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REGULATORY FUNCTIONS AND ACADEMIC PERFORMANCE IN ADOLESCENTS: NEUROPSYCHOLOGICAL AND EEG STUDY

FUNCIONES REGULADORAS Y RENDIMIENTO ACADÉMICO EN ADOLESCENTES: ESTUDIO NEUROPSICOLÓGICO Y EEG

FUNÇÕES REGULATÓRIAS E DESEMPENHO ACADÊMICO EM ADOLESCENTES: ESTUDO NEUROPSICOLÓGICO E DE EEG

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Palabras clave: Funciones ejecutivas; Rendimiento académico; Sistemas córtico-subcorticales; Análisis EEG.

Palavras-chave: Funções executivas; Desempenho académico; Sistemas córtico-subcorticais; Análise EEG.

ABSTRACT

The aim of the study was to analyze the relationship between brain executive functions (EF) and academic performance in adolescents, and to investigate the dependence of this relationship on the brain cortico-subcortical regulatory systems. We used an interdisciplinary approach including qualitative neuropsychological and EEG analyses of brain regulatory functions. Both methods were based on A.R. Luria's principle of qualitative syndrome analysis of deviations of cognitive (in case of neuropsychological assessment) or brain functional systems (in case of EEG analysis). The study has found correlations between the efficiency of the brain's executive functions and academic performance in adolescents aged 12-16 years. The dependence of these correlations on the brain regulatory cortico-subcortical systems was revealed: the specific relations were found between academic performance in the Russian language and math and separate EF components in groups of adolescents with EEG signs of suboptimal functioning of fronto-thalamic, fronto-limbic and fronto-basal systems.

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R E S U M E N

El objetivo del estudio fue analizar la relación entre las funciones ejecutivas cerebrales (FE) y el rendimiento académico en adolescentes, e investigar la dependencia de esta relación de los sistemas reguladores cortico-subcorticales cerebrales. Utilizamos un enfoque interdisciplinar que incluía análisis cualitativos neuropsicológicos y EEG de las funciones reguladoras cerebrales. Ambos métodos se basaron en el principio de A.R. Luria de análisis cualitativo del síndrome de las desviaciones de los sistemas cognitivos (en el caso de la evaluación neuropsicológica) o funcionales cerebrales (en el caso del análisis EEG). El estudio ha encontrado correlaciones entre la eficiencia de las funciones ejecutivas del cerebro y el rendimiento académico en adolescentes de 12 a 16 años. Se reveló la dependencia de estas correlaciones de los sistemas reguladores cerebrales cortico-subcorticales: se hallaron relaciones específicas entre el rendimiento académico en lengua rusa y matemáticas y componentes separados de las FE en grupos de adolescentes con signos EEG de funcionamiento subóptimo de los sistemas fronto-talámico, fronto-límbico y fronto-basal.

R E S U M O

O objetivo do estudo foi analisar a relação entre as funções executivas (FE) cerebrais e o desempenho acadêmico em adolescentes e investigar a dependência dessa relação com os sistemas reguladores córtico-subcorticais cerebrais. Usamos uma abordagem interdisciplinar que incluiu análises neuropsicológicas qualitativas e de EEG das funções reguladoras do cérebro. Ambos os métodos foram baseados no princípio de A.R. Luria de análise de síndrome qualitativa de desvios de sistemas cognitivos (no caso de avaliação neuropsicológica) ou funcionais do cérebro (no caso de análise de EEG). O estudo encontrou correlações entre a eficiência das funções executivas do cérebro e o desempenho acadêmico em adolescentes de 12 a 16 anos. A dependência dessas correlações com os sistemas córtico-subcorticais reguladores do cérebro foi revelada: as relações específicas foram encontradas entre o desempenho acadêmico no idioma russo e em matemática e os componentes separados das FE em grupos de adolescentes com sinais de EEG de funcionamento abaixo do ideal dos sistemas fronto-talâmico, fronto-límbico e fronto-basal.

In adolescence, the role of self-coordination and self-management skills in school learning increases dramatically due to both the increased complexity of educational tasks and a larger portion of independent study. Such changes imply heightened cognitive demands associated not only with the information processing, but also with voluntary control of mental activity and behavior attributed as executive functions (EF). It is known that EF maturity in preschool and primary school children significantly affects their acquisition of new skills and, more generally, their academic performance (Zakharova et al., 2022). The relationship between EF and academic performance has not been studied as much for adolescents. The development of EF is significantly influenced by both social experiences and neurodevelopmental changes. An interdisciplinary approach combining neuropsychological assessment with electroencephalographic (EEG) analysis of individual characteristics of the brain functioning in the resting state allows us to identify the role of brain factors that determine the effectiveness of cognitive processes at different stages of ontogenesis, including adolescence. The proposed interdisciplinary approach to the analysis of cognitive processes is based on A.R. Luria's principle of dynamic localization of mental functions (Luria 1978), which is based not on the assessment of individual cognitive processes (i.e. individual types of memory, attention, speech functions, visual perception, etc.), but on the analysis of the main functional components of mental activity, namely information processing, programming, selective regulation and control of behavior (EF in the broad sense), and maintainance of alertness. In the present study, this approach is used to investigate the relationship between age-related characteristics of the brain's regulatory systems (RS) and academic performance in adolescents.

