEYWORDS

vigilance
inhibitory control
cerebral blood oxygenation
prefrontal cortex
ADHD

BACKGROUND

Attention deficit hyperactivity disorder (ADHD) occurs in 3-8% of the population aged < 18 and is the most frequent neuropsychiatric disorder in children before the age of 7 (Reinhardt & Reinhardt, 2013; von Polier et al., 2012). The disorder manifests itself in increased hyperactivity, impulsivity, and attention deficit (Hechtman, 2005). There are three types of ADHD presentations: the predominantly hyperactive-impulsive type (ADHD-HI), the predominantly inattentive type (ADHD-I), and the combined type (ADHD-C). ADHD-HI occurs less frequently (less than 15% of cases) and is associated mainly with behavioral problems. ADHD-I (20-30% of cases) concerns attention deficit and difficulties in learning. ADHD-C is the most frequently occurring type (50-75% of cases) and manifests itself both in psychomotor hyperactivity as well as attention deficit (Millichap, 2008). In addition, children exhibiting the ADHD-C type are more prone to be affected by coexisting psychiatric disorders, such as oppositional defiant disorder, anxiety disorders, and depressive states (Kollins, 2008; Mihan et al., 2018). ADHD is more commonly diagnosed in boys. It is estimated that ADHD affects one girl in 2-10 boys. Girls are more likely to exhibit attention disorder symptoms only, whereas boys are more likely to show hyperactivity and impulsivity in behavior (Biederman et al., 2005; Fayyad et al., 2007).

Studies to date have shown the influence of a genetic factor in ADHD. Mutations within genes associated with dopaminergic, noradrenergic and serotonergic activity lead to changes at the biochemical and structural level of the brain (Comings et al., 2001). When analyzing the etiology of ADHD, special role is attributed to abnormalities in the functioning of neuronal connections between the cortex and basal nuclei (Krain & Castellanos, 2006). Research on neuroanatomical lesions using nuclear magnetic resonance (NMR) have shown an average encephalon volumetric decrease of ca. 3-4% (Paclt et al., 2016; Qiu et al., 2011). These differences do not concern the entire cerebral tissue, but rather the prefrontal-striatal and posterior temporoparietal areas. Studies using positron emission tomography (PET) have revealed the total brain glucose metabolism to be reduced by 8% (Apostolova et

Corresponding author: Sebastian Skalski, Polish Academy of Sciences, Institute of Psychology, Jaracza 1, 00-378 Warsaw, Poland.

E-mail: sebastian.skalski@sd.psych.pan.pl

al., 2015), mainly in the dorsal anterior cingulate cortex, the premotor cortex, and the basal nuclei. Studies using single photon emission computed tomography (SPECT) have revealed hypoperfusion in the prefrontal and striatum regions (Capa Kaya et al., 2002; Öner et al., 2005). Data from neuroimaging studies allow for a better understanding of the neurobiological sources of cognitive deficits in children with ADHD.

The frontal cortex covers as much as a third of the brain's surface. Its anterior part is referred to as the prefrontal cortex (PFC) and it plays a key role in organizing complex forms of behavior (Koechlin et al., 2003). There is no full agreement on PFC topography. The most frequent distinction involves the dorsolateral PFC, orbitofrontal PFC, dorsomedial PFC, ventromedial PFC, and ventrolateral PFC. However, one may often come across a simplified functional division into left PFC (lPFC), medial PFC (mPFC), and right PFC (rPFC).

Anatomical studies have confirmed that cytoarchitecturally differentiated PFC areas are specifically linked to other cortical and subcortical brain areas (Petrides et al., 2012). For example, the connections with the medial dorsal nucleus of the thalamus were used to determine the extent of the PFC. It is commonly recognized that visible abnormalities in the structure and function of the prefrontal lobes are related to cognitive deficits in children with ADHD, including working memory, inhibitory control, vigilance, visual search, and divided attention (Arns et al., 2008; Barry et al., 2003; Bush, 2011; McGuire & Botvinick, 2010; Sripada et al., 2014). Studies to date have shown the existence of certain cortical activity patterns in the PFC as well as response patterns in cognitive tests which suggest ADHD (Toomim & Carmen, 2009). Activity patterns are assessed using quantitative electroencephalography (Q-EEG) and hemoencephalography (HEG) techniques. Data thus far suggest that children with more severe hyperactive-impulsive symptoms show lower activity in the lPFC, while children with more severe inattentiveness display lower mPFC activity. Similarly, lower activity in the lPFC conditions commission errors, whereas lower activity in the mPFC conditions omission errors and a longer reaction time (RT) for responses (González-Castro et al., 2013; Rodríguez et al., 2016; Toomim et al., 2004). Moreover, researchers observed reduced activation in the PFC during an inhibitory task in children with ADHD (Okazaki et al., 2002).

Vigilance, also termed "sustained concentration," is one of the aspects of selective attention. It allows for monitoring the environment for an extended period of time in order to search for stimuli that match the assumed criteria, while ignoring noise (distractors) so as not to raise a false alarm for apparent threat (Thomson et al., 2015). Vigilance is limited due to energy loss as a result of prolonged scanning of the perceptive field, as well as due to a low activation level of the cognitive system (Langner & Eickhoff, 2013). One of the first tasks that dealt with monitoring vigilance was the Mackworth clock task (Mackworth, 1948). It consisted of a prolonged check of a clock's large dial face and detection of rare, irregular jumps of the clock hand. The test lasted 2 hours and was used primarily to measure sustained concentration in air traffic controllers. Based on the test, other vigilant assessment tools were created, often referred to as continuous performance tests (CPTs). These tasks are characterized by a low occurrence probability of a signal according to the criterion and an uncomplicated information selection rule. Existing studies have indicated vigilance deficiency in children with ADHD (Berger et al., 2013; Boxhoorn et al., 2018; Egeland, Johansen, & Ueland, 2009). Continuous performance tests tests are a common neuropsychological tool used in disorder prediction (Berger et al., 2013). It should be noted that not all researchers have indicated significant differences in ADHD presentation types in terms of vigilance (Chhabildas et al., 2001; Tucha et al., 2006)—we described possible response patterns in cognitive tests above.

Inhibitory control is considered an aspect of executive control. It is a mental process which allows for delaying or blocking a premature reaction that has been previously learned and reinforced, as well as for organizing a response using attention and reasoning (Schall et al., 2017). Inhibitory control determines a suitable reaction, adapted to changing situational requirements. It contributes to anticipation, goal setting, and planning. Three levels of inhibitory control can be distinguished: motor, attentional, and behavioral (Nigg, 2001; Schall et al., 2017). The first level concerns the reduction of hyperactive and impulsive activity patterns. The second pertains to the organization of selective attention. The last one involves controlling behavior related to emotions and affect. One of the most popular tools for measuring inhibitory control is the Stroop task, which uses the effect of interference (Okruszek & Rutkowska, 2013). The task is to name the font color of words that are names of other colors. Naming a color is a less automated process and is more time-consuming than reading a word. According to studies to date, deficient inhibitory control is one of the evident deficits in children with ADHD, next to limited vigilance (Nigg, 2001). However, not all researchers revealed significant differences in the ADHD types of presentation regarding inhibition (Chhabildas et al., 2001; Tucha et al., 2006).

