Особенности познавательной деятельности современных детей, подростков и молодежи в контексте проблем образования

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Research article

Influence of EEG-based functional connectivity and inhibitory control on educational web search performance among adolescents

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Abstract

Introduction. Digital technologies have become an essential aspect of modern life, necessitating research into their effects on children's learning processes. Additionally, it is crucial to investigate other factors that impact the successful completion of educational tasks. Brain functional connectivity has been shown to correlate with intellectual abilities and the quality of cognitive task performance. Furthermore, changes in connectivity patterns are associated with learning processes within the brain. Despite this, there is a paucity of research examining functional connectivity metrics in the context of children's learning. Inhibitory control is another critical parameter that significantly influences learning outcomes. Therefore, this study investigates whether the performance of an educational task utilizing web search is associated with various functional connectivity metrics and inhibitory control.

Materials and Methods. Fifty children participated in the study. EEG was recorded at rest with eyes closed to determine the metrics of functional connectivity in the EEG sensor space. The following connectivity metrics were used for further analysis: global efficiency, modularity, and assortativity. The ReBOS method (E. G. Vergunov) was used to study inhibitory control. Statistical processing was performed using the Python programming language, and the data were analyzed using binary logistic regression and the non-parametric Mann-Whitney U test.

Results. The variable of web information search related to an educational task is influenced by the number of web links used by the participants, the average reaction time during the inhibitory control task, and the modularity metric of functional connectivity in the EEG sensor space. The greater the number of web links a child uses when searching for educational information, the shorter their reaction time during the inhibitory control task, and the higher their modularity index, the more likely they are to successfully find an answer to the educational task.

Conclusion. The success of educational web search depends on the level of inhibitory control and the characteristics of EEG functional connectivity.

Keywords: digital technologies, functional connectivity, inhibitory control, EEG, children's learning, web search, cognitive tasks

Научная статья

Влияние функциональной коннективности ЭЭГ и тормозного контроля на образовательный веб-поиск

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Аннотация

Введение. Цифровые технологии стали важным аспектом современной жизни, что требует исследования их влияния на процессы обучения детей. Кроме того, крайне важно исследовать другие факторы, влияющие на успешное выполнение образовательных задач. Было показано, что функциональные связи мозга коррелируют с интеллектуальными способностями и качеством выполнения когнитивных задач. Более того, изменения в моделях подключения связаны с процессами обучения в мозге. Несмотря на это, исследований, изучающих показатели функциональной связи в контексте обучения детей, недостаточно. Тормозной контроль — еще один важный параметр, который существенно влияет на результаты обучения. Таким образом, это исследование направлено на то, чтобы выяснить, связано ли выполнение образовательной задачи с использованием веб-поиска с различными метриками функциональной коннективности и тормозным контролем.

Материалы и методы. В исследовании приняло участие 50 детей. Для определения метрик функциональной коннективности в пространстве электроэнцефалографии (ЭЭГ) была записана ЭЭГ в покое с закрытыми глазами. Для дальнейшего анализа были использованы следующие метрики коннективности: глобальная эффективность, модулярность и ассортативность. Для исследования тормозного контроля была использована методика ReBOS (Е. Г. Вергунов). Статистическая обработка проводилась с использованием языка программирования Python, данные анализировались с помощью бинарной логистической регрессии и непараметрического критерия U Манна — Уитни.

Результаты. Переменная результативности поиска веб-информации, связанного с выполнением учебного задания, зависит от количества веб-ссылок, использованных участниками, среднего времени реакции при выполнении задачи на тормозной контроль, а также от параметра «модулярность» функциональной коннективности в пространстве ЭЭГ сенсоров. Чем больше веб-ссылок использует ребенок при поиске учебной информации, чем меньше время его реакции при выполнении задачи на тормозной контроль и чем выше индекс модулярности, тем выше вероятность того, что он успешно найдет ответ на учебное задание.

Заключение. Успешность учебного веб-поиска зависит от уровня тормозного контроля и особенностей ЭЭГ функциональной коннективности.