During adolescence, significant changes occur in all physiological systems of the body, which justifies its classification as a critical period of development (Fuhrmann et al., 2015). Sex hormones exert differentiated effects on the maturation and functioning of various brain structures, mainly through their influence on the development of synaptic connections between neurons in both cortical and subcortical regions (Laube, van den Bos, & Fandakova, 2020). Moreover, these processes mainly affect the regulatory systems of the brain (RS) - the integrations of cortical areas and subcortical formations (Spear, 2013), providing various aspects of the modulation of cognitive processes. According to (Regulation of behavior... , 2023), RSs can be divided into three functional classes: ((1) brainstem and diencephalic structures that provide general brain activation and

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maintain the level of alertness necessary for effective behavior; (2) subcortical (striatopallidal and limbic) structures in the depths of the frontal and temporal lobes that participate in motivational and emotional regulation, and (3) the frontal cortex with its connections to the postcentral associative cortex and subcortical structures, including the fronto-thalamic and fronto-parietal systems, that facilitate selective voluntary attention, selective preparation for cognitive processes, strategic planning, and self-regulation.

How can the functional state of different RS be related to learning problems in adolescents?

In his 1963 work, A. R. Luria points to the flexibility and adaptability of the brain's systems for regulating cognitive processes in response to changing environmental conditions. Such functional reorganization is a necessary component of adaptation (Luria, 1963). Adolescence is characterized by significant structural and neurochemical changes in the hippocampus, prefrontal cortex, and subcortical structures, including the limbic system (Wierenga et al., 2018; Regulation of behavior..., 2023). These changes contribute to an additional set of factors affecting the structural and functional reorganization of brain systems essential for the integration of EF, memory, and motivational-emotional regulation. School knowledge involves the acquisition of action algorithms, whether in the context of solving mathematical problems or in the sequential organization of textual information through the construction of grammatically correct sentences (Van Dyck et al., 2021). According to (Menon, Boyett-Anderson, & Reiss, 2005), the suboptimal functional state of the RSs weakens the contribution of the medial temporal cortex to information retrieval and simultaneously strengthens its functional interactions with the dorsolateral PFC. On the one hand, this may improve memory retention, but on the other hand, it may reduce cognitive flexibility and variability in solving, for example, mathematical problems (Qin et al., 2014). Functional connectivity studies reveal different responsibilities of cortical-subcortical systems during different stages of learning and algorithm implementation. At the initial stage of visual-motor skill acquisition, the frontoparietal network may interact with motor areas to form an integration of visuospatial images and motor commands (Hikosaka et al., 2002). At a later stage, the involvement of the basal ganglia can provide the realization of the program of movement sequences (Hardwick et al., 2013). For mathematical abilities in adolescents, the role of white matter pathways of the fronto-basal and fronto-parietal systems has been described in (Navas-Sanchez et al., 2014).

In the present study, we try to answer the question to what extent academic performance is related to the efficiency of different EF components and how the correlation between EF and academic performance depends on the functional state of different brain RSs in adolescents.

METHODS

Adolescents aged 12-16 years (N = 183, girls = 65 (35.5%), mean age = 14.29±1.18 years) participated in the current study. All of them didn't have a history of mental and/or neurological disorders and were attending regular comprehensive Moscow schools. The adolescents themselves and their parents gave written informed consents for participation in the study.
The indicators of academic achievements were grades in math, the Russian language and the average grade in two subjects (a scale of 1 to 5 points was used).

