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Review
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Modern research on primary school children brain functioning in the learning process: Review

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Abstract. The *purpose* of this article is to review studies related to the study of primary school children's brain activity in the educational process. In addition, to find out how common such researches are and to define the main directions of scientists' activities on the topic, and their chosen research approaches. *Methods*. Qualitative content analysis was used to select articles suitable for the topic under study: several sets of keywords, journals with a quartile of at least the second, and English language publications were identified as requirements. *Results*. The analysis of research papers showed an increasing interest in the subject matter among scientists. Six main groups of research in the field of neuroimaging are identified: measurement of cognitive abilities, comparison of age categories, technical and methodological nuances of researches based on neuroimaging, study of the influence of various factors on indicators, use of neuroimaging tools in the learning process, registration of brain activity in children with developmental disabilities. Works devoted to the development of memory and attention are highlighted. The features of the study of mathematical abilities and skills, as well as reading, are considered. Advantages and disadvantages of portable electroencephalography are noted. The features of the magnetic resonance imaging procedure in children with developmental disabilities are indicated. *Conclusion*. Despite the variety of research areas, the use of brain–computer technologies in the learning process was not found in the review. According to the authors, there is a lack of long-term research with the use of such technologies in the specifics of subject learning, which would allow tracking its progress. Conclusions on the need for further study of this issue are presented.

Keywords: electroencephalography, functional magnetic resonance imaging, brain–computer interface, brain research, primary school children, education.

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Современные исследования функционирования мозга детей младшего школьного возраста в процессе обучения: обзор

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Аннотация. *Цель* настоящего обзора – рассмотреть исследования, связанные с изучением мозговой активности младших школьников в образовательном процессе; выяснить, насколько подобные работы распространены, определить основные направления деятельности ученых в данной области, а также избранные подходы к исследованиям. *Методы*. Для отбора подходящих к изучаемой теме статей использовался качественный контент-анализ: в роли требований были определены несколько наборов ключевых слов, журналы с квартилем не ниже второго, а также английский язык публикации. *Результаты*. Анализ исследовательских работ показал повышающийся интерес к затрагиваемой теме среди ученых. Были выделены шесть основных групп исследований в области нейровизуализации: измерение когнитивных способностей, сравнение возрастных категорий, технические и методические нюансы проведения исследований посредством нейровизуализации, изучение влияния на показатели различных факторов, применение средств нейровизуализации в процессе обучения, регистрация мозговой активности у детей с отклонениями в развитии. Выделены работы, посвященные развитию памяти и внимания. Рассмотрены особенности исследования математических способностей и навыков, а также чтения. Отмечены преимущества и недостатки портативной электроэнцефалографии. Указаны особенности проведения процедуры магнитно-резонансной томографии у детей с отклонением в развитии. *Заключение*. Несмотря на многообразие направлений исследований, применение технологий интерфейс мозг–компьютер в процессе обучения в ходе обзора не встретилось. По мнению авторов, не хватает длительных исследований с применением подобных технологий в специфике предметного обучения, позволяющего отслеживать его прогресс. Представлены выводы о необходимости дальнейшего изучения данного вопроса.

Ключевые слова: электроэнцефалография, функциональная магнитно-резонансная томография, интерфейс «мозг–компьютер», исследование мозга, младшие школьники, обучение.

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Introduction

Neuroscience has been studying the brain for a long time, and over the centuries, various methods have been developed to understand it.

The child's brain is even more impressive since it is an unstable and developing system. In its development process, it becomes necessary to timely monitor any changes, evaluate the effectiveness of learning, and adjust the educational strategy. To achieve these goals, we need informative and convenient tools to fit into the learning process and not inconvenience the subjects.

It is relevant to consider recent scientific developments related to the study of the child's brain and technologies that continuously assess the person's cognitive and personal characteristics in the different activities, including educational ones [1–4]. The brain–computer interface (BCI) is an example. The correct application of such technologies can make it possible to personalize learning by creating an objective assessment system of children's psychophysiological state in the learning process and timely response to these changes.

