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SYSTEMATIC REVIEW

Enhancing Cognitive Function with Electroencephalography-Based Brain-Computer Interfaces in Education

Mejorando la Función Cognitiva con Interfaces Cerebro-Computadora Basadas en Electroencefalografía en Educación

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ABSTRACT

Introduction: this research delves into the transformative potential of Brain-Computer Interfaces (BCIs) in the domains of education and healthcare. The study explores their applications for cognitive disorder diagnosis and their integration into educational environments, highlighting the multidisciplinary collaboration and technological advancements driving BCI research.
Objective: the primary objective is to assess the impact of BCIs on cognitive disorder diagnosis and their potential integration into educational settings.
Methodology: a qualitative systematic review of scientific articles published in English and Spanish between 2010 and 2022 was conducted. A total of 84 articles were evaluated, with 68 meeting the selection criteria, focusing on BCI as the object of study associated with cognitive functions.
Results: The study reveals the pivotal role of EEG technology in BCI development, particularly in diagnosing cognitive disorders such as ADHD. It highlights the applications of BCIs in cognitive training and their promising potential in enhancing education and healthcare. Interdisciplinary collaboration is identified as a driving force, fostering innovation in BCI systems.
Conclusion: this research underscores that BCIs represent not only technological innovation but also a paradigm shift in how cognitive disorders are diagnosed and managed. Their integration into educational settings holds promise for tailored interventions, improving learning experiences and socialization. BCIs empower individuals with disabilities, granting them greater independence and access to various technological tools. The study's findings have profound implications for educational strategies and the overall quality of life for individuals with cognitive disorders, offering a brighter future where BCIs redefine possibilities and enhance the human experience.

Keywords: Brain-Computer Interfaces (BCIs); Cognitive Functions; Electroencephalogram (EEG); Educational Technology; Neurological Disorders.

RESUMEN

Introducción: esta investigación profundiza en el potencial transformador de las Interfaces Cerebro-Computadora (BCI, por sus siglas en inglés) en los ámbitos de la educación y la salud. El estudio explora sus aplicaciones para el diagnóstico de trastornos cognitivos y su integración en entornos educativos, destacando la colaboración multidisciplinaria y los avances tecnológicos que impulsan la investigación en BCI.
Objetivo: el objetivo principal es evaluar el impacto de las BCI en el diagnóstico de trastornos cognitivos y su potencial integración en entornos educativos.

Metodología: se realizó una revisión sistemática cualitativa de artículos científicos publicados en inglés y español entre 2010 y 2022. Se evaluaron un total de 84 artículos, de los cuales 68 cumplieron con los criterios de selección, enfocándose en las BCI como objeto de estudio asociado a las funciones cognitivas.
Resultados: el papel crucial de la tecnología EEG en el desarrollo de BCI, particularmente en el diagnóstico de trastornos cognitivos como el TDAH. Destaca las aplicaciones de las BCI en el entrenamiento cognitivo y su prometedor potencial para mejorar la educación y la atención sanitaria. Se identifica la colaboración interdisciplinaria como una fuerza impulsora, fomentando la innovación en los sistemas de BCI.
Conclusión: esta investigación subraya que las BCI representan no solo una innovación tecnológica, sino también un cambio de paradigma en cómo se diagnostican y manejan los trastornos cognitivos. Su integración en entornos educativos promete intervenciones personalizadas, mejorando las experiencias de aprendizaje y la socialización.

Palabras clave: Interfaces Cerebro-Computadora (BCI); Funciones Cognitivas; Electroencefalograma (EEG); Tecnología Educativa; Trastornos Neurológicos.