OBJECTIVE OF THE STUDY

Previous studies have shown prefrontal hypoperfusion as well as different patterns of cortical activity and response in cognitive tests in children with ADHD. Moreover, lower cortical activation was observed at the visual information processing stage in ADHD. Thus, the purpose of our study was to seek answers to the following research questions:

1. Is there a difference between ADHD children and typically developing (TD) children with regard to vigilance and inhibitory control? Do significant differences occur between the different ADHD presentation types as well?
2. Do children with ADHD display different regional cerebral blood oxygenation (rCBO2) in PFC compared to TD children in resting state? Do significant differences occur between the different ADHD presentation types as well?
3. Do children with ADHD have a different rCBO2 growth in mPFC compared to TD children in conditions of a cognitive task regarding vigilance? Do significant differences occur between the different ADHD presentation types as well?

4. Are errors in the cognitive task regarding vigilance related to the level of rCBO2 in mPFC?

We put forward the following hypotheses. (a) children with ADHD may exhibit deficits in vigilance and inhibitory control. Children with ADHD-HI and ADHD-C may show more commission errors in the vigilance task compared to children with ADHD-A. Children with ADHD-A and ADHD-C may exhibit more omissions in the vigilance task and a longer RT in the inhibitory control task compared to children with ADHD-HI; (b) children with ADHD may exhibit hypoperfusion in the PFC. Children with ADHD-I may display higher rCBO2 in the lPFC than children with ADHD-HI and ADHD-C. Children with ADHD-HI may display higher rCBO2 in the mPFC compared to children with ADHD-I and ADHD-C. (c) TD children may exhibit a bigger increase in rCBO2 during a cognitive task than children with ADHD. (d) The number of omission errors may be more closely related to the increase in rCBO2 in the mPFC compared to the number of commission errors. The data obtained will enable a better understanding of ADHD issues.

MATERIALS AND METHODS

The study was conducted in 2019. Participation in the study required the consent of the children and their parent or legal guardian. The study involved 150 children aged 9-12 years (M = 10.43, SD = 1.12) diagnosed with ADHD by a neurologist or pediatric psychiatrist. The diagnosis was also confirmed by a psychologist based on a structured diagnostic test of psychomotor hyperactivity as per the DSM-5. Children were categorized due to ADHD presentation types: 49 children exhibited ADHD-I symptoms (38 boys and 11 girls), 47 children showed ADHD-HI symptoms (39 boys and 8 girls), while 54 children displayed ADHD-C symptoms (42 boys and 12 girls). None of the patients received pharmacotherapy in relation to the ADHD diagnosis (participation condition). The comparison group consisted of 51 TD children (39 boys and 11 girls) aged 9-12 years (M = 10.72, SD = 1.28). The absence of neurological diseases as well as intellectual capacity within the standard constituted recruitment prerequisites for both groups. Recruitment was carried out among patients of psychological and pedagogical support centers in Polish cities: Warsaw, Kraków, Wrocław and Rzeszów.

The following methods were employed in the study:

–Raven's Colored Progressive Matrices (CPM) in a Polish normalization (Szustrowa & Jaworowska, 2003) for measuring fluid intelligence in children. The tool consists of 36 tasks in the form of incomplete matrices (patterns). The participants identify the missing matrix fragment from a choice of possible options.

–Shortened version of the Mackworth Clock Task for measuring vigilance. The participants observe a moving clock hand on the screen. The hand moves in regular jumps every 1 s, like the second hand of an analog clock. At irregular and rare intervals, the hand makes a double jump by 2 s. The participants' task is to detect double hand jumps by pressing a button. The number of omission and commission errors is recorded. The shortened version of the test lasts 5 min (300 hand jumps). During the test, there are 18 irregular (double) hand jumps (6% probability).

–The Stroop Task for assessing inhibitory control. The screen displays single words denoting the names of colors. The participant's task is to react to the font color (red, green, blue and yellow) by pressing the right button, at the same time ignoring the meaning of the words. The trial lasts approximately 5 min and consists of 40 boards with control tasks (with the font color congruent with the meaning of the word) and 40 boards with interference tasks (font color incongruent with the meaning of the word) interlaced with one another. The test measures the average RT for correct responses in control and interference tasks, as well as the difference between mean values.

The Mackworth clock task and Stroop task were administered through Java computer applications. The tasks were presented on a 19 in. screen. The distance of the participants from the screen was about 70 cm.

–The hemoencephalography system (32 samples/sec) using near infrared spectroscopy (NIRS) together with a 10-channel FlexComp Infiniti amplifier was used for rCBO2 recording. This measurement method uses different optical properties (light absorption) of hemoglobin (Hb) and oxyhemoglobin (oxy-Hb). The HEG system consists of an emission optode, that is, two electroluminescent diodes (LEDs) mounted next to each other, which alternately emit red light at 660 nm and infrared light at 850 nm, as well as a detection optode (optical probe). The light beams are dispersed, refracted, and reflected. A small amount of light, modified by absorption, returns to the surface (Toomim et al., 2004). The light absorption by Hb and oxy-Hb for a wavelength of 800-850 nm is similar and is very low. For wavelengths below this value, Hb absorbs light strongly and reflects it poorly, whereas oxy-Hb reflects light strongly and absorbs it poorly. The role of the optical probe is to detect reflected light in order to determine the local level of hemoglobin saturation with oxygen. Red light is the measure of hemoglobin saturation with oxygen, whereas infrared light serves as a reference value. As per the modified Beer-Lambert law, the depth of light beam penetration depends on the distance between the emission and detection optode and equals up to 1/2 of that distance (Maikala, 2010). In the case of the HEG system, the distance between the optodes equals 3 cm. Therefore, the light penetrates up to 1.5 cm and reaches the capillaries in the gray matter at the base of the cerebral cortex (Wolf & Greisen, 2009). The HEG system is designed to prevent light permeation into the environment and the influence of external light. Peripheral blood pressure has only a slight effect on capillary oxygenation, which is mainly controlled by the energy demand of the tissue. Thus, hemoglobin saturation with oxygen is a convenient and useful measure of local cerebral perfusion. The obtained data were processed in Biograph Infiniti 6.2 (including data filtering). The measure of rCBO2 was the HEG ratio, calculated from the formula: HEG red / HEG IR × 200, where HEG red denotes the values of reflected red light and HEG IR denotes the values of reflected infrared light based on the mean value recorded with the optodes. Changes in rCBO2 are assessed using HEG gain, that is, the percentage slope of the HEG ratio calculated from the following formula: mean value of the HEG ratio from the measurement / mean from the first 10 s –1.