Neuroimaging is a relatively young technology that was initially used in surgery and psychiatry and made it possible to diagnose various diseases more effectively. In the process of developing new ways of neuroimaging, scientists opened up new opportunities for its use. In their article, G. Papanastasiou et al. [5] show the variety of brain–computer interface technology applications when working with healthy people and those with various developmental disabilities. Research on the impact of neurofeedback training on attention, memory, and cognitive skills is quite popular. The authors emphasize the need to improve technology due to many factors that reduce its efficiency: dependence on the subject's health, the difficulty of assessing the accuracy of the results obtained, the fatigue of subjects during work, and high cost.

To achieve this goal, it is essential to understand how widespread and effective such developments are. First of all, the main interest was the work aimed at studying the brain using electroencephalography and other monitoring methods in children in the learning process.

1. Review of research papers

Over the past decade, there has been a significant increase in interest in the designated topics, which is reflected in Fig. 1. We selected the following leading scientific journals as sources: *Cognitive Development, Brain and Cognition, Computers & Education, Computers in Human Behavior, Developmental Cognitive Neuroscience, Heliyon, International Journal of Psychophysiology, Journal of Sport and Health Science, Trends in Neuroscience and Education.*

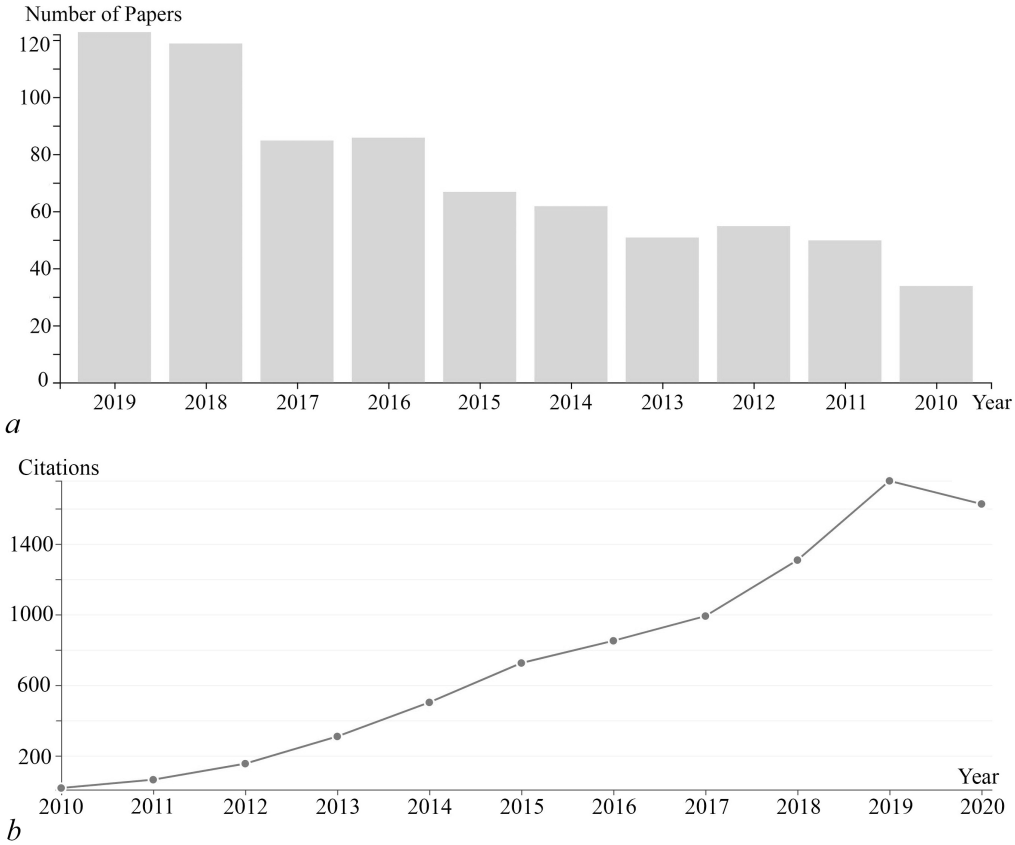

Fig. 1. Number of papers (*a*) and number of citations (*b*) related to brain research in the learning of school children over the last ten years (according to Web of Science)

Over the last 5–6 years, we have found in these journals a significant number of studies on the use of different methods for registering the child's brain activity. We used the following keywords in our search: brain–computer interface (BCI), electroencephalography (EEG), functional near-infrared spectroscopy (fNIRS), functional magnetic resonance imaging (fMRI), magnetoencephalography (MEG), school, child, children, education, training, learning.

