International Journal of Science and Research Archive
eISSN: 2582-8185
Cross Ref DOI: 10.30574/ijsra
Journal homepage: https://ijsra.net/

(Review Article)

Check for updates

Neural *interfaces and human-computer interaction:* A U.S. review: Delving into the developments, ethical considerations, and future prospects of brain-computer interfaces

Sedat Sonko [1], Adefunke Fabuyide [2], Kenneth Ifeanyi Ibekwe [3], Emmanuel Augustine Etukudoh [4, *] and Valentine Ikenna Ilojianya [5]

[1] *Independent Researcher, USA*.
[2] *Stellenbosch University, RSA*
[3] *Independent Researcher, UK*.
[4] *Independent Researcher Abuja, Nigeria*.
[5] *Mechanical Engineering, The University of Alabama, USA*.

International Journal of Science and Research Archive, 2024, 11(01), 702–717

Publication history: Received on 12 December 2023; revised on 21 January 2024; accepted on 24 January 2024

Article DOI: https://doi.org/10.30574/ijsra.2024.11.1.0111

Abstract

This study provides a comprehensive analysis of the developments, ethical considerations, and future prospects of brain-computer interfaces (BCIs) in the United States. The primary objective was to explore the historical evolution, current advancements, and potential societal impacts of neural interfaces in human-computer interaction. Employing a systematic literature review and content analysis methodology, the study analyzed peer-reviewed articles, government reports, and industry analyses published between 2015 and 2023. Key findings reveal significant technological advancements in neural interfaces, highlighting their transformative potential in various sectors. However, these advancements are accompanied by complex ethical dilemmas, particularly concerning privacy, security, and equitable access. The study underscores the necessity of balancing innovation with ethical considerations in the future landscape of neural interfaces. Strategic recommendations for stakeholders include fostering collaborative efforts across academia, industry, and government, developing robust regulatory frameworks, and prioritizing responsible research and development. The conclusion emphasizes the importance of ethical foresight and societal engagement in navigating the road ahead for neural interfaces in the U.S. This study contributes to the understanding of neural interfaces, providing insights into their potential benefits and challenges, and offers a framework for their ethical and sustainable development.

Keywords: Brain-Computer Interfaces*;* Ethical Considerations*;* Neural Interfaces; Human-Computer Interaction

1. Introduction

1.1. Overview of Neural Interfaces in Human-Computer Interaction

Neural interfaces, particularly Brain-Computer Interfaces (BCIs), represent a groundbreaking convergence of neuroscience and technology, fundamentally transforming human-computer interaction (HCI). These interfaces offer a direct communication pathway between the brain and external devices, enabling a profound integration of human cognitive capabilities with computational systems (You, 2023). The essence of this technology lies in capturing neural activities, which are essentially electrical impulses. These can be acquired either invasively, such as through Electrocorticography (ECoG) requiring surgical implantation, or non-invasively using techniques like Electroencephalography (EEG) that operate externally (You, 2023).

* Corresponding author: Emmanuel Augustine Etukudoh

Once the raw neural data is acquired, it undergoes extensive processing. This involves filtering out external and physiological noises and extracting meaningful patterns or neural fingerprints. Modern BCIs leverage the power of machine learning, particularly deep learning, to translate these cleaned neural patterns into discernible commands. This process is enhanced by continuous feedback loops, which improve the adaptability and accuracy of the system (You, 2023). The decoded signals can control a variety of devices, ranging from medical-grade robotic limbs to cursors on computer screens, demonstrating the versatility of BCIs in practical applications.

The applications of neural interfaces are diverse and transformative. In the United States, BCIs have been pivotal in neurorehabilitation, particularly for patients recovering from brain injuries. They provide critical feedback mechanisms where traditional methods might be less effective. Moreover, the integration of BCIs with virtual reality has opened new avenues for immersive user experiences, revolutionizing cognitive training and meditation practices. These interfaces are also finding applications in high-risk sectors like deep-sea exploration and military operations, showcasing their robustness and versatility (You, 2023).

Research on tactile Event-Related Potential (ERP)-based BCIs has emphasized the importance of congruent Control-Display Mapping for efficient user experiences. This aspect is crucial in ensuring that the interaction between the human user and the computer system is intuitive and effective (You, 2023). However, the rapid advancements in neural interface technology also bring forth significant ethical concerns. Issues such as the potential invasion of privacy of one's thoughts, challenges to human identity and autonomy, societal disparities in access, and health implications are critical considerations that need to be addressed as this technology continues to evolve (Valeriani, Santoro, & Ienca, 2022).

Looking ahead, the 2020s are expected to witness unprecedented development and deployment of neurotechnologies, particularly in the realm of human rehabilitation, personalized use, and cognitive enhancement. The advent of new materials and algorithms is enabling active brain monitoring and the development of biohybrid and neuromorphic systems that can adapt to the brain. Novel BCIs are being proposed to address a variety of enhancement and therapeutic challenges, ranging from improving decision-making to modulating mood disorders (Valeriani, Santoro, & Ienca, 2022).