Test Procedure

Fluid intelligence was assessed 3-4 days before the study during the project qualification. The study was of a quasi-experiment nature. At first, the rCBO2 (HEG ratio) was measured in the prefrontal areas of Fp1, Fpz, and Fp2, in a 10:20 system, in resting state with open eyes (for 1 min). Next, the participants performed the cognitive tasks: the Mackworth clock task and the Stroop task, which were preceded by a short training session. During the Mackworth clock task, HEG gain was measured at Fpz for one minute (at the beginning of the test, at the same time for each participant). The HEG gain measurement procedure followed the recommendations of the ethics committee regarding the limitation of excessive testing in children. The total experiment time for one participant was about 20 minutes (without fluid intelligence assessment).

Statistical Data Analysis

Statistical data analysis was conducted using IBM SPSS Statistics version 26. Normality distribution was verified using the Kolgomorov-Smirnov test. Levene's test was used to assess the homogeneity of variance. The results obtained allowed for applying parametric tests. Multivariate repeated ANOVA was used to determine the significance level of differences. Tukey's test was used for post hoc comparisons. Pearson's *r* correlation analysis was used to determine the relations between variables. The effect size was assessed based on partial η^2.

RESULTS

Mean values compared between groups in terms of fluid intelligence, vigilance, inhibitory control, and rCBO2 are shown in Table 1. The analyses did not reveal statistically significant differences between ADHD and TD children regarding fluid intelligence. Moreover, age and sex did not have a statistically significant impact on the results.

In order to check whether the ADHD presentation type affects vigilance, we conducted a one-way multivariate repeated analysis of variance (ANOVA). The factor measured between individuals was inclusion in one of the research groups, while the dependent variables included omission and commission errors. The results showed a statistically significant multidimensional group membership effect, $F(6, 394) = 19.22$, $p < .001$, $\eta^2 = .23$. Univariate *F* tests displayed significant effects for both controlled variables. For omission errors, $F(3, 197) = 29.36$, $p < .001$, $\eta^2 = .31$, and for commission errors, $F(3, 197) = 19.53$, $p < .001$, $\eta^2 = .23$. Post hoc comparisons were used to assess the differences. Children with ADHD had more omission and commission errors compared to TD children ($p < .001$). Children with ADHD-HI had more commission errors than children with ADHD-I ($p = .033$). Children with ADHD-I had more omission errors than children with ADHD-HI ($p = .025$). Children with ADHD-C had more omission errors than children with ADHD-HI ($p = .002$) and more commission errors than children with ADHD-I ($p = .001$). Other comparisons proved to be statistically insignificant.

The ANOVA confirmed the multidimensional effect of group membership on inhibitory control, $F(6, 394) = 19.29$, $p < .001$, $\eta^2 = .23$. Univariate *F* tests showed significant effects on the dependent variables. For simple trial RTs, $F(3, 197) = 18.65$, $p < .001$, $\eta^2 = .22$, for interference trial RTs, $F(3, 197) = 38.65$, $p < .001$, $\eta^2 = .37$, and for the RT difference between the trials, $F(3, 197) = 27.09$, $p < .001$, $\eta^2 = .29$. According to post hoc comparisons, children with ADHD showed longer RTs in simple and interference trials (ADHD-HI vs. control group RT in simple trials: $p = .038$, in other cases, $p < .001$), as well as higher RT differences between trials (ADHD-HI vs. control group: $p = .001$, in other cases, $p < .001$) compared to TD children. Children with ADHD-I had longer RTs in simple ($p = .037$) and interference ($p = .001$) trials, as well as greater

TABLE 1.
Intelligence, Vigilance, Inhibitory Control and rCBO2 in ADHD and TD Children

	ADHD-HI (*N* = 47)		ADHD-I (*N* = 49)		ADHD-C (*N* = 54)		TD children (*N* = 51)	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
CPM	73.04	12.16	72.67	9.68	70.96	10.33	73.59	9.05
Mackworth clock task (number of errors)								
Omissions	7.32	3.07	8.71	2.50	9.13	2.37	4.96	1.95
Commissions	6.74	2.08	5.43	2.61	7.19	2.29	4.10	2
Stroop task RT								
Simple trials	2561.89	1086.95	3036.06	875.41	3252.94	867.48	2094.67	532.69
Interference trials	3135.06	1098.47	3842.49	942.26	4075.39	829.32	2406.47	538.41
Difference	573.17	357.03	806.43	316.31	822.44	438.09	311.80	109
HEG ratio in resting state								
Fp1	76.24	8.93	84.29	9.59	73.72	7.27	100.71	16.88
Fpz	87.74	16.71	79.59	11.02	77.57	8.52	105.26	19.23
Fp2	79.72	13.04	78.81	10.95	77.61	8.31	103.83	15.01
HEG ratio slope in a cognitive task								
Fpz HEG Gain	3.77	2.44	2.33	1.72	2.04	1.48	9.51	1.70

Note. rCBO2 = regional cerebral blood oxygenation, ADHD = attention deficit hyperactivity disorder, ADHD-HI = hyperactive-impulsive type, ADHD-I = inattentive type, ADHD-C = combined type, TD = typically developing *N* = number of observations, *CPM* = Raven's Colored Progressive Matrices (result in centiles), *RT* = reaction time in ms, *Fp1*, *Fpz*, *Fp2* = locations according to the 10:20 placement, successively: left prefrontal cortex, medial prefrontal cortex, right prefrontal cortex.

RT differences between trials (p = .004) than children with ADHD-HI. Children with ADHD-C obtained longer RTs in simple and interference trials (p < .001), as well as bigger RT differences between trials (p = .001) than children with ADHD-HI. Other comparisons proved to be statistically insignificant.

The ANOVA confirmed the multidimensional effect of group membership on rCBO2, $F(12, 588) = 25.55$, $p < .001$, $\eta^2 = .34$. Univariate F tests showed significant effects on the dependent variables. For the HEG ratio in Fp1 in resting state, $F(3,197) = 59.48$, $p < .001$, $\eta^2 = .48$, for the HEG ratio in Fpz in resting state, $F(3, 197) = 39.20$, $p < .001$, $\eta^2 = .37$, for the HEG ratio in Fp2 in resting state, $F(3, 197) = 55.80$, $p < .001$, $\eta^2 = .46$, and for the HEG gain in Fpz in a comparative task pertaining to vigilance, $F(3, 197) = 181.51$, $p < .001$, $\eta^2 = .73$. According to post hoc comparisons, TD children showed a higher HEG ratio in all controlled locations in resting state and a higher HEG gain in the cognitive task compared to children with ADHD (p < .001). Children with ADHD-HI obtained a higher HEG ratio in Fpz in resting state than children with ADHD-I (p = .031) and ADHD-C (p = .003), as well as a higher HEG gain in the cognitive task compared to children with ADHD-I (p = .001) and ADHD-C (p < .001). Children with ADHD-I obtained a higher HEG ratio in Fp1 in resting state than children with ADHD-HI (p = .003) and ADHD-C (p < .001). Other comparisons proved to be statistically insignificant.

A correlation matrix was used in order to determine the relation between the HEG ratio slope (HEG gain) in Fpz and vigilance. HEG gain showed a statistically significant correlation with omission and commission errors. Detailed results are presented in Table 2.