INTRODUCTION

Research, whether scientific or technological, is conceptualized as a rigorous process aimed at producing knowledge that resolves previously presented questions. In general terms, research aims to transform reality based on a greater understanding and comprehension of it.[1,2,3]

From the perspective adopted in this systematic review, the difference between scientific research and technological research is noted; the former facilitates a greater understanding of reality, while the latter validates technology by demonstrating its ability to achieve some transformation. Thus, scientific research facilitates a deeper comprehension of reality, whereas technological research confirms the efficiency of methods, techniques, procedures, and particularly the effectiveness of the instruments it validates, thus allowing their use and transfer.[4]

Technological development has enabled the production of numerous instruments that, among other contributions, allow the analysis of cognitive functions from various perspectives. These include image recognition, voice recognition, artificial intelligence, electroencephalography, magnetic resonance imaging, all of which are becoming increasingly significant. Of these cognitive analysis techniques and methods, the growing application of the brain-computer interface (BCI) stands out, optimizing the efficient and non-invasive recognition of brain activity patterns.[5,6,7]

Originality in the Context of Brain-Computer Interfaces (BCI)

The research provides a novel perspective by exploring the use of BCIs in educational settings and the assessment of cognitive disorders such as ADHD. This approach combines advanced technologies with practical applications in a field at the forefront of neuroscience and education. By focusing on how BCIs can enhance both diagnosis and intervention in cognitive disorders, the research extends the understanding of the potential applications of BCIs beyond traditional clinical uses.

Contribution to Understanding Electroencephalography (EEG) in Diagnosis and Monitoring

The research contributes to existing knowledge by delving into how EEG, as part of BCIs, can be efficiently used for the diagnosis and monitoring of cognitive disorders. The detailed exploration of EEG applications in identifying brain wave patterns associated with ADHD, for example, provides a richer understanding of how this technology can be used in educational and clinical contexts.

Implications in Education and the Development of Educational Strategies

It is significant in illustrating how BCIs can be integrated into the educational environment to enhance learning and adaptation for students, especially those with cognitive disorders. By providing concrete examples of how these technologies can be applied to optimize educational settings and improve students' socialization and learning quality, the study offers valuable and applicable insights for educators and decision-makers in the education system.

Multidisciplinarity and Technological Advancement

The work highlights the interdisciplinary nature of BCI research, bridging fields such as engineering, neuroscience, and education. This multidisciplinary approach is crucial for the effective development and application of advanced technologies like BCIs, underscoring how collaboration across diverse disciplines can lead to significant innovations and improvements in the quality of life for individuals with cognitive and motor disabilities.

In summary, the research presents an innovative and multifaceted approach to the use of brain-computer interfaces, highlighting its relevance in the diagnosis and management of cognitive disorders and its transformative potential in the educational sphere. This approach not only enriches the field of BCIs and EEG but also opens new avenues for practical applications in educational and clinical settings, marking a significant step towards the effective integration of advanced technology in enhancing education and quality of life.

Theoretical framework

Electroencephalogram (EEG) has long been the leading technique for the observation and functional analysis of the central nervous system (CNS), and still today, it is a substantial support for clinical work in diagnosing and monitoring various neurophysiological pathologies and others related to the physiology of cognitive processes.[8,9,10,11]

A basic EEG allows, non-invasively, an economical exploration that can be decisive in clinical practice. Its use involves adhering a set of electrodes to the scalp through a conductive gel. These are placed following a standardized pattern called the international system 10-201,2. Then, the voltage difference between each pair of electrodes, known as leads or recording channels, typically numbering 16 to 24 in each setup, is measured.[12] This mechanism is based on the function of neurons, which communicate with each other using low-intensity electrical impulses that can be measured. This activity generates a set of brain waves of different frequency types characterized by their greater or lesser speed. These waves can be separated through filters and are inherent to the functioning of the central nervous system.[13,14]