NEUROPSYCHOLOGICAL ASSESSMENT

EF effectiveness was assessed using the A.R. Luria neuropsychological examination, adapted for adolescents (Semenova, Machinskaya, & Lomakin, 2015; Machinskaya et al., 2020), including eight tests: a response selection test, copying the Taylor figure, a dynamic praxis test, a graphic test, drawing up a story using a series of plot pictures and a complete plot picture (based on H. Bidstrup's drawings), memorizing non-verbalized figures (six figures), retelling a fable ("Head and Tail of a Snake"), memorizing a series of ten words. Each error, depending on its type (e.g. impulsive or omission), was assigned to specific neuropsychological indices reflecting difficulties in realization of particular EF components. The final score for each index was calculated as the mean value for errors of the same type across all 9 tests. The indices ranged from 0 to 1, with 0 being the best and 1 the worst. Using the scheme proposed by O.A. Semenova (Semenova, Machinskaya, & Lomakin, 2015), the results of neuropsychological tests were used to assess the severity of difficulties in realization of seven EF components:

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assimilation of new activity algorithms (I); creation of a behavioral strategy (II); overcoming immediate reactions (III); timely termination of an action and switching from one action to another one (IV); switching from one mode of action to another one, from program to program (V); sustained maintenance of the acquired program (VI); and control of execution of own actions (VII). In addition three integrated EF indices were determined: the state of programming functions (VIII, including I and II); the state of selective regulation (IX, including III, IV, V, and VI) and the general index of the voluntary regulation (X: the mean coefficients of the components I–VII).

EEG ANALYSIS

In this study, we used the structural EEG analysis presented in our previous publications **(**Machinskaya et al., 2020**)**. It is based on the principle of association of certain EEG deviations (patterns) with suboptimal functioning of the brain cortex and cortico-subcortical systems (the principle of functional classification of EEG patterns) which is similar to A.R. Luria's principle of functional classification of the cognitive activity deviations. **(**Luria,1978**)**.

Suboptimal functioning and/or immaturity of cortico-subcortical brain RSs are reflected in EEG in the form of bilaterally synchronous changes in homologous leads in both hemispheres (Niedermeyer, 2011). In EEG structural analysis, based on clinical and neuronal data, the bilaterally synchronous patterns differing in the localization, frequency, and shape of oscillations are attributed to the EEG signs of suboptimal states of various brain RSs. According to the EEG structural analysis scheme **(**Machinskaya et al., 2020), groups of bilaterally synchronous theta waves (4-6 Hz) in the frontal and/or frontal and central frontal areas were classified as signs of a suboptimal state of fronto-thalamic system (FTS). Groups of bilaterally synchronous spindle-shaped oscillations in the low-frequency alpha range (6-10 Hz) in the frontal and/or frontal and anterior temporal areas were classified as EEG signs of a suboptimal state of the fronto-limbic system (FLS). EEG signs of a suboptimal state of the fronto-basal system (FBS) included bursts of bilaterally synchronous spindle-shaped beta-activity (20-30 Hz) in the frontal, central, and/or frontal and anterior temporal areas.

Considering the objectives of the present study, below, we show the individual examples of the bilaterally synchronous patterns of fronto-thalamic (FTS, figure1), fronto-limbic (FLS, figure 2) and fronto-basal (FBS, figure 3) systems origin.