DISCUSSION

The study confirmed all of the formulated hypotheses.

Children with ADHD have exhibited a vigilance deficit. Moreover, the ADHD presentation type determined the response patterns among the participants. Children with higher intensity of hyperactive-impulsive symptoms (ADHD-HI, ADHD-C) were more prone to making commission errors, whereas children with more pronounced inattentiveness symptoms (ADHD-I, ADHD-C) were more likely to make omission errors. This seems understandable, since commission errors are considered to be a measure of impulsive behavior, whereas omission errors indicate distracted attention (inattentiveness). It should be added that in our case, the task lasted only 5 min. A significant reduction in performance is observed after 30-45 min of continuous attention, mainly as a result of energy loss. The effects during school classes may be much more significant if concentration in cycles of 45 min is required. Our findings are consistent with previous studies on vigilance deficits in children with ADHD using the paradigm of continuous performance, both in traditional tests and virtual reality (VR; Berger et al., 2013; Boxhoorn et al., 2018; Cueli et al., 2015; Egeland et al., 2009; González-Castro et al., 2013). Interestingly, according to recent studies, CPTs in VR technology show greater diagnostic power (sensitivity and specificity) regarding ADHD compared to standard computer tests (Areces et al., 2018). These tools allow for correcting the results using other recorded parameters, such as head or eyeball movement or viewing angle. Finally, it should be noted that not all studies revealed differences between ADHD presentation types in terms of vigilance. For example, in the Tucha et al. (2006) study, children with different ADHD presentation types showed similar (significant) vigilance deficit.

TABLE 2.
Correlation Coefficient Between HEG Gain Versus Omission and Commission Errors.

HEG gain	*Omissions*	*Commissions*
ADHD-HI (N = 47)	−.57***	−.33*
ADHD-I (N = 49)	−.56***	−.35*
ADHD-C (N = 54)	−.53***	−.37**
TD children (N = 51)	−.58***	−.34*
Total (N = 201)	−.56***	−.35***

* p < .05, ** p < .01, *** p < .001

Children with ADHD showed greater susceptibility to an interference effect and, therefore, a deficit of inhibitory control. Significant differences between ADHD presentation types were obtained. Children with ADHD-I and ADHD-C presentation types achieved lower results than children with ADHD-HI. Our findings are in line with previous reports (Li et al., 2008; Nigg et al., 2005), and indirectly with the study by Schmitz et al. (2002), who did not observe any differences between ADHD-HI and the control group. A slower RT indicates low quality of information from the stimulus. A longer response in cognitive tasks (regardless of the content) is a common observation in children with ADHD-I and ADHD-C compared to children with ADHD-HI (Areces et al., 2018; González-Castro et al., 2013). However, a slower RT does not compensate for the number of errors made in the tasks. It should be added that the proper performance of the Stroop task requires the involvement of other cognitive functions, including working memory and selective attention, which may also explain worse results in children with ADHD-I and ADHD-C presentation types.

Children with ADHD exhibited reduced PFC oxidation at each of the controlled sites. It is estimated that 87% of children with attention deficit disorders are affected by hypoperfusion (Amen et al., 2012). The ADHD presentation type determined PFC oxidation. Children with higher intensity of hyperactive-impulsive symptoms (ADHD-HI, ADHD-C) showed lower rCBO2 in the lPFC, whereas children with more severe symptoms of inattentiveness (ADHD-I, ADHD-C) presented lower rCBO2 in the mPFC. According to previous reports, cortical activity in the lPFC correlates primarily with the inhibitory control of the response and the control of motor impulsiveness (Loose et al., 2003). Activity in the mPFC is mainly related to vigilance (Rodríguez et al., 2016). Activity in the rPFC correlates with emotion and affect control (Liu et al., 2012; Salas et al., 2016). Some researchers also link activity in the rPFC with the controlled processing of attentive information of neutral emotional content, but the relationship between the inhibition of this content and the lPFC is generally more pronounced (Goya-Maldonado et al., 2010; Jourdan Moser et al., 2009). To our knowledge, this is the second study which assesses rCBO2 in

ADHD presentation types using the HEG system. The results support the previous findings of Rodríguez et al. (2011). Our measurement was carried out on a larger cohort, which increases the possibility of generalizing conclusions.

Our study showed low activation of the mPFC in children with ADHD in the vigilance task. Typically developing children showed a bigger growth of rCBO2 at the stage of visual information processing compared to children with ADHD. It is believed that rCBO2 may vary ± 10% depending on the activity context (Mize, 2004). We used HEG gain to assess the differences because rCBO2 growth was linear in nature. We assumed that this method of assessing cortical activation, which determines the percentage increase of rCBO2, is easier to interpret compared to techniques of repeated measurement and differentiation of absolute values. Our findings are indirectly correlated with previous reports. Okazaki et al. (2002) observed lower cortical activation during CPTs in children with ADHD when testing event-related potentials. The administration of psychostimulants improved cortical activation and performance in CPTs, while the obtained results did not differ from the control group. Using functional NIRS, Miao et al. (2017) observed an increase of rCBO2 in the lPFC during the inhibitory control task (the Go/No-Go Task) in TD children, whereas children with ADHD showed reduced activation in this area. In our study we also observed differences in ADHD types of presentation. Children with more severe symptoms of inattentiveness (ADHD-I, ADHD-C) presented lower mPFC activation than children with ADHD-HI, which may account for the higher number of commission errors. It is believed that differences in cortical activation may be corrected with neurofeedback. In studies by Toomim et al. (2004), the differences in rCBO2 increase in children with ADHD compared to the control group disappeared after just a few sessions. Thus, reduced cortical activation in children with ADHD seems to be associated with deficits of self-control and motivation and may be corrected by external amplification. These assumptions are also supported by neuropsychological studies in which children with ADHD have significantly improved their performance in cognitive tests in conditions of increased motivation (McInerney & Kerns, 2003; Reijnen & Opwis, 2008). It should be noted that our measurement of rCBO2 was limited to a minute, which could increase the reported gain. After a few minutes of sustained attention, a decrease in cortical activation can be observed due to physiological fatigue (Mize, 2004; Toomim et al., 2004). Usually a short, even 20 s break allows for further efficiency. Finally, it should be noted that our results confirm the possibility of applying the HEG system in NIRS technology in brain hemodynamics imaging and, hence, cortical activation in neuropsychiatric development studies in children with ADHD. In previous studies, the HEG system allowed for differentiating cortical activation in cognitive content compared to emotional content (Serra-Sala et al., 2012) and proved to be more accurate in rCBO2 measurements than standard NIRS cameras due to the higher sampling rate (Gersten et al., 2009).

As a result of the analyses, we also obtained a linear relationship between mPFC activation and vigilance. The number of omissions proved to be more strongly correlated with the increase in rCBO2 (moderate dependence) compared to the number of commission errors (poor dependence). This observation supports the reports mentioned above when interpreting differences between groups regarding rCBO2. The MPFC seems more involved in sustaining attention and less in controlling response inhibition. In previous studies, commission errors correlated more strongly with the lPFC (González-Castro et al., 2013; Rodríguez et al., 2016).

