BRAIN-COMPUTER INTERFACES AND NEUROTECHNOLOGY

INTERFACES CÉREBRO-COMPUTADOR E NEUROTECNOLOGIA

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ABSTRACT

In recent decades, technological advances have created a new frontier between biology and engineering: brain-computer interfaces (BCIs). These systems enable direct communication between the human brain and external devices, eliminating the need for muscle intervention. Neurotechnology, a field that combines neuroscience, engineering, computer science, and artificial intelligence, has expanded the capabilities of BCIs with promising applications, particularly in medicine. However, despite the progress already made, significant challenges remain, such as the inaccuracy of collected signals, the complexity of neural processing, and accessibility difficulties. Therefore, this paper aims to present a current overview of BCIs and neurotechnology. It is concluded that, by facilitating direct communication between the human brain and computer systems, these innovations usher in a new era of therapeutic, functional, and cognitive opportunities. From their theoretical development to current clinical and experimental implementations, BCIs have proven to be immensely valuable tools for patient recovery, supporting individuals with disabilities, and the search for new ways to interact with the digital world. Advances in brain signal capture techniques, improved decoding algorithms, and improved physical devices have enabled an increasingly precise connection between mind and machine, establishing this field as a strategic hub for scientific and technological innovation.

Keywords: Brain-Computer Interfaces. Neurotechnology. Neuroscience. Artificial Intelligence.

RESUMO

Nas últimas décadas, o progresso na tecnologia resultou na criação de uma nova fronteira entre biologia e engenharia: as interfaces cérebro-computador (ICC), ou brain-computer interfaces (BCI). Esses sistemas possibilitam uma comunicação direta entre o cérebro humano e aparelhos externos, dispensando a intermediação muscular. A neurotecnologia, um campo que une neurociência, engenharia, ciência da computação e inteligência artificial, tem ampliado as capacidades das ICC com aplicações promissoras, principalmente na medicina. Entretanto, apesar dos progressos já realizados, existem desafios relevantes, como a imprecisão dos sinais coletados, a complexidade do processamento neural e as

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dificuldades de acessibilidade. Dessa forma, este trabalho tem como objetivo apresentar um panorama atual das ICC e da neurotecnologia. Conclui-se que, ao facilitar a comunicação direta entre o cérebro humano e sistemas computacionais, essas inovações inauguram uma nova era de oportunidades terapêuticas, funcionais e cognitivas. Desde o seu desenvolvimento teórico até as atuais implementações clínicas e experimentais, as ICC têm se revelado ferramentas de imenso valor para a recuperação de pacientes, o suporte a indivíduos com deficiência e a busca por novas formas de interação com o universo digital. O progresso nas técnicas de captação de sinais cerebrais, o aprimoramento dos algoritmos de decodificação e a melhoria dos dispositivos físicos têm permitido uma conexão cada vez mais precisa entre mente e máquina, estabelecendo esse campo como um núcleo estratégico para a inovação científica e tecnológica.

Palavras-chave: Interfaces Cérebro-Computador. Neurotecnologia. Neurociência. Inteligência Artificial.

RESUMEN
En las últimas décadas, el progreso tecnológico ha dado lugar a la creación de una nueva frontera entre la biología y la ingeniería: las interfaces cerebro-computadora (BCI). Estos sistemas permiten la comunicación directa entre el cerebro humano y dispositivos externos, eliminando la necesidad de intermediación muscular. La neurotecnología, un campo que combina la neurociencia, la ingeniería, la informática y la inteligencia artificial, ha ampliado las capacidades de las BCI con aplicaciones prometedoras, particularmente en medicina. Sin embargo, a pesar de los avances ya alcanzados, existen desafíos importantes, como la inexactitud de las señales recogidas, la complejidad del procesamiento neuronal y las dificultades de accesibilidad. Así, este trabajo pretende presentar un panorama actual de la ICC y la neurotecnología. Se concluye que, al facilitar la comunicación directa entre el cerebro humano y los sistemas informáticos, estas innovaciones inauguran una nueva era de oportunidades terapéuticas, funcionales y cognitivas. Desde su desarrollo teórico hasta las implementaciones clínicas y experimentales actuales, las ICC han demostrado ser herramientas inmensamente valiosas para la recuperación de pacientes, el apoyo a personas con discapacidades y la búsqueda de nuevas formas de interactuar con el mundo digital. Los avances en las técnicas de captura de señales cerebrales, las mejoras en los algoritmos de decodificación y las mejoras en los dispositivos físicos han permitido una conexión cada vez más precisa entre la mente y la máquina, estableciendo este campo como un centro estratégico para la innovación científica y tecnológica.