During the review, we identified six main groups of research in the field of neuroimaging applied to the study of primary school children's brain activity in the educational process (Fig. 2):

- measurement of cognitive abilities;
- comparison of age categories;
- technical and methodological nuances of researches based on neuroimaging;
- study of the influence of various factors on indicators (errors, stress, motor activity, the subject's attitude to the testing process, intelligence level, gender, etc.);
- use of neuroimaging tools in the learning process (when solving educational tasks);
- registration of brain activity in children with developmental disabilities.

According to observations, the main efforts of scientists are focused on the study of brain responses under the influence of various external and internal factors, as well as the study of age-related differences in the development for cognitive functions. Although the question of applying the obtained knowledge in pedagogical practice is often not raised by the authors.

The works devoted to the study of memory and attention turned out to be quite numerous. There are no found correlation between age and attention levels in children of 6–8 ages by A. Diaz et al. [6], but the memorization and retrieval skills of older children were higher. The difference in skills of active controlled retrieval between children and adults was noted by F. Simard and G. Cadoret [7]: in the process of solving the active controlled retrieval task, a lower level of memorization and retrieval skills was revealed in children compared to adults. Both groups also showed difficulties in retrieval the shape rather than the color. As well as a more extensive deflection of N400 in children, which may be an indicator of the disambiguation process and a signature of active controlled retrieval in children [7], and Y. Cycowicz – the improved performance of the memory orienting response with age, and differences in the processing of unfamiliar visual symbols [8]. In an experiment with working memory, children's neural networks became more active with increasing cognitive load, as was noticed by V. Vogan et al. [9]. The relationship between daily vigorous physical activities and cognitive control

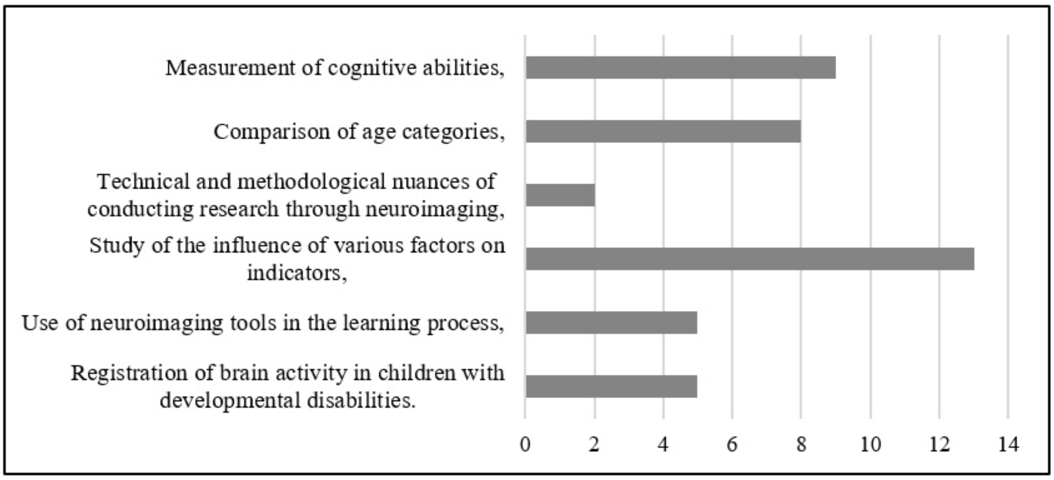

Fig. 2. The main groups of research identified in the review process

indicators, paying attention to the need and importance of objective measurement of physical activity indicators due to the complexity of forming uncertain conclusions and the possibility of erroneous and inaccurate indicators, was studied by D. Pindus et al. [10]. M. Maguire and M. Schneider tried to find a connection between the family's social status and the child's cognitive abilities [11].