Ключевые слова: цифровые технологии, функциональная коннективность, тормозной контроль, ЭЭГ, обучение детей, веб-поиск, учебные задачи

Introduction

Digital technologies are gaining momentum in education. In the future, education will rely even more on digital technologies, and future careers will depend on digital skills (Qureshi et al. 2021). Therefore, studying the use of digital technologies in education is crucial. Web search makes a significant contribution to the educational process (Nagel et al. 2020). Therefore, in this article, we examine the relationship between web search during the completion of an educational task, metrics of functional connectivity in the EEG sensor space and inhibitory control.

Brain maturation can be studied using functional connectivity, which represents the integration and segregation of networks (Uchitel et al. 2022). Functional connectivity can be explored through the perspective of graph theory. Functional connectivity is a statistical relationship (a correlation) between network nodes, in particular, between the physiological time series of two regions. Nodes can be voxels, different brain regions, or electrodes (sensors). The statistical relationships between nodes are referred to as edges. Using these fundamental units of a network, such as nodes and edges, we can calculate various metrics (global efficiency, modularity, etc.) that will characterize a particular network. It is possible to assess the segregation and integration parameters of networks (Handiru et al. 2021).

In particular, small-world topology is characterized by an optimal balance of segregation and integration. The architecture of a small-world network is characterized by a short path length between nodes, typically consisting of only a few edges, while the majority of nodes are not directly connected to each other (Yang et al. 2022). On a global level, a highly integrated network with many connections requires substantial maintenance costs. Conversely, in a highly clustered (segregated) network, information transmission is slower. Therefore, small-world architecture is considered optimal for information transfer in brain networks. Small-worldness is characterized by modularity, since neighboring nodes are grouped into clusters, and relatively short path length (few edges), since clusters are connected through hubs. In other words, the optimal combination of functional integration and segregation reflects the properties of a small-world network (Akin et al. 2024).

Functional integration is the ability to rapidly connect multiple distinct regions (modules) with each other. Functional integration is often defined in terms of path length; the shorter the path length between nodes, the higher the functional integration. Global efficiency can be used as an indicator of functional integration, as it represents the average shortest path length between all pairs of nodes (in this study — electrodes or sensors) (Conti et al. 2022). Another network metric — modularity — reflects the extent to which a network can be divided into distinct, relatively autonomous groups or clusters (Kang et al. 2024). In addition, assortativity is a metric that indicates the likelihood of nodes with a similar number of connections (edges) to connect with each other (Ismail, Karwowski 2020). A network is considered disassortative if nodes with a higher number of edges tend to connect with nodes with fewer edges. Conversely, a network is assortative if nodes with many connections tend to link with other highly connected nodes. Assortative networks with numerous connections are generally more stable, whereas disassortative networks, such as biological networks, are typically less stable (Conti et al. 2022). Global efficiency is considered as a measure of the functional integration of a network. A parameter such as modularity is considered as a measure of the functional segregation of the network. Additionally, assortativity is considered as an indicator of network stability (Massullo et al. 2022).

It has been shown that the state of brain networks is associated with cognitive abilities (Uchitel et al. 2022). For example, a more integrated state is associated with faster and more accurate performance on cognitive tasks (Menon, D'Esposito 2022). In children, switches between different network configurations occur less frequently, with one network state being maintained for longer periods (Ryali et al. 2016). As the brain matures, intermodular connections become weaker, while intramodular connections become stronger, leading to an increase in modularity. This increase in the independence of modules results in greater specialization of brain functions. During adolescence, there is an enhancement in cognitive functions and an increase in the independence of modules (Xuan 2020). Relatively high network modularity can be an indicator of brain plasticity as a result of learning. Furthermore, modular networks increase ability to better learn new skills (Gallen, D'Esposito 2019). However, the relationship between functional connectivity and Internet use is more often studied in the context of addiction rather than education (Lee et al. 2022).