The obtained intergroup effects were generally moderate (excluding cortical activation in the cognitive task, where a large effect was obtained). They highlight the nonhomogeneous symptoms in children within ADHD presentation types, which leads to difficulties in diagnosing the disorder. Previous studies have also been inconclusive (Chhabildas et al., 2001; Schmitz et al., 2002; Tucha et al., 2006). Furthermore, it seems that cognitive deficits in children with ADHD are not permanent neuropsychological impairments. The differences can be modulated by other disorder-related factors not included in the study, such as self-control, motivation, and energy deficits, as supported by recent reports (McInerney & Kerns 2003; Reijnen & Opwis 2008).

Our study is affected by certain limitations. The measurement technique used (HEG system) allowed for assessing rCBO2 in the brain tissue at a depth of about 1.5 cm. The instrument is equipped with one detection optode, which prevented the simultaneous assessment of cortical activation in other PFC areas during the cognitive task. However, we selected the HEG system due to the high sampling rate. The application of additional imaging techniques (e.g., SPECT) would allow for better assessment of differences in brain activity. In the case of the cortical activation measurement in PFC, the values of signals between correct and error trials were not differentiated – a recent study showed that activation in dorsomedial PFC are different between ADHD and TD in error NoGo trials but not in correct Go trials (Cai et al., 2019). The homogeneity of the participants' age made it impossible to draw any conclusions regarding the possible development of cortical activity and cognitive functions. Also, the occurrence of additional disorders that could affect the results was not controlled in the study. None of the participants underwent pharmacotherapy, which prevented the assessment of the impact of medication on rCBO2 and cognitive abilities. Taking these factors into account may prove to be an inspiration for further research. Despite the aforementioned limitations, our study introduced new data regarding rCBO2 patterns and cognitive deficits in children with ADHD. In the future, it could be worthwhile to use VR neuropsychological tests which allow for correcting results by recorded physiological parameters. The obtained data can be helpful in understanding cognitive dysfunctions in ADHD children.

Currently, there is no single test that would allow for an effective assessment of ADHD—TOVA- or MOXO-type CPTs serve as support in the diagnostic process (Areces et al., 2018; Dobrakowski & Łebecka, 2019). The most common method applied is clinical interview, which may lead to errors of insufficient or excessive diagnoses of the disorder (Hall et al., 2016; Lange et al., 2014). The data we have obtained have an applied value. They may be used in clinical practice, for example, in diagnosing ADHD. Children with ADHD may exhibit different

rCBO2 patterns in the prefrontal areas, lower cortical activation in the cognitive task, as well as deficiency of vigilance and inhibitory control. The results may vary depending on the ADHD presentation type. Children with more severe hyperactive-impulsive symptoms (ADHD-HI, ADHD-C) may exhibit lower rCBO2 in the lPFC as well as more commission errors. Children with more severe symptoms of inattentiveness (ADHD-I, ADHD-C) may display lower rCBO2 in the mPFC, lower cortical activation in the mPFC during the vigilance task, longer reaction time in neuropsychological tests, as well as more omission errors. Minor effects suggest differentiation within ADHD presentation types. We suggest that the conclusions obtained be treated only as support of the diagnosis process. In addition, our study confirmed the relationship between vigilance and increase of rCBO2 in the mPFC, as well as the possibility of applying the NIRS technique to assess cortical activation in cognitive tasks.

ACKNOWLEDGEMENTS

In loving memory of my mom, Violetta Futkowska (†56), who passed away when I was working on this manuscript - SS (first author).

Funding. The study was conducted within the framework of project no. RPMP.01.02.03-12-0165/19 co-financed by the European Union from the European Regional Development Fund.

Author contributions. SS (65%) and PD (35%) designed the experiments and wrote the paper. SS conducted the experiments and analyzed the data.

Conflict of interest statement. The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Ethical approval. All procedures performed in studies involving human participants were in accordance with the ethical standards of The Committee for Ethics in Scientific Research of The Institute of Psychology, Polish Academy of Science (Research project approval # 15/VIII/2019).

REFERENCES

Amen, D. G., Highum, D., Licata, R., Annibali, J. A., Somner, L., Pigott, H. E., … Willeumier, K. (2012). Specific ways brain SPECT imaging enhances clinical psychiatric practice. *Journal of Psychoactive Drugs, 44*, 96–106. doi: 10.1080/02791072.2012.684615

Apostolova, I., Derlin, T., Salamon, J., Amthauer, H., Granström, S., Brenner, W., … Buchert, R. (2015). Cerebral glucose metabolism in adults with neurofibromatosis type 1. *Brain Research, 1625*, 97–101. doi: 10.1016/j.brainres.2015.08.025

Areces, D., Rodríguez, C., García, T., Cueli, M., & González-Castro, P. (2018). Efficacy of a continuous performance test based on virtual reality in the diagnosis of ADHD and its clinical presentations. *Journal of Attention Disorders, 22*, 1081–1091. doi: 10.1177/1087054716629711

Arns, M., Gunkelman, J., Breteler, M., & Spronk, D. (2008). EEG phenotypes predict treatment outcome to stimulants in children with ADHD. *Journal of Integrative Neuroscience, 7*, 421–438. doi: 10.1142/S0219635208001897

Barry, R. J., Clarke, A. R., & Johnstone, S. J. (2003). A review of electrophysiology in attention-deficit/hyperactivity disorder: I. Qualitative and quantitative electroencephalography. *Clinical Neurophysiology, 114*, 171–183. doi: 10.1016/S1388-2457(02)00362-0

Berger, I., Slobodin, O., Aboud, M., Melamed, J., & Cassuto, H. (2013). Maturational delay in ADHD: evidence from CPT. *Frontiers in Human Neuroscience, 7*, e691. doi: 10.3389/fnhum.2013.00691

Biederman, J., Kwon, A., Aleardi, M., Chouinard, V. A., Marino, T., Cole, H., … Faraone, S. V. (2005). Absence of gender effects on attention deficit hyperactivity disorder: Findings in nonreferred subjects. *American Journal of Psychiatry, 162*, 1083–1089. doi: 10.1176/appi.ajp.162.6.1083

Boxhoorn, S., Lopez, E., Schmidt, C., Schulze, D., Hänig, S., & Freitag, C. M. (2018). Attention profiles in autism spectrum disorder and subtypes of attention-deficit/hyperactivity disorder. *European Child and Adolescent Psychiatry, 27*, 1433–1447. doi: 10.1007/s00787-018-1138-8

Bush, G. (2011, June 15). Cingulate, frontal, and parietal cortical dysfunction in attention-deficit/hyperactivity disorder. *Biological Psychiatry, 69*, 1160–1167. doi: 10.1016/j.biopsych.2011.01.022