Palabras clave: Interfaces Cerebro-Computadora. Neurotecnología. Neurociencia. Inteligencia Artificial.

1 INTRODUCTION

In recent decades, progress in technology has resulted in the creation of a new frontier between biology and engineering: brain-computer interfaces (BCI). These systems enable direct communication between the human brain and external devices, dispensing with muscle intermediation. Such technologies are based on the capture of neural signals, their decoding through algorithms and the conversion into commands to operate prostheses, computers, wheelchairs and other tools, bringing a revolution in the interaction between humans and machines.

Neurotechnology, a field that unites neuroscience, engineering, computer science, and artificial intelligence, has expanded the capabilities of CCIs with promising applications, especially in medicine. Individuals with motor paralysis, neurodegenerative conditions, or amputations are already benefiting from innovations that restore some of their independence. Furthermore, the use of these technologies in non-clinical contexts, such as entertainment, education, and alternative communication, indicates a future in which thinking can control digital systems in a more intuitive and fluid way.

The choice of this theme is based on the growing scientific and social importance of brain-computer interfaces in today's society, both for the positive impact on the lives of people with disabilities and for the opportunities they present to expand human cognition and interaction with devices. Understanding the foundations, uses, and limitations of these technologies is essential to reflect on their ethical, technical, and social consequences.

However, despite the progress already made, there are relevant challenges, such as the imprecision of the signals collected, the complexity of neural processing, and accessibility difficulties. In this context, the following question arises: what are the main current developments, obstacles and applications of brain-computer interfaces and neurotechnology in the current scenario?

Thus, this work aims to present a current overview of CHFs and neurotechnology, emphasizing their scientific bases, main areas of application, challenges faced and future perspectives, focusing on the social and ethical impacts resulting from their large-scale adoption.

The approach used in this study is bibliographic research, based on scientific publications, books, specialized journals and recent academic articles, with the intention of gathering and organizing the existing knowledge on the subject to provide a critical and grounded analysis.

2 DEVELOPMENT

2.1 FUNDAMENTALS OF BRAIN-COMPUTER INTERFACES

According to Maiseli et al. (2023), Brain-Computer Interfaces, often referred to by the acronym BCI, are systems that enable a direct connection between the human brain and external devices, eliminating the need for involvement of peripheral muscles or the autonomic nervous system. Such systems operate by capturing electrical or metabolic signals that result from brain activity, which are processed and converted into digital commands. The foundation of CHF originates from research in neurophysiology that investigates the electrical potentials of the brain and its link with stimuli, as well as with motor, sensory, and cognitive responses. With progress in biomedical engineering and artificial intelligence, these technologies have been implemented more accurately and effectively, allowing users to control computers, robotic prostheses, wheelchairs, and even applications and communication, using only their mental activity.

The functioning of CCIs is divided into three main stages according to Young et al. (2021): the collection of neural signals, the analysis of these signals with the identification of important characteristics, and the conversion of this information into commands that can be triggered. To do this, the system needs to distinguish patterns of brain activity that refer to specific intentions, such as moving a cursor on the screen or activating a function on a prosthesis. The intricate nature of the human brain, along with the variability of signals between different people, poses significant challenges to creating large-scale applicable systems, requiring algorithms that are robust and adaptable. In addition, individual training is required, where the user must learn to control their brain signals to improve the effectiveness of using the system. Therefore, the success of CCIs depends on both the technology used and the user's ability to adapt.

The successful implementation of a brain-computer interface thus requires a comprehensive understanding of neuroscience, electrical engineering, computer science, and cognitive psychology. CCIs not only work from biological signals, but also involve aspects of human behavior, motivation, and real-time interaction with machines. This direct connection between mind and machine establishes a new paradigm in assistive and interactive technologies, challenging traditional methods of communication and control. Simultaneously, it raises significant questions about the limits of technology, the conception of consciousness, and the role of cognition in the era of neurophysiological digitalization (MAISELI et al. 2023).

Among the various types of CHF, they can be divided into three major groups, as pointed out by Karsanach et al. (2016): invasive, non-invasive, and semi-invasive. Invasive

CHF consists of inserting electrodes directly into brain tissue, enabling the capture of neural signals with high spatial and temporal accuracy. This technology is used, for example, in individuals suffering from serious motor neuraltic injuries, such as those affected by locked-in syndrome, because direct interaction with neurons results in faster and more accurate responses. However, this methodology requires surgery and poses substantial risks to the patient's health, as well as high costs and complicated ethical issues.