Another characteristic important in learning is an executive function known as inhibitory control. Executive functions can be defined as the 'top-down' or intentional control that an individual exerts over their thoughts and actions to achieve a specific goal or outcome (Zelazo 2020). Inhibitory control is the ability to suppress a dominant (attractive or learned) response in favor of a response or action that is more appropriate to the current task or goal (Chevalier et al. 2012). Executive functions in childhood are important predictors of academic achievement and future learning problems. Executive function deficits impact school performance, which in turn has a profound impact on subsequent development at all levels: education, employment, and social life. Increased inhibitory abilities in children have been associated with better reading skills (Johann et al. 2020) and mathematics performance (Chamandar et al. 2019; Diamond 2013). Executive functions affect an individual's ability to master complex skills, acquire new knowledge and concentrate on school tasks (Diamond 2013).

Materials and Methods

The study involved 50 adolescents (age: 13.360 ± 2.136 years; including 30 girls). Of these, 23 individuals found the answer to an educational question using an Internet search.

Data collection of electroencephalographic (EEG) recordings was conducted using an Italian BE Plus LTM EEG amplifier from the EBNeuro family. Resting-state EEG with closed eyes was recorded immediately after the participants searched for answers to an educational question on the Internet. The recording was made using 62 electrodes arranged according to the 10–20 system and lasted for three minutes. During the preprocessing stage, artifacts were manually removed using the Matlab-based EEG LAB software. The EEG recording sampling rate was 256 Hz. Filters from 1 to 45 Hz were applied, and data re-referencing was performed. Independent Component Analysis (ICA) was then conducted, and components containing artifacts were removed. Further processing was performed using the Python programming language with the MNE and NetworkX modules. Continuous data were segmented into epochs of 5 seconds each. The NetworkX module was used to construct the adjacency matrixes of connectivity in the electrode space. The study focused on the alpha activity spectrum (8–13 Hz). The connectivity pattern was assessed using the phase lag index (PLI) with a threshold of 0.5 (Hasan, Al-Sharqi 2023; Imperatori et al. 2019). Network metrics such as global efficiency, modularity, and assortativity were measured.

Additionally, the children performed computerized reflexometry with biofeedback (ReBOS). It was developed by E. G. Vergunov (Nikolaeva, Merenkova 2017) to study inhibitory control. In the first session, the child was required to press the space bar in response to all circles that sequentially appeared and disappeared on the screen at varying frequencies. In the second session, the task was to refrain from pressing the space bar when red circles appeared, which required inhibitory control. In this method, omissions refer to instances when the respondent fails to press the button in response to a stimulus that should be pressed, and errors refer to instances when the respondent presses the button in response to a red circle, which should be avoided.

We conducted a logistic regression analysis because research data did not follow a normal distribution. To do so, we turned to Maximum Likelihood Estimation (MLE) method with Newton-Raphson optimization algorithm. Both of them have been considered effective in relevant applications (Smita 2021). In order to perform logistic regression, we employed the Logit function from the StatsModels Python library.

The dependent variable has two possible values: 0 — 'Do not answer the question', 1 — 'Answer'. Logistic regression gives the opportunity to consider the relationship between the binary dependent variable and several independent variables (Pathak et al. 2020). Log-likelihood value relates to the null model value as –20.280 and –34.497. This means that our model is better suited for the data because the log-likelihood is closer to 0 than that of the null model. Furthermore, Likelihood Ratio Test (LLR) p-value = 0.002, which is less than 0.05. Hence, our model better describes the data than the null model (Moscarelli 2023). In addition, the functional connectivity metrics and inhibitory control of the participants were also analyzed based on their web search task performance using the Mann-Whitney U test.

Results and discussion

As is shown in Table 1, significant differences are observed in the variable 'Number of web links viewed' ($U = 423.000$; $p = 0.017$). Children who completed the educational task (answered the question correctly) used significantly more web links during their information search compared to those who did not answer the question. Additionally, significant differences were found in the variable 'Average reaction time' ($U = 196.000$; $p = 0.026$), which was assessed during the inhibitory control task. Adolescents who answered the educational question exhibited significantly faster average reaction times when responding to the correct visual stimuli. It is important to note that in the inhibitory control task, some stimuli require a response, while the others must be ignored.