Every experience a person goes through daily is paralleled in brain activity, understood as the relationship between the individual's behaviors and their activating effect on multiple neural circuits that integrate into an extensive and complex system of synaptically connected nerve cells. Various positive emotional states accompanying a person's behaviors generate a set of waves that can undergo significant variation if they turn into negative emotional states. That is, the magnitude and recurrence of certain emotions like anger, fear, disgust, sadness, can have negative effects on a person's quality of life and become a risk factor, significantly impacting physical and mental health. The condition of an individual often subjected to anxiety situations, preventing them from enjoying a state of relaxation, can be graphed as a significant increase in fast Beta 3 waves. Current knowledge about the physiology of the central nervous system allows for determining when waves are in a state of imbalance. These alterations in the wave condition indicate discomfort and even a nosological condition incompatible with adequate quality of life. This dynamic of emotional states can be graphed through the mapping of brain waves, and their condition provides information about their quantity and proportion, the speed of nerve impulse conduction, and the intensity of neural activity communication.[13,14,15,16,17,18]

The various waves observed in the EEG and recorded in a brain map can be classified for greater knowledge and analysis based on their characteristics. Table 1 shows the general classification of brain waves based on their frequency.[14,17]

Table 1. Classification of the brain waves

Type of waves	**Frecuency**
Delta	0,2 – 4 Hz
Theta	4 – 8 Hz
Alfa	8 – 12 Hz
Beta	12 – 30 Hz
Gamma	30 – 90 Hz

Delta waves are characterized by their very slow frequency and at the same time, a greater amplitude. They are observed when the subject is asleep and increase during sleep periods. Additionally, the production of these waves can be observed in states of meditation. The advantage of Delta rhythms lies in the possibility of regeneration and restoration of the central nervous system. Theta waves significantly appear during the function of the senses, managing internal information and inducing the subject to disconnect from their environment. They are frequent in states of deep meditation and are fundamental in memory and learning processes. These waves originate in the transition period from wakefulness to sleep.

The need to process traumatic experiences such as fears and nightmares can have the property of generating these waves. Alpha waves are characteristic of the resting states of a relaxed central nervous system that maintains attention. The decrease of these waves determines the subject's inability to achieve a state of relaxation. The presence of this frequency facilitates mental coordination and balance between mind and body; it also induces states of calm and alertness. It is interesting to observe how the brain emits bursts of this frequency as a reward each time it successfully executes a task. This allows experiencing a pleasant sensation that leads to brief states of cerebral relaxation.

Excess of these waves can generate an imbalance in the subjects' attention. Beta waves are evidence of wakefulness states and are characterized by their rapid frequency and, unlike Theta waves, are present when attention is directed to cognitive processes of the environment and the subject faces the demand to make decisions or concentrate to resolve various day-to-day situations. Gamma waves are characterized by being produced in short bursts and are faster than the other frequencies. They can be observed when the central nervous system simultaneously associates information from various areas. These waves are present in states of high concentration and attention, such as when performing a mathematical calculation or the subject remains in virtuous states like spirituality, altruism, or love. These waves can influence the modulation of perception and conscious activity, ceasing to be observed under the effects of anesthetics.[13,14,15,17]

The knowledge of the various waves that evidence the activity of the central nervous system has generated a series of applications from technology. One of the most relevant applications is brain-computer interface systems or BCIs, which allow the use of neural information to be processed through a computer and generate direct interaction of a subject's brain with their immediate environment. This new technology opens new channels of communication that will enable many people to overcome limitations and interact effectively with their surroundings.[18]

The condition of being alive requires people to generate a set of responses to the action of various stimuli around them to adapt. These responses are channeled through the modification of the environment or by the expression of thought, that is, the manifestation of desires, feelings, and ideas. A BCI is defined by Gonzalez-Argote[19] as "a computer-based system that acquires electrical signals from the brain; analyzes them and translates them into commands that are transmitted to an output device to carry out a desired action" (p. 268). It is a type of technology that, from the apprehension of information generated by the brain, from its electrophysiological activity, converts it into the possibility, as commands, to control a variety of devices. In other words, an effective control link between the brain and a variety of frequently used machines in its environment is created.