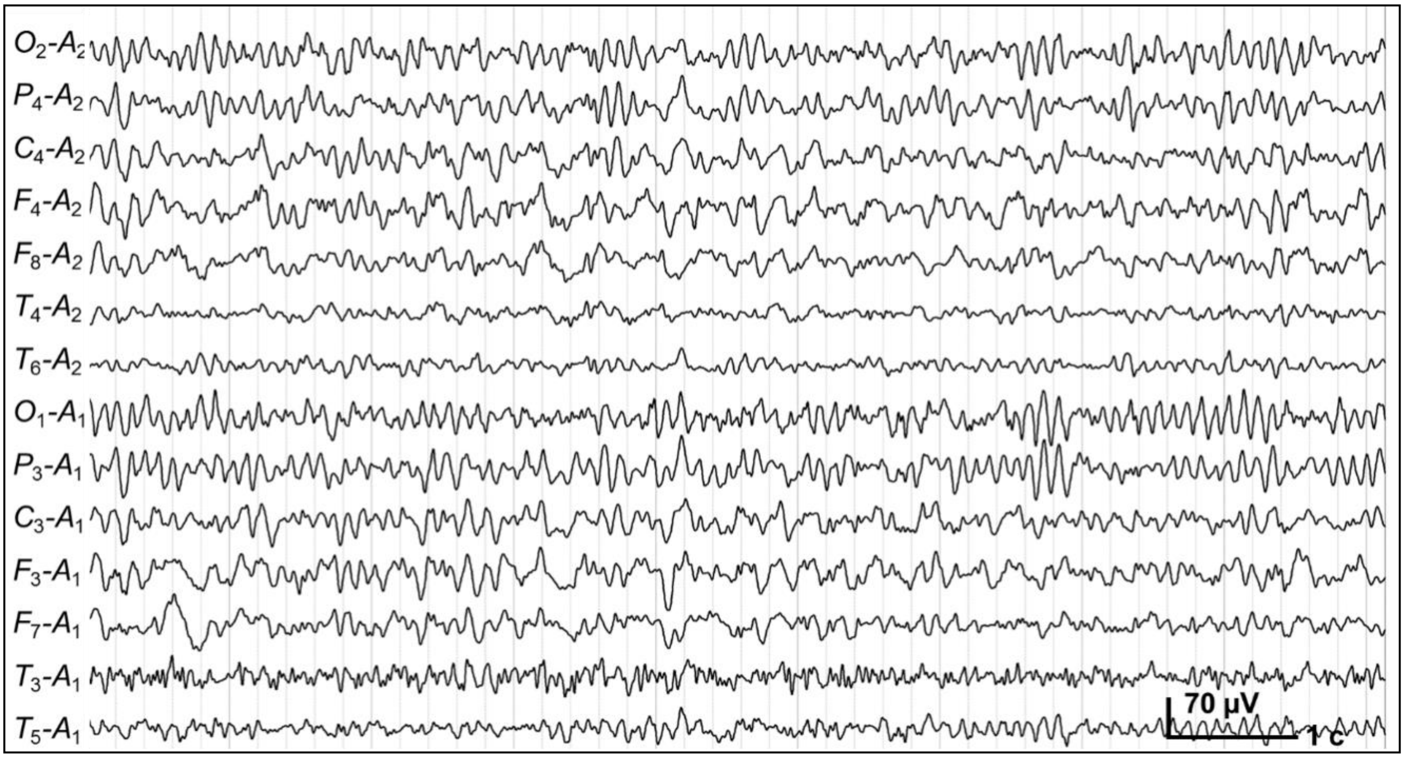

Figure 1. *An EEG segment (A. G., 13 yrs.) with the patterns of fronto-thalamic origin - groups of bilaterally synchronized theta waves with a frequency of 5 Hz in the frontal and central leads.*

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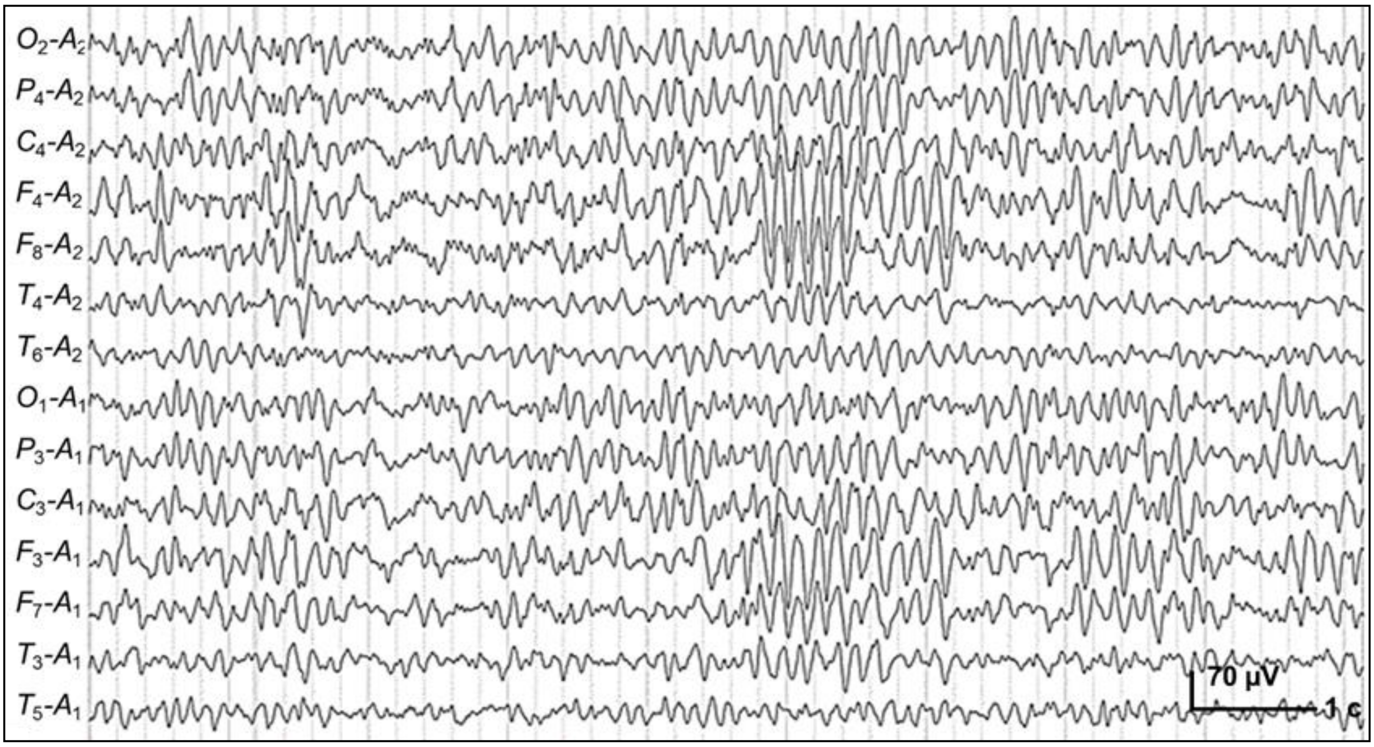