Reading and math skills were also studied. A. Dębska et al. examined the interrelationship between the activation of specific brain regions in solving problems requiring auditory phonological processing in the process of studying reading and spelling [12]. Differences in mental flexibility in children and adults (children relied more on parietal areas to solve a shift task) were found by A. Mogadam et al. [13]. The intraparietal sulcus scores of children and adults in number processing tasks and solving arithmetic examples were compared by A. Matejko and D. Ansari [14]. Children with less developed mathematical skills need to make more effort to control attention when solving problems on comparing numbers, as was found by A. Gonzalez–Garrido et al. [15]. The possibility of personalized training of mathematical skills based on the results of initial tests of subjects was considered by F. Nemmi et al., who also noted the different effectiveness of training schemes depending on children's initial data [16]. A. Kersey and K.-M. Wakim showed dissociation between math and reading in regions of the cortex and also revealed "unique for a child" patterns of neural activity in the process of solving such tasks [17]. Even a short-term demonstration of mathematical problems causes a neural reaction of avoidance and distraction from this task, revealing similarities with phobia manifestations, as it was determined by R. Pizzie and D. Kraemer [18]. Margaret Semrud–Clikeman in her review noted that the structure and development of the brain in children with dyslexia differs, as well as the course of information processing. While reading, they activate atypical areas of the brain, perceiving this process as new and unaccustomed [19].

Many researchers developed their own testing tasks and approaches that would fully meet their needs, and standardized testing methods were also applied. Most authors used technologies for recording brain activity during short-term testing (one or more tests) of subjects to track specific patterns.

The most preferred technologies are EEG and fNIRS, which are relatively cheap and quite effective. The development of technologies makes it possible to make more and more large-scale and accurate calculations and simplify the research process for subjects. However, it is still necessary to distinguish between models used for the mass user and the narrowly focused specialist. When using such technologies in the educational process, they are also necessary to be compact and light, without significant loss of quality of reading input data. Some authors also pay attention to this.

Studies that used PEEG technologies (portable EEG) in educational research were analyzed and summarized by J. Xu and B. Zhong [20]. According to the review results, they concluded that this technology was mainly used for reading data about the phases of the subjects' increased attention and relaxation. Moreover, the validity of the results obtained for almost half of the selected papers was based on previous research, and the sample was small.

Also, most of the researches were conducted in the framework of individual tests. Analysis of various subject areas, in addition to reading and counting skills, was conducted much less frequently [20], although the specifics of teaching various sciences must be taken into account when analyzing neurophysiological signals.

However, the principal and indisputable advantage of portable technology is the absence of the need for numerous sensors and wires, the inconvenience of which, despite the higher accuracy, can spoil the indicators, especially in children and in those with various deviations and diseases, in particular.

In developing personalized learning technology, it is necessary to remember that the level of development and psychophysiological state of children will differ. Moreover, there is a possibility that there may be several "special" children in the same group where such technologies are supposed to be used, and the approach to working with them will differ. This work requires additional preparation.

For this purpose, E. Pua et al. [21] developed a set of measures that allow children with autism spectrum disorders to get acquainted in detail with the upcoming procedure in advance to minimize the stress level during it. This package includes:

- an application that allows one to learn how the study is conducted in the format of a game;
- an illustrated story;
- recording the noise produced by the device during operation;
- a study trip to the venue;
- training on the layout of the EEG device.

These steps are selected individually, depending on the child's health and readiness for the next stage. According to the study results, such preparatory work significantly improved the quality of the obtained indicators, in particular, by reducing artifacts from head movement.

Mobile EEG systems are seen as promising in working with special children (and, of course, with healthy ones) [22]. A. Lau-Zhu et al. believe that mobile EEG can open up unprecedented opportunities for studying disorders of the nervous system and get closer to unraveling the etiology and mechanisms of psychopathology throughout life.

Conclusions

Brain research is a challenging and essential area of science. Even considering the acquired knowledge and high technology development, there are still many "dark spots" and questions. The child's brain is an even more complicated system because the timely recording of its transformations can be an impossible task due to rapid age changes and significant differences at various stages of development.

The use of methods for recording brain activity in the learning process is still an insufficiently developed topic due to the complexity of technical implementation and correct evaluation of the results obtained. At the moment, the main focus is on subjects' one-time testing in the process of studying their brain structures and activities. Studies of the various teaching specifics and continuous training were not conducted so actively.

However, the presence of a large number of such studies can be a reasonable basis for further work and upgrowth of studying brain responses during educational activities and evaluating the individual learning trajectories' effectiveness.

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