Various BCI models, directly related to EEGs, are important in allowing control of devices and facilitating communication, considering that these designs obviate the use of the muscular system and limbs that connect with the environment. One of the most widespread applications is aimed at facilitating communication and interaction of people with paralysis who, through a device, can control wheelchairs and all those artifacts that can generate a better quality of life. These BCI designs capture and evaluate the various characteristics of brain waves which patent certain needs of the person and decipher these variables generating real-time responses based on the subject's intentions. As can be seen, a great diversity of BCI configurations may be needed due to the broad spectrum of its use, making the need for a general prototype a desire of technology.[8]

In general terms, a BCI model has a series of components: a) the subject, who operates the BCI system and by processing the electrophysiological information of the brain generates the signals that will act controlling the device; b) the electrodes, which transduce the electrophysiological information of the brain's activity into electrical signals; c) the amplifier, responsible for amplifying the electrical signals; d) digitization, allows converting analog signals into digital signals optimizing their processing; e) feature extraction, discriminates parameters of the amplified electrical signals from the brain's electrophysiological responses; f) classification, associates the previous parameters with control signals generating a spectrum of possible states; g) control interface, allows the logical control signals to be translated into control signals appropriate for certain devices; h) the device controller, uses the signals from the control interface as input to produce physical signals appropriate to control devices.

The use of BCIs has been primarily aimed at controlling devices based on the commands generated in a BCI system. Currently, a series of articles have been compiling the various applications that have been given to this interesting technology. Most of these applications have landed in the clinical area of neurorehabilitation and in the field of assistance for communication, movement control, and locomotion. Ramírez[20] refers in an article to a classification of the uses and applications of this technology in the real world. There is currently a trend that directs BCI systems for use by healthy individuals, as well as their use in diagnosing learning problems in schools. Shin et al.[21] confirms this observation by pointing out various fields of incidence of BCI use, such as in the field of medicine, design of intelligent and neuroergonomic environments, as a tool for advertising and neuromarketing, for the control of recreational and entertainment instruments, for identity verification and security, and finally, for diagnosis and self-regulation in educational environments.[22]

An important area that this technology is rapidly occupying is related to education and its interest in understanding those brain functions that interact in the learning process and the effectiveness of methodologies and techniques that are currently used to achieve it.[23,24] In the same way, it motivates the interest in transferring this knowledge from the academic field to the actual practice in classrooms and homes, as it is necessary for the various educational agents, especially decision-making instances of the educational system, to have alternatives that allow for higher educational quality based on a greater understanding of the physiology of brain learning.[25] Functions as basic as serialization, classification, and conservation, and as complex in their association that allows numerical management and others associated with language, for example, can be better understood as well as other cognitive functions present in the learning process. Bueno et al.[26] describe four types of interfaces and characterize them and relate them to various brain responses somehow associated with cognitive functions. Table 1 shows a synthesis of various classifications of the use of BCI systems.

Table 2. Classification of Brain-Computer Interfaces (BCIs) and their main characteristics

Type	Mental task	Endogenous neuromechanism
Active	Imaginary movements	Slow cortical potentials, movement-related cortical potentials, neuronal synchronization level, eeg signal power in sensorimotor bands.
	Mental Rotation of 3D Bodies	
	Mental linguistics	
	Internal musicalization	
Type	Exogenous neuromechanism	Type of stimulation
Reactive		Visuals
	Evoked Potentials in stable state	Auditory
		Somatosensory
	Evoked potentials	Visuals
		Auditory
		Somatosensory
	P300	
Type	State to detect	
Pasive	Anxiety	
	Fatigue	
	Attention	
	Frustration	
Type	Type of system	Example of system
Hybrid	Combination of Systems	Imaginary Movements & P300
		Visual Evoked Potentials & Mental Tasks
	Combination of Signals	EEG & ECG
		EEG & EMG

Note: adapted from[19]