Figure 2. *An EEG segment (D.R., 13 years old) with the patterns of limbic origin (groups of bilaterally synchronous alpha-like oscillations with a frequency of 7–8 Hz in the frontal, inferior frontal, and fronto-temporal leads.*

Figure 3. *An EEG segment (M. G., 14 years old) with the pattern of fronto-basal origin (beta-spindles with an oscillation frequency of 20–25 Hz in the frontal and inferior frontal leads) and hypothalamic origin (generalized bilateral synchronous patterns consisting of two-phase peaks and sharp waves of alpha and beta ranges).*

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The EEG was recorded in a resting state with closed eyes, using a multi-channel electroencephalograph (Electrical Geodesics, Inc., USA) in the frequency range of 0.1-70 Hz (digital frequency is 250 Hz) from 129 electrodes located on the HydroCel GSN EEG cap (HCGSN, USA), one of which (vertex electrode) was used as a reference for EEG recording. For the visual analysis of the EEG curves in this work, we used monopolar (with ipsilateral ear reference electrodes) and bipolar (with large and small distances between the sensors) virtual assemblies, which included a limited number of leads over the left and right hemispheres, the localization of which corresponded to the international system 10-20%: Occipital (O1, 2), Parietal (P1, 2), Central (C3, 4), Frontal (F3, 4), Frontal inferior (F7, 8), Anterior Temporal (T3, 4) and Posterior Temporal (T5, 6). The description and assessment of the individual characteristics of the functioning of the cortex and RSs of the brain at rest was performed using the EEG structural analysis scheme independently by two experts, without additional information about the participants. Each participant's EEG was evaluated in the binary system for the presence/absence of the EEG patterns, described above. The criterion for the presence of certain patterns was their appearance at least 3 times during a 10–15-minute recording.

According to the presence of one of the above types of EEG patterns (isolated or in combination with non-paroxysmal changes of hypothalamic origin), EEG subgroups of adolescents were formed: fronto-talamic (FTS, N = 19), fronto-limbic (FLS = 49), fronto-basal (FBS, N = 18), and the control group (CNT, N = 64) which included adolescents without deviated patterns or with non-paroxysmal EEG patterns of hypothalamic origin in the form of generalized bilaterally synchronous sharp waves in the alpha and theta range and/or spindle-shaped high-frequency activity in the alpha and beta range. Non-paroxysmal patterns of hypothalamic origin were recorded in most cases and were considered normal in adolescence (Machinskaya et al., 2020).

STATISTICAL ANALYSIS

Spearman correlation was used to estimate the relationship between academic achievement and neuropsychological EF indices. The listed above EEG subgroups CNT, FTS, FLS and FBS were compared using the non-parametric Kruskal-Wallis test for multiple comparisons and the Mann-Whitney test for pairwise comparisons.

RESULTS

NEUROPSYCHOLOGICAL ASSESSMENT AND ACADEMIC ACHIEVEMENT

The correlations of neuropsychological EF indices with grades in math and the Russian language in the whole sample are shown in Table 1. The analysis demonstrated significant negative correlations of average grades with the composite general neuropsychological index of voluntary regulation ($r = -0.34$, $p < 0.001$), the index of selective regulation ($r = -0.33$, $p < 0.001$), and the index of programming functions ($r = -0.25$, $p < 0.001$). Grades in math were also correlated with these integrated indices ($p < 0.001$) in all cases: for the general index of voluntary regulation ($r = -0.34$); for the index of selective regulation ($r = -0.31$) and for the index of programming functions ($r = -0.27$). The correlations with grades in Russian were weaker but still significant ($r = -0.28$, $p < 0.001$; $r = -0.27$, $p < 0.001$; $r = -0.20$ $p <0.01$ for the general index of voluntary regulation, the index of selective regulation and the index of programming functions respectively).