Non-invasive brain control interfaces are currently the most researched and used, mainly because they are safe, accessible, and applicable in various contexts, both clinical and non-clinical. These systems capture signals from the brain through sensors placed on the scalp, often using the electroencephalography (EEG) technique. Although spatial resolution is limited due to attenuation of signals by skull structures, non-invasive CCIs show enormous potential for practical applications such as motor rehabilitation, alternative communication, and human-machine interaction. In addition, they are often used in academic and clinical investigations to examine neuroplasticity and cognitive behavior (YOUNG et al. 2021).

In the middle ground, Sousa et al. (2022) cite that semi-invasive CHF appears as an intermediate option, where the electrodes are placed on the cortical surface or just below the dura mater, without penetrating deep into the brain tissue. A common example of this type of technology is electrocorticography (ECoG), which provides superior resolution compared to noninvasive methods while presenting fewer risks than intracortical procedures. Although it is still considered experimental in many countries, ECoG has shown promising results for patients who need high-performance solutions without the aggressiveness of deep implants. Thus, the choice between the different types of CHF is influenced by factors such as the purpose of the application, the clinical condition of the user, technical feasibility, and ethical and legal considerations.

For the proper functioning of these interfaces, also according to Sousa et al. (2022), it is essential that neural signals are captured in a reliable and stable manner. One of the most common methods for obtaining brain signals is EEG (electroencephalography), a non-invasive technique that measures electrical potentials generated by neural activity on the surface of the scalp. EEG is popular because it is portable, cost-effective, and offers good temporal resolution, although its limitation in spatial resolution makes it difficult to detect activity in deeper brain areas. Another significant technique is functional magnetic resonance imaging (fMRI), which makes it possible to map activated brain areas with high spatial resolution, monitoring variations in blood flow associated with neural activity. However, fMRI is used less frequently in operational CCIs due to its high cost, equipment size, and lower temporal resolution.

ECoG is a technique that involves placing electrodes directly on the brain surface, functioning as an intermediary between methods that are invasive and non-invasive. This approach picks up signals with greater precision and accuracy, making it valuable in challenging clinical situations and investigations that require high acuity. In addition, other methods, such as functional near-infrared spectroscopy (fNIRS), are being investigated; This method analyzes changes in blood oxygenation in the brain, offering a non-invasive option for the supervision of cognitive functions. The variety of techniques available reflects the continuous effort to find solutions that harmonize signal quality, security, and ease of use (SUN AND YE, 2023).

According to Maiseli et al. (2023), the decision on which fundraising method to use is deeply related to the intended purpose and the infrastructure available, given that each approach has its own advantages and limitations. For example, in controlled clinical settings, more invasive and precise approaches may be appropriate, while in situations at home or at school, simpler and more comfortable technologies are preferred. The advancement of these techniques is crucial to ensure that CCIs are efficient, responsive, and safe, regardless of the audience or context in which they are inserted.

After the neural signals are captured, Sun and Ye (2023) point out that they need to be analyzed by computer systems that are capable of converting them into commands that make sense. This phase includes the pre-processing of the signals, which involves noise elimination and filtering, the extraction of significant characteristics, such as frequency and amplitude, and, finally, the categorization of this information through algorithms, usually based on artificial intelligence and machine learning. These algorithms are trained with reference data to identify brain patterns related to specific intentions or stimuli, such as imagining the movement of a hand or focusing on a point on the screen.

The effectiveness of these algorithms depends on the quality of the data, the user's adaptation, and the resistance to physiological and environmental variations. Thus, Sousa et al. (2022) cite that many modern systems employ personalized continuous learning models, which progressively adjust to the user's peculiarities due to prolonged interaction. The combination of computational neuroscience and machine learning is therefore one of the key foundations for the progress of CCIs, as it allows for the reliable translation of human mental activity into language that the machine can understand, ushering in a new era in brain-technology communication.

2.2 NEUROTECHNOLOGY: INTEGRATION BETWEEN BRAIN AND MACHINE

For Russel et al. (2024), neurotechnology refers to technological innovations that connect to the human nervous system for the purpose of observing, altering, or improving its functions. This growing sector is based on neuroscience and engineering, and is responsible for the creation of devices and systems that enable the reading, writing, stimulation or controlled modification of neural activity. The uses of neurotechnology are wide-ranging, ranging from clinical areas – such as the therapy of neurological disorders, hearing implants and neurological prostheses – to applications outside the medical scope, such as the enhancement of cognitive capabilities, augmented reality and the control of equipment through thought. By dissolving the boundaries between the biological and the technological, neurotechnology opens a new era of interaction between the human brain and artificial systems.