Cai, W., Griffiths, K., Korgaonkar, M. S., Williams, L. M., & Menon, V. (2019). Inhibition-related modulation of salience and frontoparietal networks predicts cognitive control ability and inattention symptoms in children with ADHD. *Molecular Psychiatry, 1-10*. doi: 10.1038/s41380-019-0564-4

Capa Kaya, G., Pekcanlar, A., Bekis, R., Ada, E., Miral, S., Emiroğlu, N., & Durak, H. (2002). Technetium-99m HMPAO brain SPECT in children with attention deficit hyperactivity disorder. *Annals of Nuclear Medicine, 16*, 527–531. doi: 10.1007/bf02988629

Chhabildas, N., Pennington, B. F., & Willcutt, E. G. (2001). A comparison of the neuropsychological profiles of the DSM-IV subtypes of ADHD. *Journal of Abnormal Child Psychology, 29*, 529–540. doi: 10.1023/A:1012281226028

Comings, D. E., Gade-Andavolu, R., Gonzalez, N., Wu, S., Muhleman, D., Blake, H., … P MacMurray, J. (2001). Comparison of the role of dopamine, serotonin, and noradrenaline genes in ADHD, ODD and conduct disorder: Multivariate regression analysis of 20 genes. *Clinical Genetics, 57*, 178–196. doi: 10.1034/j.1399-0004.2000.570304.x

Cueli, M., Rodríguez, C., García, T., Areces, D., & González-Castro, P. (2015). Estudio experimental sobre el Neurobiofeedback: una mejora de la concentración en el TDAH a través del nirHEG y la fluidez sanguínea [Experimental study on neurobiofeedback: improved ADHD concentration through nirHEG and blood fluidity]. *Revista de Psicología Clínica Con Niños y Adolescentes, 2*, 135–141.

Dobrakowski, P., & Łebecka, G. (2019). Individualized neurofeedback training may help achieve long-term improvement of working memory in children with ADHD. *Clinical EEG and Neuroscience, 51*, 94–101. doi: 10.1177/1550059419879020

Egeland, J., Johansen, S. N., & Ueland, T. (2009). Differentiating be-

tween ADHD sub-types on CCPT measures of sustained attention and vigilance. *Scandinavian Journal of Psychology, 50*, 347–354. doi: 10.1111/j.1467-9450.2009.00717.x

Fayyad, J., De Graaf, R., Kessler, R., Alonso, J., Angermeyer, M., Demyttenaere, K., … Jin, R. (2007). Cross-national prevalence and correlates of adult attention-deficit hyperactivity disorder. *British Journal of Psychiatry, 190*, 402–409. doi: 10.1192/bjp.bp.106.034389

Gersten, A., Perle, J., Raz, A., & Fried, R. (2009). Probing brain oxygenation with near infrared spectroscopy. *NeuroQuantology, 7*, 258–266.

González-Castro, P., Rodríguez, C., López, Á., Cueli, M., & Álvarez, L. (2013). Attention Deficit Hyperactivity Disorder, differential diagnosis with blood oxygenation, beta/theta ratio, and attention measures. *International Journal of Clinical and Health Psychology, 13*, 101–109. doi: 10.1016/S1697-2600(13)70013-9

Goya-Maldonado, R., Walther, S., Simon, J., Stippich, C., Weisbrod, M., & Kaiser, S. (2010). Motor impulsivity and the ventrolateral prefrontal cortex. *Psychiatry Research–Neuroimaging, 183*, 89–91. doi: 10.1016/j.pscychresns.2010.04.006

Hall, C. L., Valentine, A. Z., Groom, M. J., Walker, G. M., Sayal, K., Daley, D., & Hollis, C. (2016). The clinical utility of the continuous performance test and objective measures of activity for diagnosing and monitoring ADHD in children: a systematic review. *European Child and Adolescent Psychiatry, 25*, 677–699. doi: 10.1007/s00787-015-0798-x

Hechtman, L. (2005). Attention Deficit / Hyperactivity Disorder. In B. Sadock, V. Sadock, & H. Kaplan (Eds.), *Kaplan and Sadock's Comprehensive textbook of psychiatry* (pp. 3183–3212). Lippincott Williams & Wilkins.

Jourdan Moser, S., Cutini, S., Weber, P., & Schroeter, M. L. (2009). Right prefrontal brain activation due to Stroop interference is altered in attention-deficit hyperactivity disorder–A functional near-infrared spectroscopy study. *Psychiatry Research–Neuroimaging, 173*, 190–195. doi: 10.1016/j.pscychresns.2008.10.003

Koechlin, E., Ody, C., & Kouneiher, F. (2003). The architecture of cognitive control in the human prefrontal cortex. *Science, 302*(5648), 1181–1185. doi: 10.1126/science.1088545

Kollins, S. H. (2008). A qualitative review of issues arising in the use of psycho-stimulant medications in patients with ADHD and co-morbid substance use disorders. *Current Medical Research and Opinion, 24*, 1345–1357. doi: 10.1185/030079908x280707

Krain, A. L., & Castellanos, F. X. (2006). Brain development and ADHD. *Clinical Psychology Review, 26*, 433–444. doi: 10.1016/j.cpr.2006.01.005

Lange, K. W., Hauser, J., Lange, K. M., Makulska-Gertruda, E., Takano, T., Takeuchi, Y., … Tucha, O. (2014). Utility of cognitive neuropsychological assessment in attention-deficit/hyperactivity disorder. *ADHD Attention Deficit and Hyperactivity Disorders, 6*, 241–248. doi: 10.1007/s12402-014-0132-3

Langner, R., & Eickhoff, S. B. (2013). Sustaining attention to simple tasks: A meta-analytic review of the neural mechanisms of vigilant attention. *Psychological Bulletin, 139*, 870–900. doi: 10.1037/a0030694

Li, Q. Q., Guo, L. T., Huang, X. Z., Yang, C., Guo, T. Y., & Sun, J. H. (2008). Analysis on neuropsychological characteristics of subtypes of attention deficit hyperactivity disorder. *Zhonghua Er Ke Za Zhi. Chinese Journal of Pediatrics, 46*, 64–68.