Regarding the indices of the more specific EF components, the correlation analysis revealed the following. For the grades in math and Russian, a similar correlation was obtained with the indices of assimilation of new activity algorithms ($r = -0.28$, and $r = -0.27$, for the Russian language and math, respectively, $p < 0.001$ in both cases), switching from one mode of action to another ($r = -0.26$ and $r = -0.25$, $p < 0.001$ in both cases), sustained maintenance of the acquired program ($r = -0.25$ and $r = -0.28$, , $p < 0.001$ in both cases), controlling one's own actions ($r = -0.24$, $p < 0.001$ and $r = -0.20$, $p < 0.01$ for the Russian language and math, respectively). In addition, grades in math (but not in Russian) have weaker but still significant correlations with the indices of termination of an action and switching from action to action ($r = 0.20$, $p<0.01$) and the index of creation of a behavioral strategy ($r = -0.15$, $p<0.01$). Overcoming immediate reactions was not correlated with academic grades.

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Table 1

Spearman's correlations between school grades and neuropsychological indices

Neuropsychological indices	Math	Russian language	Average grades
Assimilation of new activity algorithms (I)	-0.27**	-0.28**	-0.30**
Creation of a behavioral strategy (II)	-0.15*	-0.07	-0.12
Overcoming immediate reactions (III)	-0.09	-0.01	-0.04
Termination of an action and switching from action to action (IV)	-0.20**	-0.11	-0.18*
Switching from one mode of action to another one (V)	-0.26**	-0.25**	-0.28**
Sustained maintenance of the acquired program (VI)	-0.25**	-0.28**	-0.30**
Control of execution of own actions (VII)	-0.24**	-0.20**	-0.25**
Programming functions (VIII: the sum of I и II)	-0.27**	-0.20*	-0.25**
Selective regulation (IX: the sum of III, IV, V и VI)	-0.31**	-0.27**	-0.33**
General index of voluntary regulation (X: the sum of I-VII)	-0.34**	-0.28**	-0.34**
** p <0.001, *p <0.05.			

ACADEMIC PERFORMANCE AND EXECUTIVE FUNCTIONS IN EEG SUBGROUPS

Comparison of the average grades in all the EEG subgroups showed a significant difference ($\chi2 = 11.72$, $p < 0.01$). The mean grade was 3.77 (0.55) in the control subgroup (CNT), it was 3.32 (0.48) in the FTS subgroup, it was 3.47 (0.66) in the FLS subgroup, and it was 3.44 (0.48) in the FBS subgroup. According to the paired Mann-Witney test, the mean grades were significantly lower ($p < 0.01$) in all groups with suboptimal RS functioning against CNT.

Table 2 shows the means of the neuropsychological EF indices in each EEG subgroup and the results of their statistical comparison. Significant ($p<0.05$) differences were found for two neuropsychological indices: the index of the control of execution of own actions, and the index of selective regulation. A sub-significant effect ($p=0.086$) was found for general index of voluntary regulation ($p = 0.086$). The effect was not significant for the index of the programming functions.

Pairwise Mann-Whitney comparisons showed the significantly higher general index of voluntary regulation ($U = 383.00$, $p < 0.05$) and index of selective regulation ($U = 333.00$, $p < 0.05$) in the FTS group compared to the CNT group. The index of the control of execution of own actions was significantly higher in the FBS group than in the CNT ($U = 393.00$, $p < 0.05$). The EF indices in the FLS group did not significantly differ from those in the CNT group.

Table 2.

The mean values of EF indices in the EEG subgroup

NEUROPSYCHOLOGICAL INDICES	CNT	FTS	FLS	FBS	KRUSKAL WALLIS
	M(sd)	M(sd)	M(sd)	M(sd)	χ^2
Control of execution of own actions	0.35 (0.24)	0.46 (0.24)	0.43 (0.22)	0.53 (0.26)*	8.14*
Programming functions	0.28 (0.24)	0.38 (0.25)	0.28 (0.23)	0.23 (0.14)	3.71
Selective regulation	0.32 (.16)	0.46 (.17)*	0.35 (.18)	0.32 (.16)	9.45*
General index of voluntary regulation	0.32 (0.15)	0.43 (0.18)*	0.36 (0.18)	0.36 (0.15)	6.6 +

*p < 0.05, + p< 0.1; M – mean, sd – standard deviation.

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SUBOPTIMAL STATE OF BRAIN REGULATORY SYSTEMS AND CORRELATIONS BETWEEN EF AND ACADEMIC PERFORMANCE

To study the dependence of relationships between EF and academic performance on the suboptimal functional state of RSs the correlations between grades and neuropsychological indices were calculated separately in the control group and in the other EEG subgroups. In the CNT group, a significant negative correlation was found between the index of assimilation of new activity algorithms and average grades ($r = -0.33$, $p < 0.05$) and grade in math ($r = -0.29$, $p < 0.05$). The index of difficulties in selective regulation correlated with grades in math ($r = -0.31$, $p < 0.05$) and with average academic performance ($r = -0.28$, $p < 0.05$) in the CNT group. Finally, the general index of voluntary regulation correlated significantly with grades in math ($r = -0.29$, $p < 0.05$) in this group.