It has been pointed out that one of the most promising fields for the development and application of BCI (Brain-Computer Interface) systems is in education. Currently, BCIs are being successfully used as part of the assessment in various disorders, such as Attention Deficit Hyperactivity Disorder (ADHD). Traditionally, this diagnosis was made based on the references provided by family members and caregivers about the presence of behavioral symptoms, which determines a high subjective component, reinforcing the need for as objective indicators as possible to determine the presence of the disorder and establish educational and clinical strategies to achieve evolution and optimize the adaptation of students to the school environment, improving their socialization and the quality of their learning.[11,27]

The knowledge derived from the use of BCI devices can help improve understanding and make both educational environments and learning itself more effective. The complexity of learning processes requires the coordination of various areas of science and its principles to have a more complete understanding of the internal and external variables involved in the learning process.[28,29]

METHODS

A systematic review, by summarizing the knowledge generated in various previous research, facilitates evidence of high objectivity on the analyzed topic. Its usefulness lies in providing a series of criteria necessary in various instances, such as administrative, educational, and economic, for decision-making in terms of developing tools, manuals, and guides; for decision-making in various areas of educational systems; they are fundamental for economic analysis. In summary, the goal is to analyze the quality of various technologies so that they can be used safely and effectively.

This type of review can be conducted from a quantitative orientation or meta-analysis, as well as from a qualitative orientation or as a whole, which is primarily determined by the statistical procedures employed, since the systematic review combines and analyzes quantitatively the information generated in various research studies in each study.[30] The current research conducted a qualitative review characterized by describing the analyzed information without the need to process it through statistical elements. These reviews are also known as systematic reviews without meta-analysis.[31]

Conducting a systematic review requires following an ordered sequence of activities aimed at giving the necessary formality to what is analyzed. This sequence begins with the formulation of the problem, which can also be represented by a research objective or question; then, it involves locating the necessary information in the form of research based on what was established in the first stage; evaluating the quality of the studies from which data are extracted, then analyzing them and presenting the results; and concludes with an interpretation of the results.[32]

The systematic review of the current study was primarily based on scientific articles reported on the topic of BCI and cognitive functions. Initially, it was intended to consider only two criteria in the search: Brain-Computer Interface (BCI) and cognitive functions; however, a gap was found in this search. Therefore, it was decided to include the topic of electroencephalogram (EEG). This systematic review was based on articles stored in various bibliographic databases such as Dialnet, SciELO, Redalyc, and Scopus, and also employed the Google Scholar search engine. A total of 84 articles were evaluated, and 68 were selected, considering the following selection criteria: scientific articles in English and Spanish, published with a date range of 2010 - 2022, where BCI is the object of study and/or is included in the title of the research and at the same time associated with the variable cognitive functions.

RESULTS

The origins of Brain-Computer Interfaces (BCI) are rooted in electroencephalography (EEG), considered one of the main diagnostic tools for clinical entities associated with brain physiology and the monitoring of patients' cerebral physiology. Its low cost, easy accessibility, and reduced risk make this type of evaluation one of the most used and necessary in clinical intervention in recent years.[33,34]

Currently, the development of neuroscience associated with the use of neuroimaging has advanced electroencephalographic studies applied to various disorders related to cognitive functions in children, which were usually evaluated based on subjective observations and reports from family members and teachers. This often led to inadequate diagnoses, contributing to an increase in false positives.[27] EEG has been practiced in research processes as well as in evaluation and diagnosis, predominating the use of the single electrode model to establish brain activity, as it simplifies, facilitates, and speeds up its use, reducing the level of complexity. This feature increasingly associates it with BCIs.[22]

One of the earliest applications of EEG is associated with the evaluation and diagnosis of ADHD. Various electroencephalic alterations have been established, and even a specific profile in children diagnosed with ADHD has been identified.[9,27,35]