The reach of neurotechnology goes beyond the simple interface between human and machine for Coelho (2015), as it also involves the capture, analysis and modification of brain data for therapeutic, functional and, in some situations, commercial purposes. This encompasses technologies such as deep brain stimulation, neurofeedback, neuromodulation, and brain-computer interfaces, which fit as a subfield within the broad domain of neurotechnology. The ability to impact the central and peripheral nervous system has significant consequences for the understanding of the mind, human behavior, and individual autonomy, requiring reflection on not only what is technically feasible, but also what is ethically desirable.

In this way, neurotechnology should be seen as a strategic sector for the future in the areas of health, education, communication, and in the very definition of humanity. According to Nolêto et al. (2020), by providing solutions for individuals with neurological limitations, it helps to promote inclusion and raise quality of life. On the other hand, by enabling the expansion of cognitive capacities in healthy individuals, neurotechnology challenges traditional notions of normality, competence and merit, raising bioethical discussions about access, inequality and the manipulation of behavior. Progress in this field thus requires a critical and comprehensive perspective that takes into account the social, cultural, and legal consequences of new neural technologies.

In addition, the growth of neurotechnology is fueled by a variety of interests – academic, clinical, military, and corporate – which further increases its scope and complexity. Large technology companies, such as Neuralink, Meta, and Kernel, have invested billions of dollars in creating neural devices capable of reading and writing brain in real time.

Simultaneously, educational institutions and research centers around the globe are developing technologies with a focus on rehabilitation and inclusion. This diverse landscape shows that neurotechnology is, firstly, a growing domain that reflects and influences the direction of contemporary society in the face of new and unexplored possibilities of connection between brain and machine (COELHO, 2015).

According to Russel et al. (2024), interdisciplinarity represents an essential characteristic of neurotechnology, as its implementation requires cooperation between various areas of knowledge. Neuroscience offers the principles on how the brain works, its connections, the processes of synaptic plasticity, and the activation patterns of neuronal networks. With this understanding, engineering and computer science professionals create systems that can capture, interpret, and react to brain stimuli. This collaboration is crucial to developing devices that are functional, safe, and have the ability to operate in real-time, with the precision needed to meet clinical and operational needs.

Artificial intelligence plays an increasingly crucial role in the analysis of neural data. For Mussatto and Silva (2024), using machine learning algorithms and deep neural networks, it is feasible to discover complex patterns in brain signals that would not be detected by conventional statistical methods. These systems not only organize signals, but also learn and adjust over time, greatly improving the effectiveness of brain-computer interfaces and other neurotechnological technologies. AI makes it possible, for example, for a robotic prosthesis to "understand" the user's motor intention through subtle brain signals, resulting in more fluid and precise movements.

Biomedical engineering acts as an intermediary between theory and practical implementation, being responsible for the development of physical devices – such as sensors, electrodes, chips, and interfaces – that connect to the human body. This field must balance aspects such as technical performance, biocompatibility, durability, and comfort, while still following the strict regulatory standards applicable to any medical devices. The miniaturization of components and the innovation of flexible and less invasive materials have been crucial advances, making devices safer and longer-lasting, both in hospital and nursing home settings (SANTOS et al. 2022).

Other disciplines have equally significant roles according to Kawala-Sterniuk et al. (2021). Psychology, for example, assists in the analysis of how neural technologies affect users' behavior, perception, and subjective experiences. Law and bioethics enrich the discussion about liability, privacy related to neural data, and the limits of brain intervention. The intersection of varied knowledge is what makes neurotechnology a fascinating and challenging field, as each new technical discovery carries with it various social and ethical implications that require careful and in-depth analysis.

Cooperation between these areas is not only desired, but essential. Also according to Kawala-Sterniuk et al. (2021), without collaboration between neuroscience, engineering, computer science, psychology, and ethics, it would not be feasible to create truly effective, safe, and human-centered systems. Therefore, neurotechnology demands an innovation model that integrates technical development with critical reflection, ethical regulation, and social inclusion, ensuring that the benefits of these technologies are widely distributed and avoiding new forms of exclusion or dependence.