Liu, J., Blond, B. N., van Dyck, L. I., Spencer, L., Wang, F., & Blumberg, H. P. (2012). Trait and state corticostriatal dysfunction in bipolar disorder during emotional face processing. *Bipolar Disorders, 14*, 432–441. doi: 10.1111/j.1399-5618.2012.01018.x

Loose, R., Kaufmann, C., Auer, D. P., & Lange, K. W. (2003). Human prefrontal and sensory cortical activity during divided attention tasks. *Human Brain Mapping, 18*, 249–259. doi: 10.1002/hbm.10082

Mackworth, N. H. (1948). The breakdown of vigilance during prolonged visual search. *Quarterly Journal of Experimental Psychology, 1*, 6–21. doi: 10.1080/17470214808416738

Maikala, R. V. (2010). Modified Beer's Law–historical perspectives and relevance in near-infrared monitoring of optical properties of human tissue. *International Journal of Industrial Ergonomics, 40*, 125–134. doi: 10.1016/j.ergon.2009.02.011

McGuire, J. T., & Botvinick, M. M. (2010). Prefrontal cortex, cognitive control, and the registration of decision costs. *Proceedings of the National Academy of Sciences of the United States of America, 107*, 7922–7926. doi: 10.1073/pnas.0910662107

McInerney, R. J., & Kerns, K. A. (2003). Time reproduction in children with ADHD: Motivation matters. *Child Neuropsychology, 9*, 91–108. doi: 10.1076/chin.9.2.91.14506

Miao, S., Han, J., Gu, Y., Wang, X., Song, W., Li, D., … Li, X. (2017). Reduced prefrontal cortex activation in children with attention-deficit/hyperactivity disorder during Go/No-Go task: A functional near-infrared spectroscopy study. *Frontiers in Neuroscience, 11*, e367. doi: 10.3389/fnins.2017.00367

Mihan, R., Shahrivar, Z., Mahmoudi-Gharaei, J., Shakiba, A., & Hosseini, M. (2018). Attention-deficit hyperactivity disorder in adults using methamphetamine: Does it affect comorbidity, quality of life, and global functioning? *Iranian Journal of Psychiatry, 13*, 111–118.

Millichap, J. G. (2008). Etiologic classification of attention-deficit/hyperactivity disorder. *Pediatrics, 121*, 358–365. doi: 10.1542/peds.2007-1332

Mize, W. (2004). Hemoencephalography–A new therapy for attention deficit hyperactivity disorder (ADHD): Case report. *Journal of Neurotherapy, 8*, 77–97. doi: 10.1300/J184v08n03_06

Nigg, J. T. (2001). Is ADHD a disinhibitory disorder? *Psychological Bulletin, 127*, 571–598. doi: 10.1037/0033-2909.127.5.571

Nigg, J. T., Stavro, G., Ettenhofer, M., Hambrick, D. Z., Miller, T., & Henderson, J. M. (2005). Executive functions and ADHD in adults: Evidence for selective effects on ADHD symptom domains. *Journal of Abnormal Psychology, 114*, 706–717. doi: 10.1037/0021-843X.114.3.706

Okazaki, S., Maekawa, H., Ozaki, H., & Futakami, S. (2002). Topographic changes of ERP during a CPT-AX task at pre- and post-medication of methylphenidate in children with ADHD. *International Congress Series, 1232*, 705–710. doi: 10.1016/S0531-5131(01)00814-7

Okruszek, Ł., & Rutkowska, A. (2013). Badanie kontroli wykonawczej za pomocą Testu Interferencji Stroopa u chorych na schizofrenię i osób z uszkodzeniami płatów czołowych [Executive control ability in Stroop task in patients with schizophrenia and in patients with frontal lobe lesions]. *Polskie Forum Psychologiczne, 18*, 215–225.

Öner, Ö., Öner, P., Aysev, A., Küçük, Ö., & Ibis, E. (2005). Regional cerebral blood flow in children with ADHD: Changes with age. *Brain and Development, 27*, 279–285. doi: 10.1016/j.braindev.2004.07.010

Paclt, I., Přibilová, N., Kollárová, P., Kohoutová, M., Dezortová, M., Hájek, M., & Csemy, L. (2016). Reverse asymmetry and changes in brain structural volume of the basal ganglia in ADHD, developmental changes and the impact of stimulant medications. *Neuroendocrinology Letters, 37*, 29–32.

Petrides, M., Tomaiuolo, F., Yeterian, E. H., & Pandya, D. N. (2012). The prefrontal cortex: Comparative architectonic organization in the human and the macaque monkey brains. *Cortex, 48*, 46–57. doi: 10.1016/j.cortex.2011.07.002

Qiu, M. G., Ye, Z., Li, Q. Y., Liu, G. J., Xie, B., & Wang, J. (2011). Changes of Brain structure and function in ADHD children. *Brain Topography, 24*(3–4), 243–252. doi: 10.1007/s10548-010-0168-4

Reijnen, E., & Opwis, K. (2008). Visual search in children with ADHD: The influence of feedback on selective attention. *Journal of Vision, 8*, 774–774.

Reinhardt, M. C., & Reinhardt, C. A. U. (2013). Attention deficit-hyperactivity disorder, comorbidities, and risk situations. *Jornal de Pediatria, 89*, 124–130. dio: 10.1016/j.jped.2013.03.015

Rodríguez, C., Fernández-Cueli, M., González-Castro, P., Álvarez, L., & Álvarez-García, D. (2011). Cortical blood flow differences in ADHD subtypes. Preliminary study. *Aula Abierta, 39*, 25–36.

Rodríguez, C., González-Castro, P., Cueli, M., Areces, D., & González-Pienda, J. A. (2016). Attention deficit/hyperactivity disorder (ADHD) diagnosis: An activation-executive model. *Frontiers in Psychology, 7*, e1406. doi: 10.3389/fpsyg.2016.01406

Salas, C. E., Castro, O., Yuen, K. S., Radovic, D., d'Avossa, G., & Turnbull, O. H. (2016). 'Just can't hide it': a behavioral and lesion study on emotional response modulation after right prefrontal damage. *Social Cognitive and Affective Neuroscience, 11*, 1528–1540. doi:10.1093/scan/nsw075

Schall, J. D., Palmeri, T. J., & Logan, G. D. (2017). Models of inhibitory control. *Philosophical Transactions of the Royal Society B: Biological Sciences, 372*, e0193. doi: 10.1098/rstb.2016.0193

Schmitz, M., Cadore, L., Paczko, M., Kipper, L., Chaves, M., Rohde, L. A., … Knijnik, M. (2002). Neuropsychological performance in DSM-IV ADHD subtypes: An exploratory study with untreated adolescents. *Canadian Journal of Psychiatry, 47*, 863–869. doi: 10.1177/070674370204700908

Serra-Sala, M., Timoneda-Gallart, C., & Pérez-Álvarez, F. (2012). Evaluating prefrontal activation and its relationship with cognitive and emotional processes by means of hemoencephalography (HEG). *Journal of Neurotherapy, 16*, 183–195. doi: 10.1080/10874208.2012.705754

Sripada, C. S., Kessler, D., & Angstadt, M. (2014). Lag in maturation of the brain's intrinsic functional architecture in attention-deficit/hyperactivity disorder. *Proceedings of the National Academy of Sciences of the United States of America, 111*, 14259–14264. doi: 10.1073/pnas.1407787111

Szustrowa, T., & Jaworowska, A. (2003). *TMK–Test Matryc Ravena w Wersji Kolorowej* [Raven's Colored Progressive Matrices]. Pracownia Testów Psychologicznych.

Thomson, D. R., Besner, D., & Smilek, D. (2015). A resource-control account of sustained attention. P*erspectives on Psychological Science, 10*, 82–96. doi: 10.1177/1745691614556681

Toomim, H., & Carmen, C. (2009). Hemoencephalography: photon-based blood flow neurofeedback. In T. Budzynski, H. Budzynski, J. Evans, & A. Abarbanel (Eds.), *Introduction to quantitative EEG and neurofeedback: Advanced theory and applications* (pp. 169–194). Academic Press.