In the FTS group the average grades correlated negatively with the index of sustained maintenance of the acquired program ($r = -0.46$, $p < 0.05$). Grades in Russian correlated significantly with the indices of switching from one mode of action to another ($r = -0.70$, $p < 0.01$), sustained maintenance of the acquired program ($r = -0.57$, $p < 0.05$), control over the execution of one's own actions ($r = -0.47$, $p < 0.05$), selective regulation ($r = -0.55$, $p < 0.05$) and the general index of voluntary regulation ($r = -0.51$, $p < 0.05$).

In the FLS group we found the significant negative correlations of the math score with the general index of voluntary regulation ($r = -0.31$, $p < 0.05$) and with the index of switching from one mode of action to another one ($r = -0.30$, $p <0.05$). In addition, sub-significant correlations of the average grades with the index of selective regulation ($r = -.28$, $p = 0.06$) and the general index of voluntary regulation ($r = -.29$, $p = 0.051$) were found.

In the FBS group all correlations between grades and neuropsychological indices were insignificant ($p>0.01$).

DISCUSSION

The aim of our study was to analyze the relationship between brain executive functions (EF) and academic achievement in adolescents. Most research on EF development in children and adolescents has been carried out within the framework of the cognitive approach according to which inhibition of irrelevant actions, cognitive flexibility, and updating information in working memory are the (Diamond, 2013). These studies showed significant relationships between EF efficiency, general academic achievement and specific achievement in language and math (Clarren, Martin, & Townes, 1993; Best et al., 2011). The study of 14-18 years-old adolescents shows the general increase in EF efficiency along with the heterochrony in the development of basic components of EF: significant progress in inhibition and no changes in working memory and task switching (Theodoraki et al., 2020). Such heterochrony is associated with different rates of plastic synaptic transformation in the various areas of the prefrontal cortex and deep brain structures, that can affect the effectiveness of individual components of the EF in adolescents (Blakemore & Choudhury, 2006). In turn, individual differences in the effectiveness of separate EF components may influence success in learning different school subjects. In (Blair & Diamond, 2008), the authors emphasize the importance of cognitive flexibility and planning in preventing school failure.

Indeed, some studies demonstrate relationships between EF development and academic achievement in math (Andersson, 2008; Bull & Lee, 2014; Lee et al., 2009; Van der Ven et al., 2012), and language (Monette et al., 2011; St Clair-Thompson & Gathercole, 2006), and varying degrees of predictive power of different components of EF for language and math achievement (Chen, Tsao, Liu, & Huang, 2024).

The advantage of qualitative neuropsychological analysis over cognitive tests is the possibility to evaluate the efficiency of the regulatory components of mental activity during subject’s performance of tasks of various mode (verbal and nonverbal) in different modalities (visual, auditory or tactile). This makes it possible to minimize the impact of these factors on the assessment of executive functions.

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In our study, we have found significant negative correlations between the general neuropsychological index of EF deficit and the average academic grade. Detailed neuropsychological analysis has shown that general academic achievement depended mostly on the functions of selective regulation and programming including the assimilation of new activity algorithms, switching from one mode of action to another one, and self-control. These results are consistent with observations reported in (Deary et al., 2006; Xu and Li, 2015) which testify to the importance of the instructional acquisition and sustained maintenance of the acquired program for the processes of encoding and retrieval of information necessary for successful learning. A decrease in the efficiency of the instructions and algorithms acquisition can lead to a decrease in the accuracy of information retrieval, for example, during testing procedure (Miriam et al., 2011).

The observed negative correlations between neuropsychological indices of the different EF components and academic achievements (listed above) appeared to be practically the same for language and math. Some differences were found for math: in this case, an additional EF component correlated with academic grades – termination of an action and switching from action to action. It is interesting to note that higher level of testosterone in male adolescents correlates with lower efficiency of task switching (Nguyen et al., 2017).

In our study, the importance of switching between different programs was shown for both math and language. This could be explained by the role that this component of EF plays in school learning: the ability to switch between different rules, formulas, algorithms and apply them to solve various tasks certainly affects the efficiency and speed of completing individual tasks and tests. Success in mastering mathematical skills is largely based on a) the ability to determine the type of task (for example, a mathematical problem) and to create an optimal strategy for its implementation, b) the ability to switch from one action to another, which is important for the implementation of counting operations.

Taking into consideration the specific functional role of different fronto-subcortical regulatory systems in brain organization of EF (Machinskaya, 2015) we compare academic performance and the correlation between EF deficits and academic performance in groups of adolescents with suboptimal functional state of various RSs.