Advances in hardware and software technology for neurotechnology have been instrumental in improving brain-computer interfaces in terms of accuracy, stability, and accessibility. With regard to hardware, there is a rapid improvement in the quality of neural sensors, highlighting the creation of electrodes that are more sensitive, compact and with higher resolution both spatially and temporally. Such innovations allow for more faithful capture of brain signals, even outside the laboratory environment. In addition, studies are being carried out to make the devices less invasive, using technologies such as electronic tattoos, epidermal implants, and wireless sensors (SANTOS et al. 2022).

Wireless connectivity is a crucial aspect in hardware progress for Maiseli et al. (2023), as it provides a freer and more integrated use of technologies in users' daily lives. Contemporary brain-computer interfaces, for example, already operate in real time with mobile or wearable devices, enabling people with disabilities to communicate in social or professional settings. The reduction in size and energy consumption of electronic components also favors greater autonomy, allowing for home and long-lasting applications. This represents a significant step forward towards democratizing access to neurotechnologies.

In the area of software, Russel et al. (2024) mention that the development of machine learning and artificial intelligence algorithms has enabled an increasingly accurate analysis of neural signals, even considering the complexity and individual variability of these data. Deep learning models, such as convolutional and recurrent neural networks, can identify subtle patterns in brain activation that reflect specific motor intentions, emotional states, or cognitive processes. These advances expand the possibilities of application of brain-computer interfaces, allowing, for example, the control of devices through specific thoughts or the detection of early neurological alterations for diagnostic purposes.

In addition to artificial intelligence, another significant innovation in software is the use of virtual and augmented reality environments that integrate with brain-computer interfaces, creating immersive and responsive experiences for rehabilitation, cognitive training, or entertainment. This integration provides richer brain stimulation, favoring neuroplasticity and accelerating neuromotor adaptation processes. These environments are particularly useful in clinical contexts, such as in the recovery of patients who have suffered stroke or spinal cord injuries, allowing controlled simulations of everyday activities with real-time feedback (COELHO, 2015).

Finally, Russel et al. (2024) point out that the combination of hardware and software in increasingly integrated and modular platforms marks a new level in the evolution of neurotechnologies. It is already possible to find devices that incorporate EEG sensors, Bluetooth, mobile apps with integrated artificial intelligence and intuitive interfaces. This merger facilitates the acceptance of the technology by both ordinary users and healthcare professionals, while enabling the continuous collection of data for the improvement of systems. In this way, advances in hardware and software not only increase the capacity of CCIs, but also help in their gradual assimilation into people's daily lives.

2.3 CURRENT APPLICATIONS OF CHF AND NEUROTECHNOLOGY

Medical uses today represent one of the most advanced and promising sections of brain-computer interface technologies, as well as neurotechnology. For Zhang et al. (2020), in particular, the application of CHF aimed at movement rehabilitation has generated remarkable results in patients who have suffered spinal cord injuries, strokes, and diseases that affect the muscles. These technologies allow a person, through motor visualization, to control robotic prostheses or stimulate their muscles using functional electrical stimulation systems, favoring not only movement, but also neuroplasticity. Often, these neural rehabilitation approaches revitalize motor areas that have been impaired, aiding in partial or full recovery of functions. The ability to adjust technology to the clinical level and individual patient needs makes CHFs an adaptable and efficient tool in therapeutic treatments.

Another important sector according to Kamgwan et al. (2022), is the control of neural prostheses and orthoses. Current technology is already capable of capturing signals from the brain and converting commands that move artificial limbs in line with the user's intentions. For example, upper limb prostheses that are sensitive to touch are directed directly by signals from the motor cortex, representing a considerable advance when compared to traditional mechanical prostheses. These innovations have a positive impact on both functionality and users' self-confidence and independence, especially after amputations. In addition, studies are underway to combine neural sensors with sensory feedback, enabling the individual to perceive the texture, pressure, and temperature of objects that are manipulated by the prosthesis.

It should be noted that alternative communication is another element in which CHF has been successfully employed, especially for those who face severe motor limitations, as is the case of patients with amyotrophic lateral sclerosis (ALS) or severe cerebral palsy. Systems that detect signals from the visual or motor cortex allow these people to select letters, words, or icons only through brain activity, enabling the formation of sentences and connection with the surrounding environment. This technology, called BCI speller, is already being used in commercial devices that feature adaptive layouts and the ability to learn the user's brain patterns. In this way, neurotechnology is offering a new form of communication to those who were previously silenced due to their neurological conditions (ZHANG et al. 2020).