Binary logistic regression analysis was performed. According to McFadden's Pseudo R-square = 0.412, we can assume that the logistic regression model explains about 41.4 % of the variance (Ewing, Park 2020). The regression model accounts for the influence of sex and age. As is shown in Table 2, the independent variable 'Number of web links viewed' ($p = 0.050$) significantly affects the dependent binary variable 'Do not answer the question (0)/ Answer (1)'. A greater number of viewed links positively influences the binary variable of web search, increasing the likelihood of providing the correct answer. The confidence interval for 'Number of web links viewed' predictor ranges from –0.001 to 1.901. Since the interval includes zero, it indicates that the effect of the number of web links viewed is on the borderline of statistical significance ($p = 0.050$).

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Table 1. Differences in inhibitory control and EEG functional connectivity metrics between groups that completed and did not complete the educational task using web search

Variables	Answer the question	Do not answer the question	Mann-Whitney U statistic	P-value
The use of the Internet for educational purposes (years)	4.130 ± 1.714	3.222 ± 1.601	403.000	0.068
Computer skills self-assessment	6.200 ± 1.600	6.600 ± 2.000	265.000	0.374
Number of requests	1.609 ± 1.270	1.519 ± 1.252	354.000	0.298
Number of web links viewed	**2.435 ± 1.472**	**1.778 ± 1.625**	**423.000**	**0.017**
Inhibitory control: average reaction time (ms)	**294.774 ± 28.891**	**312.719 ± 29.902**	**196.000**	**0.026**
Inhibitory control: number of omissions	1.870 ± 2.160	1.852 ± 1.812	294.500	0.757
Inhibitory control: number of errors	9.261 ± 4.634	9.815 ± 5.526	293.500	0.747
Modularity (Alpha)	0.062 ± 0.052	0.060 ± 0.035	277.500	0.527
Global Efficiency (Alpha)	0.855 ± 0.102	0.846 ± 0.077	353.500	0.408
Assortativity (Alpha)	–0.120 ± 0.099	–0.163 ± 0.095	394.500	0.104

Table 2. Binary logistic regression results: Impact of various factors on the success of educational task completion using web search

Variables	Coef	Std err	z	P>|z|	[0.025	0.975]
The use of the Internet for educational purposes (years)	0.330	0.300	1.101	0.271	–0.258	0.918
Computer skills self-assessment	–0.418	0.252	–1.660	0.097	–0.911	0.076
Number of requests	–0.906	0.607	–1.492	0.136	–2.096	0.284
Number of web links viewed	**0.950**	**0.485**	**1.958**	**0.050**	**–0.001**	**1.901**
Age	0.229	0.243	0.944	0.345	–0.247	0.705
Sex	2.043	1.074	1.903	0.057	–0.061	4.147
Inhibitory control: Average reaction time	**–0.034**	**0.017**	**–2.038**	**0.042**	**–0.067**	**–0.001**
Inhibitory control: number of omissions	0.073	0.252	0.289	0.773	–0.421	0.566
Inhibitory control: number of errors	–0.027	0.089	–0.305	0.760	–0.203	0.148
Modularity (Alpha)	**37.604**	**18.623**	**2.019**	**0.043**	**1.103**	**74.105**
Global Efficiency (Alpha)	7.305	7.130	1.025	0.306	–6.669	21.279
Assortativity (Alpha)	11.624	6.249	1.860	0.063	–0.622	23.871

‘Inhibitory control: Average reaction time’ ($p = 0.042$) negatively affects web search performance. Slower average reaction time is associated with a decrease in the outcome measure (Figure 1 and Table 2). Thus, the child does not find the answer to the question on the Internet. The confidence interval for this predictor ranges from –0.067 to –0.001. As the interval does not include zero, it signifies a statistically significant negative effect on the outcome variable ($p = 0.042$).