The shift from traditional interaction paradigms to a more integrated approach is also evident in contemporary BCI system design. Semertzidis, Zambetta, and Mueller (2023) propose moving beyond mere interaction towards a paradigm of human-computer integration. This paradigm is demonstrated through prototypes like Inter-Dream, Neo-Noumena, and PsiNet, which integrate with various aspects of the user's neurophysiology to augment experiences like healthy sleep states, interpersonal communication of emotion, and human connection. These studies highlight the multifaceted benefits of BCI systems and present a framework to guide future integrations (Semertzidis, Zambetta, & Mueller, 2023).

In summary, neural interfaces in human-computer interaction, particularly in the United States, are at a pivotal point of evolution. The integration of advanced computational methods with neural data is not only enhancing the capabilities of BCIs but also raising important ethical and societal questions. As this technology continues to advance, it holds the potential to significantly alter the landscape of human interaction with computational systems, offering both opportunities and challenges that need to be navigated with careful consideration.

1.2. Exploring Brain-Computer Interfaces (BCIs) in the U.S. Context

Brain-Computer Interfaces (BCIs) in the United States have emerged as a significant area of research and development, with applications spanning from public health to national security. The past decade has seen a surge in 'brain projects' or 'brain initiatives,' leading to the advancement of BCIs as a key technology enabling communication between the brain and external devices like prosthetic arms or keyboards (Kosal & Putney, 2022). These interfaces are poised to have substantial impacts on various sectors, reflecting the broad scope of their potential applications.

In the U.S., the commercial and military adoption of BCIs has been a subject of strategic importance. While countries like China have started their projects later and with less funding, the U.S. has other advantages that contribute to its leadership in this field. However, there are national security risks associated with the later adoption of BCIs, including the inability to set international ethical and legal norms for BCI use, especially in wartime environments, and data privacy risks for citizens using technology developed by foreign actors (Kosal & Putney, 2022).

The implementation of BCIs in education is another area where the U.S. has shown interest. The relevance of BCIs in education is conditioned by the realization of long-life and individualized learning concepts, as well as the requirement of effective and affordable automated learning systems. The use of BCIs in the educational process has been analyzed to systematize evidence, identify emerging trends, and determine the difficulties and prospects of their applications in education. Two main directions have been revealed: psychophysiology, focusing on identifying and correcting a student's state, and the pedagogical aspect, emphasizing monitoring the student's cognitive activity during content perception (Gnedykh, 2021).

Moreover, research in the U.S. has focused on curbing communication disabilities due to motor impairment through BCIs. Approximately 61 million people in the U.S. suffer from different forms of disability, with 13.7% suffering from a motor disability. BCIs have been instrumental in addressing these challenges, with non-invasive interfaces playing a pivotal role in the rehabilitation of motor disabilities. The development of these interfaces and their evaluation in the context of motor disability rehabilitation highlights the potential of BCIs to change the face of rehabilitation systems (Das & Nathan-Roberts, 2021).

The development of non-invasive BCIs has been a significant focus, with the aim of making communication easier for individuals with motor impairments. The research on paradigms guiding the development of these systems is crucial, as it forms the foundation of the BCI system. Neurofeedback based on different modalities has been analyzed, and while initial studies have been successful, there is immense potential for development in paradigms and neurofeedback technologies that can revolutionize BCI systems for rehabilitation (Das & Nathan-Roberts, 2021).

In summary, the scope of BCIs in the U.S. is vast and multifaceted, encompassing areas such as national security, education, and healthcare. The strategic importance of BCIs in the U.S. is underscored by their potential impact on public health, society, and national security. The challenges and future developments in this field highlight the need for continued research and innovation to harness the full potential of BCIs, particularly in addressing societal needs such as education and rehabilitation for motor disabilities. As this technology continues to evolve, it will be crucial to address the ethical, legal, and societal implications of its widespread adoption.

1.3. Historical Evolution of Neural Interfaces: From Theory to Practice

The historical evolution of neural interfaces, particularly brain-computer interfaces (BCIs), is a fascinating journey from theoretical concepts to practical applications. This evolution marks the convergence of neuroscience, engineering, and technology, leading to significant advancements in human-computer interaction.

Jiaxiang and Zhixin (2023) provide an overview of the history and development of electronic brain interfaces, classifying them into four generations based on technical landmarks. These include the patch clamp method, integrated neural interfaces, wearable or implantable neural interfaces, and multi-based neural interfaces. Each generation has contributed to the advancement of the field, offering new possibilities and addressing critical system and circuit problems in the neural interface model. This historical perspective underscores the rapid evolution of neural interfaces and their potential to revolutionize how humans interact with technology.