The interfaces between brain and computer have revealed immense potential to help people with physical or neurological limitations, favoring greater autonomy and quality of life. According to Awuah et al. (2024), for those suffering from leg paralysis, for example, systems coupled to exoskeletons allow active control of movement, facilitating reintegration into daily and social activities. These devices are configured to react to signals that indicate the intention to walk, emitted from motor regions of the brain, and can be combined with electrical stimulation of the muscles, which accelerates functional rehabilitation. In domestic environments, these technologies are adapted to ensure safety, comfort and independence for the user.

When it comes to sensory impairments, such as deafness or blindness, neurotechnology also contributes significantly according to Kamgwan et al. (2022). Cochlear implants, which are already quite common, are an established form of interface between brain and technology, converting sound into electrical impulses that stimulate the auditory nerve directly. Recently, research with visual prostheses that are based on stimulation of the retina or visual cortex has been carried out, aiming to partially restore vision through neural decoding. Although still in the experimental phase, these developments suggest that the mediation of sensory communication through neural technologies is becoming a viable reality for people with severe disabilities.

In addition to the ability to move and sensory perception, Nolêto et al. (2020) mention that neurotechnology also helps in the management of everyday devices, such as TVs, cell phones, computers, and home automation systems. Individuals with quadriplegia, for example, are already able, through helmets equipped with EEG sensors, to control their environment with simple mental commands, such as turning on lights, regulating temperature or making calls. The connection between brain-computer interfaces and virtual assistants, in addition to Internet of Things (IoT) technologies, represents a significant advance in digital accessibility, eliminating physical barriers and allowing people with mobility limitations to have greater control of their space in a more autonomous, dignified and comfortable way.

Brain-computer interfaces and neurotechnology are also expanding into areas such as digital games, education, and entertainment, where the main intention is not exclusively therapeutic, but rather enrichment of interaction. In the gaming sector, devices that use EEG already allow players to manipulate game elements with only mental commands, eliminating the use of a keyboard or controller. This technology provides unprecedented immersion, directly connecting the brain to the virtual environment in a responsive way. Such innovations not only enhance the playful experience, but also collect valuable information about attention, stress, and mental engagement, which can be used for therapies or training (VÄRBU et al. 2022).

In the educational area, Araujo et al. (2024) cite that neurotechnology has been used to observe mental states such as focus, motivation, and cognitive load during learning. Neural sensors are integrated into digital teaching platforms that adapt, in real time, to the student's level of attention, suggesting adjustments in rhythm, stimuli and content based on their brain responses. This personalized approach has great potential to increase the effectiveness of the teaching and learning process, especially in special education contexts or for students with attention difficulties. In addition, the information generated can help teachers better understand the mental processes involved in learning.

In the entertainment sector, the interaction between neuroscience and digital media has made it possible to create interactive experiences that adjust to the user's emotional and cognitive state. Movies, music, and virtual environments that react to brain activity are just a few examples that are already being explored in prototypes. There are also discussions about the possibility of developing dynamic narratives in games and films, which change according to the viewer's level of brain involvement. This combination of mind and media expands the horizons of creativity and cultural consumption, making room for a new way of interaction where the brain becomes an active participant in the construction of meaning (RUSSEL et al. 2024).

According to Kamgwan et al. (2022), a new and debated domain for the use of CCIs and neurotechnology is their application in military and security contexts. There are already research projects focused on developing systems that enable direct communication between soldiers and devices, such as drones or weapons, using signals from the brain. The purpose is to speed up the response and improve the accuracy of actions in the field, reducing the interval between perception and reaction. Although they are not yet fully operational, these systems have been subjected to tests in controlled environments and are part of strategic defense plans in nations such as the United States, China and Russia, which lights up a warning sign about the dangers associated with the militarization of sensitive technologies.

In addition to the management of weapons systems, also according to Kamgwan et al. (2022), CCIs are being investigated to monitor the psychological state of military operators, such as pilots or critical mission managers. The goal is to examine exhaustion, stress, or mental overload in real time, enabling preventive interventions that improve safety and operational effectiveness. While this application can be advantageous, it brings to light ethical issues related to mental monitoring and cognitive privacy, since the data obtained can expose unforeseen emotional states or thoughts. The distinction between care and control becomes blurred, requiring specific regulations and clear definitions on the handling of neural information.

Finally, in the area of public security, neural technologies are beginning to be analyzed for the purposes of screening, identifying lies, and detecting hostile intent, based on brain activity. For Zhang et a. (2020), several studies try to discover neural patterns associated with risky behaviors or criminal intentions, although these approaches have not yet reached a level of scientific reliability, raising significant ethical-legal questions. The idea of employing the brain as a means of evidence or as a means of predicting behavior generates profound discussions about free will, the presumption of innocence, and the limits of state intervention in the human mind. In this scenario, neurotechnology not only offers technical potential, but also imposes a great normative and philosophical challenge on today's societies.