Finally, the variable ‘Modularity’ ($p = 0.043$) in the Alpha band range, as is shown in Table 2, significantly influences Internet search performance. Greater network modularity in the Alpha frequency range is associated with successful information retrieval for educational tasks. Despite the Mann-Whitney analysis not finding significant differences between the groups for this parameter, the results of the binary regression indicate that the confidence interval for ‘Modularity (Alpha)’ ranges from 1.103 to 74.105. This wide interval does not include zero, indicating a statistically significant positive effect on the outcome variable.

According to the analysis, a higher number of web links used during the completion of an educational task is a significant predictor of task success. This result is predictable and consistent with previous findings, which indicate that the number of web links viewed for completing educational tasks positively correlates with academic performance (Macfadyen, Dawson 2010). Additionally, only the average reaction time in the inhibitory control task significantly influences whether an adolescent finds the correct answer using web

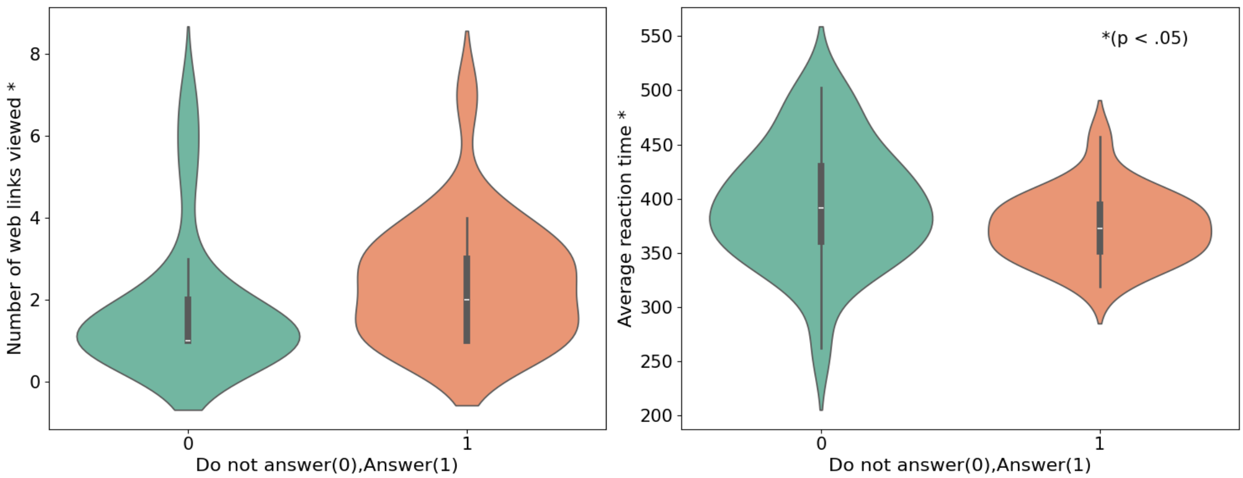

Fig. 1. Differences in the number of web links viewed and inhibitory control parameter (average reaction time) based on web search performance

resources. It has been shown that a reduction in reaction time is associated with a higher level of inhibitory control (Invernizzi et al. 2022). Therefore, it can be inferred that enhanced inhibitory control is a predictor of successful web searches for educational purposes.

Another finding of this study is that a higher modularity score in the Alpha wave range positively influences web search outcomes. Moreover, as is shown in Figure 2, the group of children who successfully completed the web search task exhibited higher small-world properties, characterized by higher modularity and global efficiency scores. However, no significant effect of global efficiency on the successful completion of educational tasks was identified.

Networks with small-world properties transmit information more efficiently (Akin et al. 2024). In addition, higher network modularity scores correlate with higher levels of cognitive function and enhanced learning abilities (Gallen, D'Esposito 2019; Xuan 2020). Our study exhibits that, specifically, modularity in the Alpha-band frequency is associated with the variable of web information search.