The FTS subgroup differed from the control group in academic achievement and showed lower scores on voluntary regulation and the general index of voluntary regulation. Correlation analysis revealed an association between the functions of algorithm switching and the Russian language grade in FTS subgroup. The FTS includes the dorsolateral prefrontal cortex, the mediodorsal nuclei (MD) of the thalamus and the pathways between them (Machinskay, 2015). In a suboptimal state of FTS, 4-6 Hz theta-oscillations are recorded on the EEG in the frontal leads. The authors of the review (Ouhaz et al., 2018) suggest that changes in the different subdivisions of the MD and their interconnections with the prefrontal cortex could plausibly lead to a number of the disparate symptoms that are associated with different cognitive disorders. The link between the theta oscillation in the fronto-thalamic network and speech is suggested by the work of H. Barbas and colleagues (Barbas et al., 2013). The link between FTS and language is indicated by clinical studies – the presence of aphasia, including anomia, verbal paraphasia, impoverishment and reduction of language fluency with relative preservation of language comprehension in cases of thalamic nuclei damage, including the MD (Crosson, 2013). In our previous interdisciplinary study in primary school children, we also observed the relationship between FTS suboptimal state and language capacities: children aged 7-8 years with the EEG signs of FTS immaturity demonstrated difficulties when performed semantic verbal neuropsychological tests (Machinskaya et al, 2014). Based on our early study of resting state cortical connectivity in 7-8-year-old children with the same RS suboptimality (Machinskaya et al., 2007), we suggested that their language difficulties were related to a decrease in local functional connections between temporal speech associated cortical areas of the left hemisphere.

The FLS subgroup as well as the FTS subgroup differed significantly from the control group in terms of academic achievement. Correlation analysis showed a relationship between the neuropsychological index of algorithm switching and math achievement in this group. The fronto-limbic system includes the ventrolateral prefrontal cortex, the cingulate cortex, the amygdala, and the pathways between them (for review see Machinskaya, 2015). In the case of suboptimal FLS functional state, alpha-like oscillations in the range of 6-10 Hz in the frontal EEG leads are registered. According to (Connemann, 2005) the source of this EEG pattern is attributed to the anterior cingulate cortex (ACC). The ACC is involved in the processes of

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conflict detection between a required action and an irrelevant action, and inhibition of the latter (Ridderinkhof et al., 2004). Difficulty in suppressing irrelevant associations is one explanation for arithmetic impairment in FLS subgroup (Damon et al., 2006). As the limbic system is involved in negative feedback processing, its suboptimal state may manifest itself as a decrease in confidence in the accuracy of the result obtained. Some studies have shown that the ventrolateral prefrontal cortex is only activated during the processing of incorrect equations (Menon, 2010). In addition, the amygdala, which has projections to both the posterior orbitofrontal cortex and the anterior cingulate cortex (Zikopoulos, B & Barbas, 2012)., plays an important role in processing negative feedback (LeDoux, 2003). Hormonal changes may be one of the potential factors of the suboptimal functioning of the FLS. A study by J.M. Spielberg et al (2015) showed that increased testosterone levels in adolescents were associated with reduced connectivity between the amygdala and orbitofrontal cortex when processing negative feedback. Thus, a suboptimal state of the fronto-limbic system may serve as a factor in reducing the efficiency of switching, with a decrease in the accuracy of evaluating errors in math.

CONCLUSION

Consistent with the results of other neuropsychological studies, our study shows that difficulties associated with voluntary behavioral regulation (executive functions) are an important factor underlying the decline in academic performance. This paper shows that the decline in math is primarily associated with difficulties in learning instructions, developing behavioral strategies and switching between actions, algorithms as well as the ability to maintain an acquired program. As grades in language subjects decline, difficulties in learning instructions, switching between programs, and maintaining an acquired program come to the fore. A.R. Luria's concept suggests that these difficulties are related to the functions of the third brain unit. The key structure of this unit is the prefrontal cortex, which is connected with various subcortical areas and forms functional systems with specific mechanisms of cognitive regulation. According to the results of our previous studies (Regulation of behavior ..., 2023), adolescents show more (compared to previous stages of ontogeny) cases of non-optimal functioning of at least three brain regulatory cortico-subcortical systems, namely fronto-thalamic, fronto-limbic and fronto-basal. The present study has shown that suboptimal functioning of these regulatory systems has a negative impact on academic performance. By identifying groups of adolescents based on qualitative analysis of EEG patterns, it was possible to establish specific relationships between the functional state of individual brain regions, EF components, and academic performance. Thus, interdisciplinary (neuropsychological and electroencephalographic) assessment of brain regulatory functions could be an effective tool for identifying individual characteristics of mental activity and behavior that negatively affect academic performance.

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