2.4 CHALLENGES, LIMITATIONS, FUTURE PROSPECTS AND ETHICAL ISSUES OF CCIS

One of the main obstacles to the full implementation of CCIs is the display of and reliance on the neural signals captured according to Maiseli et al. (2023). Despite significant advances in acquisition methods, brain signals remain extremely vulnerable, affected by both internal and external interference. Non-invasive techniques, such as EEG, have low spatial resolution and are very susceptible to noise, which can include eye movements, muscle contractions, and even changes in ambient temperature. On the other hand, invasive techniques, although they offer greater precision, present surgical risks and clinical complexity. This instability impairs the accuracy in the identification of mental intentions, compromising the performance of CCIs in real time and restricting their use outside controlled contexts. Furthermore, the variation between individuals in neural patterns makes it challenging to create universal systems, requiring continuous calibration and customization for each user.

The computational complexity required to interpret brain signals poses another considerable challenge Sun and Ye (2023). The human brain produces an enormous amount of data at various frequencies, intensities, and areas, and converting this flow into commands that can be understood by machines requires extremely advanced algorithms. Extracting important features, removing noise, and classifying brain patterns in real time require powerful processing and sophisticated artificial intelligence techniques. Even the latest machine learning algorithms face difficulties in adapting to variations in neural signals and changes in the user's mental state, such as tiredness, distraction, or stress. In addition, the efficient training of these algorithms requires large, high-quality datasets, which is not always available, especially in the case of brain signals from specific populations, such as children, the elderly, or individuals with neurological disabilities.

With respect to technological and financial challenges, there is still a long way to go to make CCIs accessible to the general public. According to Zhang et al. (2020), many advanced devices, especially those that use invasive or semi-invasive techniques, still require hospital infrastructure, highly trained professionals, and strict safety protocols. This limits its diffusion in everyday environments, such as schools, homes, or workplaces. Even non-invasive versions intended for general consumption still need improvements in areas such as ergonomics, durability, energy autonomy and connectivity, which makes it difficult to accept and adopt them widely. In addition, the lack of international standards for certification, regulation, and interoperability of these systems makes their commercialization and integration with other technologies more challenging.

From an economic perspective, the creation, maintenance, and updating of brain-computer interface technologies have high costs, which limits their access, especially for users in developing nations or with weakened health systems. Large-scale production is still not enough to cause a significant decrease in prices, and the lack of subsidies or stimulus from the government is also an impediment to its widespread adoption. As a result, there is a risk that neurotechnologies will widen social inequalities, creating a new divide between those who are able to increase their cognitive and motor skills through technology and those who remain outside of this access. This potential inequality highlights the urgency of public policies that ensure fair access to these innovations, especially in key areas such as health and education (MAISELI et al. 2023).

Another group of challenges is related to ethical issues and the protection of neural data privacy according to Sun and Ye (2023). Capturing signals from the brain implies accessing extremely sensitive information that can reveal emotions, intentions, preferences, and even unconscious thoughts. The possibility that this data will be stored, shared, or even sold by companies that develop neural technologies raises serious concerns about the right to privacy and mental self-determination. Unlike other types of biometric data, such as fingerprints or irises, brain signals include subjective and contextual elements that can be interpreted ambiguously and invasively. The lack of clear regulations on the use, storage, and protection of this information exposes individuals to substantial risks of violating their cognitive freedom.

In addition, Awuah et al. (2024) point out that the manipulation of brain activity for the purposes of behavioral modulation, neurostimulation, or performance enhancement generates profound ethical dilemmas. To what extent is it acceptable to interfere with an individual's brain activity, even if he consents? How can we ensure that the application of these technologies does not compromise freedom or cause dependence? And how to avoid the coercive or discriminatory use of brain-computer interface technologies in contexts such as work, education or the judicial system? These and other questions still remain unanswered and indicate that the advancement of brain-computer interface technologies and neurotechnology must be accompanied by meaningful public dialogue, appropriate legal norms, and an ethical approach that places human dignity at the center of technological progress.