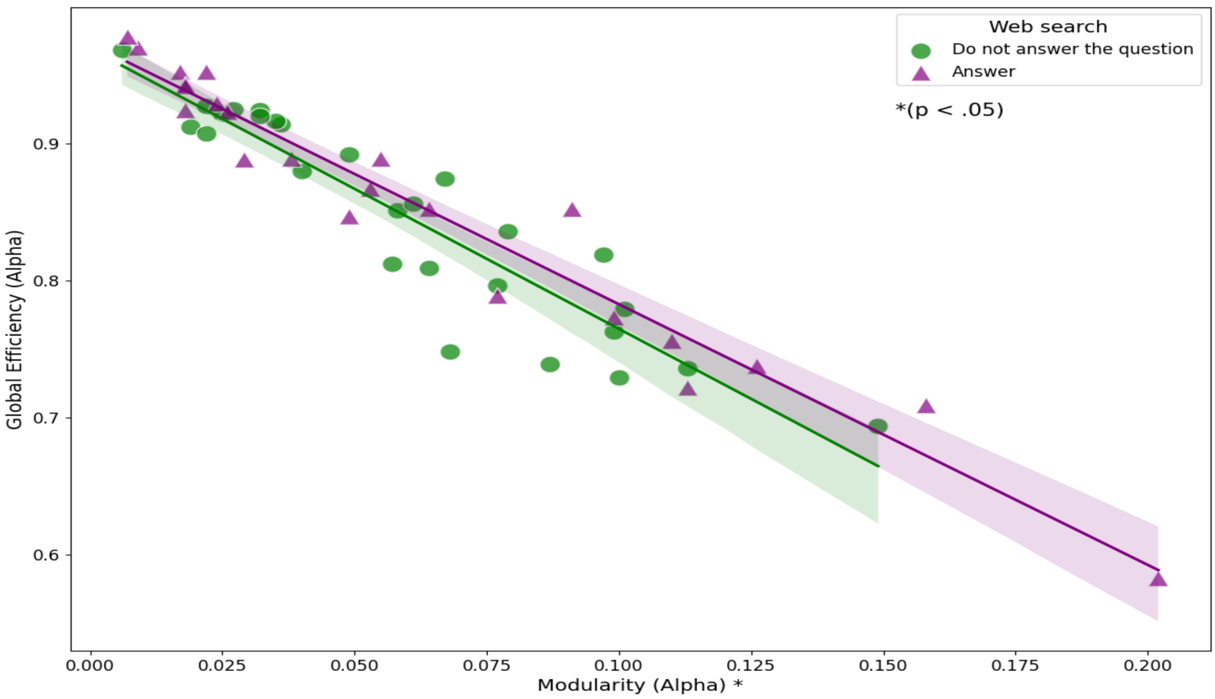

Fig. 2. Relationship between modularity and global efficiency in the Alpha band according to web search task performance

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Conclusions

The conducted study leads to the following conclusions:

- The number of web links used during the completion of an educational task is a significant predictor of task success. The more web links a child uses, the higher the likelihood of successfully completing the task.
- The average reaction time during the inhibitory control task significantly influences the success of web searches. Faster reaction times are associated with higher levels of inhibitory control, which increases the probability of finding the correct answer.
- The modularity metric of functional connectivity in the Alpha-band positively influences web search outcomes. High network modularity correlates with successful information retrieval for educational purposes.
- The group of children who successfully completed the web search task exhibited higher small-world network properties, characterized by higher modularity and global efficiency scores, although global efficiency did not have a significant effect on task success. Small-world organization of a network is associated with more efficient information transmission.

Конфликт интересов

Автор заявляет об отсутствии потенциального или явного конфликта интересов.

Conflict of Interest

The author declares that there is no conflict of interest, either existing or potential.

Соответствие принципам этики

Автор сообщает, что при проведении исследования соблюдены этические принципы, предусмотренные для исследований с участием людей и животных.

Ethics Approval

The author declares that the study complies with all ethical principles applicable to human and animal research.

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