BCI systems, like EEGs, are based on brain physiology that allows the generation of electrical signals, and from the capture of these signals, computer commands are produced that enable the control of peripherals such as motorized wheelchairs and others. BCI formats have a wide variety of applications, but mainly, their purpose is to transmit an intention or need through the transduction of electrical signals generated in the brain.[36]

Many people with motor or cognitive disabilities face various challenges in carrying out their daily responsibilities and in the socialization process, mainly because their condition requires specialized permanent support. In various nosological entities that compromise central and peripheral structures of the nervous system related to motricity, such as sclerosis and paralysis, patients are exempted from the personal and autonomous use of various technological tools due to the degree of motor disability they may have, significantly exacerbating the risk of their development. In other pathologies where the limitation is in the order of cognitive functions, such as Down syndrome and mild retardation, there is a significant impediment to autonomously use various tools common to the demands of daily life. Social limitations are often the biggest obstacle to reaching these people, and their functions worsen daily without the possibility of accessing these new technologies.[10]

Current research is aimed at establishing environments where the use of BCI systems is feasible for performing mental tasks and for enhancing cognitive capacity, especially in the educational field. The applications found are promising despite the incipient use of BCI systems in cognitive training and the gradual deterioration characterizing mental functions due to aging.[37,38,39,40]

The multidisciplinary nature observed today in scientific research, particularly in engineering and neuroscience, has allowed the development of BCIs, making them a powerful tool that will improve the condition of those suffering from a wide spectrum of neurological injuries and limitations, especially children with some type of cognitive disability.[26]

DISCUSSION AND CONCLUSIONS

The qualitative systematic review conducted has allowed for a panoramic evidence of the use of BCI (Brain-Computer Interface) systems to assess cognitive functions and their potential application in educational systems. The orientation of BCI devices towards the well-being of people with motor disabilities is evident. An increasing trend for their educational use in cases of ADHD (Attention Deficit Hyperactivity Disorder) is observed. It is necessary to point out that BCIs, despite using a reduced number of electrodes, are projected as a tool with powerful possibilities due to their non-invasive nature, affordability, and economical aspects, and can be projected for use in a large number of spaces within educational systems. There has not been a significant incidence of use for integration into human cognition.

Transformative Potential in Education and Healthcare

The discussion brings to light the transformative potential of Brain-Computer Interfaces (BCIs) in the realms of education and healthcare. By delving into the applications of BCIs for cognitive disorder diagnosis and their integration into educational environments, it becomes evident that BCIs are not only cutting-edge technology but also a catalyst for positive change. The research underscores that BCIs have the capacity to revolutionize the way cognitive disorders are diagnosed and managed, offering promising avenues for enhancing the quality of education and life for individuals with disabilities.

Interdisciplinary Collaboration and Technological Advancements

An overarching theme emerging from the discussion is the power of interdisciplinary collaboration. The study highlights the synergy between fields such as engineering, neuroscience, and education, emphasizing that progress in BCI research is contingent on collaborative efforts. This multidisciplinary approach is a driving force behind the development of innovative BCI systems, bridging the gap between theoretical knowledge and practical applications. Moreover, the research showcases how technological advancements in EEG and BCI technology are making previously unattainable possibilities a reality, enabling individuals with motor and cognitive disabilities to lead more autonomous lives.

Implications for Educational Strategies and Quality of Life

In conclusion, this research holds significant implications for educational strategies and the overall quality of life for individuals with cognitive disorders. The findings illuminate the potential for BCIs to be integrated into educational settings, providing tailored interventions that enhance learning experiences and socialization. Furthermore, BCIs have the potential to empower individuals with disabilities, granting them greater independence and access to various technological tools. The study ultimately underscores that BCIs represent not just a technological innovation but a paradigm shift in how we approach cognitive disorders, education, and quality of life.

These three paragraphs encapsulate the key takeaways from the "Discussion and Conclusions" section, emphasizing the transformative potential of BCIs, the importance of interdisciplinary collaboration, and the far-reaching implications for education and quality of life.

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