Toomim, H., Mize, W., Kwong, P. C., Toomim, M., Marsh, R., Kozlowski, G. P., … Rémond, A. (2004). Intentional increase of cerebral blood oxygenation using hemoencephalography (HEG): An efficient brain exercise therapy. *Journal of Neurotherapy, 8*, 5–21. doi: 10.1300/J184v08n03_02

Tucha, O., Walitza, S., Mecklinger, L., Sontag, T. A., Kübber, S., Linder, M., & Lange, K. W. (2006). Attentional functioning in children with ADHD - Predominantly hyperactive-impulsive type and children with ADHD - Combined type. *Journal of Neural Transmission, 113*, 1943–1953. doi: 10.1007/s00702-006-0496-4

von Polier, G. G., Vloet, T. D., & Herpertz-Dahlmann, B. (2012). ADHD and delinquency–A developmental perspective. *Behavioral Sciences and the Law, 30*, 121–139. doi: 10.1002/bsl.2005

Wolf, M., & Greisen, G. (2009). Advances in near-infrared spectroscopy to study the brain of the preterm and term neonate. *Clinics in Perinatology, 36*, 807–834. doi: 10.1016/j.clp.2009.07.007

RECEIVED 08.02.2020 | ACCEPTED 15.06.2020

SUPPLEMENTARY MATERIAL

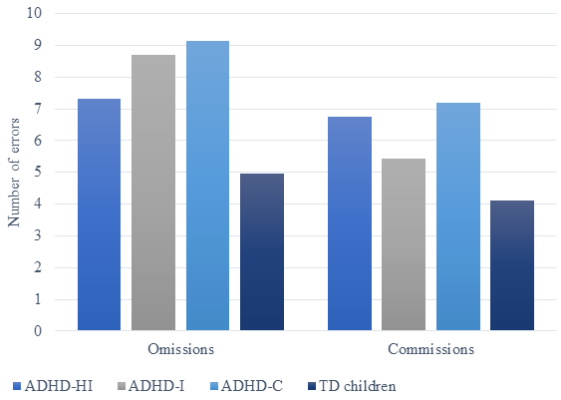

FIGURE 1.

Vigilance (the Mackworth clock task) in ADHD and typically developing (TD) children. ADHD-HI = hyperactive-impulsive type, ADHD-I = inattentive type, ADHD-C = combined type.

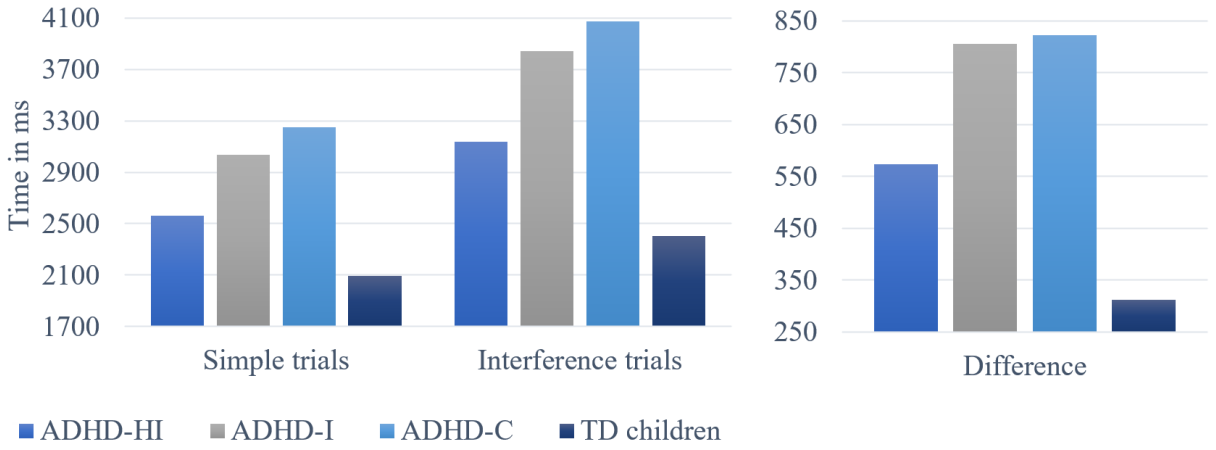

FIGURE 2.

Inhibitory control (the Stroop task) in ADHD and TD children. ADHD-HI = hyperactive-impulsive type, ADHD-I = inattentive type, ADHD-C = combined type.

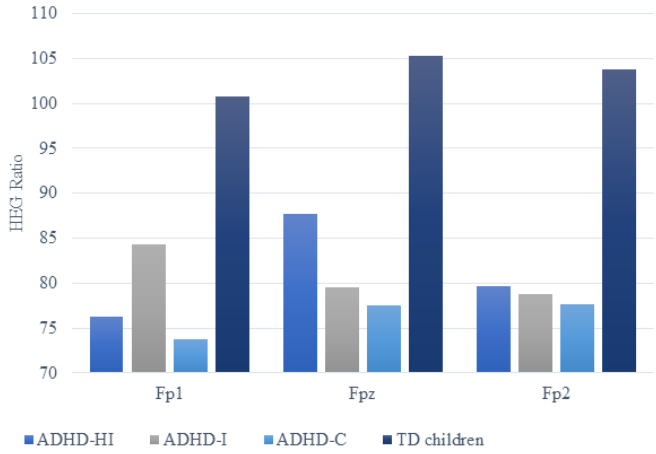

FIGURE 3.

HEG Ratio in resting state in ADHD and TD children. ADHD-HI = hyperactive-impulsive type, ADHD-I = inattentive type, ADHD-C = combined type.

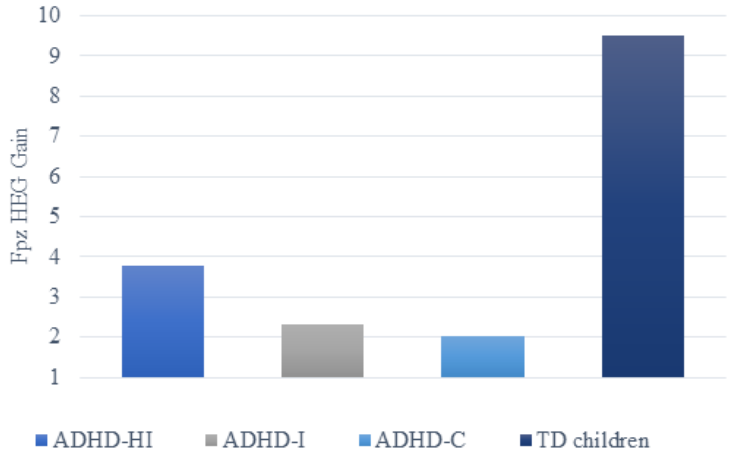

FIGURE 4.

HEG Ratio slope in a cognitive task in ADHD and TD children. ADHD-HI = hyperactive-impulsive type, ADHD-I = inattentive type, ADHD-C = combined type.