Future visions for brain-computer interfaces, as well as neurotechnology, indicate a growing union between mind and machines, driven by simultaneous advances in areas such as neuroscience, artificial intelligence, and biomedical engineering. According to Kamgwan et al. (2022), the new trends involve the creation of neural devices that are easier to carry, less intrusive, and have an improved capacity for real-time decoding. The so-called hybrid interfaces, which mix neural signals with muscle or visual data, promise to increase the accuracy and functionality of the systems. In addition, the use of deep neural networks and continuous learning algorithms is making these interfaces more adaptable to the different mental states of users, while the miniaturization of electronic components facilitates the development of more discreet and long-lasting brain implants. With these advancements, interfaces tend to move away from laboratory or clinical settings, finding space in everyday places such as smart homes, autonomous vehicles, and wearable devices.

At the same time, the domain of cognitive enhancement stands out as one of the most promising — and controversial — applications of this technology. According to Sun and Ye (2023), the possibility of improving brain functions such as memory, attention, decision-making, or creativity through electrical stimulation, neurofeedback, or collaboration with AI systems is no longer a topic of science fiction. Recent studies have already shown that it is feasible to modulate specific neural circuits to improve performance in cognitive or motor activities, opening up possibilities not only to treat disorders, but also to improve healthy people. This view has significant repercussions in fields such as education, work efficiency, and even sports competitions, suggesting the beginning of a new era in which human cognition can be adjusted and expanded as needed.

However, according to Sun and Ye (2023), this future full of technological promises brings to light important ethical dilemmas that cannot be ignored. Direct intervention in brain activity impacts sensitive aspects of human life, such as free will, authenticity of personal experience, and informed consent. To what extent is a person actually aware of the repercussions of a neurotechnological intervention on their thoughts or behaviors? How can we ensure that the decision to use such technologies is not affected by social or economic pressures? In addition, the protection of neural data becomes a crucial issue, since this information can expose intimate patterns of behavior, emotions, and preferences, making it valuable targets for commercial exploitation or population control. The danger of unauthorized access, misuse, or discrimination based on brain data demands the establishment of strict guidelines for protection and anonymization.

In view of this scenario, Kamgwan et al. (20230 cite that it is essential to establish solid mechanisms for the regulation and supervision of information and communication technologies (ICT) and neurotechnology. This framework should be interdepartmental, including not only scientists and engineers, but also bioethicists, lawyers, health professionals, and members of civil society. It is essential to create legal bases that deal with the safety of equipment, ethical consent for its use, responsibility in the face of failures, and the guarantee of fair access. In addition, it is suggested the formation of international entities to monitor the implementation of these technologies worldwide, avoiding inequalities between nations and preventing abuses. ICT supervision should be guided by values such as fairness, clarity, autonomy and beneficence, ensuring that advances in neurotechnology are used to improve people's quality of life, rather than fostering new forms of inequality, surveillance or manipulation.

3 CONCLUSION

The journey of CHIs and neurotechnology is one of the most fascinating and promising areas of modern science. By facilitating direct communication between the human brain and computational systems, these innovations usher in a new era of therapeutic, functional, and cognitive opportunities. From their theoretical development to the current clinical and experimental implementations, CCIs have proven to be tools of immense value for the recovery of patients, the support of individuals with disabilities and the search for new forms of interaction with the digital universe. Progress in brain signal capture techniques, the improvement of decoding algorithms, and the improvement of physical devices have allowed an increasingly precise connection between mind and machine, establishing this field as a strategic core for scientific and technological innovation.

However, as these innovations become more sophisticated and accessible, new challenges emerge, going beyond the technical aspect and reaching ethical, social and political factors. Limitations related to the accuracy of the signals, the high cost of development, the complexity of the algorithms and the accessibility barriers still hinder the full democratization of CCIs. In addition, the ethical issues surrounding brain manipulation, neural data collection, and the possibility of artificial enhancement of human cognition raise urgent debates about consent, privacy, and fairness. The danger that these tools will be used in an exclusionary or even coercive manner requires a critical and responsible approach, which includes strict regulations and the active participation of civil society in decision-making.

Thus, the future of brain-computer interfaces and neurotechnology will depend not only on the technical skills of scientists and engineers, but also on the ethical, political, and cultural commitment to shaping these innovations for the common good. It is the responsibility of the scientific community, policymakers, and citizens in general to collectively reflect on the desired directions of this brain-machine interaction. The sustainable progress of these technologies requires that technical evolution be accompanied by legal protections, social transparency, and a deep respect for human dignity. Only in this way will it be possible to ensure that the transformative potential of CCIs is directed to promote inclusion, autonomy, health and quality of life, and not to deepen inequalities or compromise fundamental values of humanity.

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