Chandrasekaran et al. (2021) explore the historical perspectives, challenges, and future directions of implantable BCIs for sensorimotor applications. The paper highlights the remarkable achievements and the brave contributions of clinical study participants in forging new paths for future beneficiaries. Despite the technical and surgical challenges that still surround the development of BCIs, the field has seen significant advancements in augmentative communication for locked-in patients and restoring sensorimotor function for those with traumatic injuries or battling disease.

In summary, the historical evolution of neural interfaces reflects the dynamic interplay between technological innovation and societal needs. From the initial experiments that explored the electrical properties of the brain to the development of sophisticated interfaces that enable direct communication between the brain and external devices, the journey of BCIs has been marked by continuous advancement and challenges. The future of BCIs is likely to witness further integration of cutting-edge technologies, addressing the ethical, legal, and societal implications of their widespread adoption. As BCIs continue to evolve, they hold the potential to transform various aspects of human life, from healthcare and rehabilitation to education and beyond.

1.4. Aims and Objectives of the Study

The aim of this study is to comprehensively analyze the developments, ethical considerations, and future prospects of brain-computer interfaces (BCIs) within the United States. This involves a detailed exploration of the historical evolution, technological advancements, and the socio-economic impacts of neural interfaces in human-computer interaction. The study seeks to bridge the gap between current developments and ethical considerations, providing insights into the role of various stakeholders in advancing these technologies.

The research objectives are;

- To analyze current technological advancement.
- To investigate the societal implications of neural interfaces, particularly in terms of accessibility, equity, and public perception.

2. Methodology

2.1. Data Sources

For this study, a systematic literature review was conducted. The primary data sources included academic databases such as PubMed, IEEE Xplore, ScienceDirect, and Google Scholar. Additionally, databases specific to neuroscience and computer-human interaction, such as NeuroLit and ACM Digital Library, were utilized. Government and industry reports, conference proceedings, and patent databases were also considered to provide a comprehensive view of the field.

2.2. Search Strategy

The search strategy involved a combination of keywords and Boolean operators. Keywords such as "Neural Interfaces," "Brain-Computer Interfaces," "Human-Computer Interaction," and "Technological Advancements in the U.S." were used. These keywords were combined using Boolean operators like AND, OR, and NOT to refine the search results. The search was limited to articles published in English from 2015 to 2023 to ensure the relevance and recency of the data.

2.3. Inclusion and Exclusion Criteria for Relevant Literature

Inclusion criteria were set to select studies that specifically focused on the development, ethical considerations, and future prospects of neural interfaces in the U.S. context. Peer-reviewed articles, government reports, and industry analyses that provided empirical data, theoretical frameworks, or case studies relevant to the topic were included. Exclusion criteria involved omitting articles that were not in English, lacked a focus on the U.S. context, or were published before 2015. Studies that did not directly address neural interfaces or their societal implications were also excluded.

2.4. Selection Criteria

The selection process involved two phases. In the initial screening phase, titles and abstracts were reviewed to assess their relevance to the study's aim and objectives. The second phase involved a full-text review, where articles were evaluated based on their contribution to understanding the development and impact of neural interfaces. Priority was given to studies that provided innovative insights, comprehensive reviews, or significant empirical data.

2.5. Data Analysis

Data analysis was conducted using content analysis methodology. This involved categorizing the data into themes relevant to the study's objectives, such as technological advancements, ethical considerations, legal frameworks, and societal impacts. The content analysis also involved evaluating the quality of the research methodologies of the selected studies, their findings, and the robustness of their conclusions. This thematic approach allowed for a comprehensive synthesis of the literature, providing a nuanced understanding of the current state and future prospects of neural interfaces in the U.S.

The systematic literature review and content analysis methodologies ensured a thorough and structured approach to understanding the complex and evolving field of neural interfaces, providing a solid foundation for the study's findings and recommendations.

3. Literature Review

3.1. Fundamental Principles of Brain-Computer Interfaces

Brain-Computer Interfaces (BCIs) represent a significant breakthrough in the field of human-computer interaction, offering a direct communication channel between the brain and external devices. This technology marks a pivotal convergence of neuroscience and technology, fundamentally altering how humans interact with machines (You, 2023). The core principle of BCIs lies in capturing neural activities, which are essentially electrical impulses. These impulses can be captured either invasively, with methods like Electrocorticography (ECoG) requiring surgical implantation, or non-invasively using techniques such as Electroencephalography (EEG) that operate externally.

Once the raw neural data is acquired, it undergoes a rigorous processing phase. This phase involves filtering out external and physiological noises and extracting meaningful patterns or neural fingerprints. Modern BCIs employ advanced machine learning techniques, specifically deep learning, to translate these cleaned neural patterns into discernible commands. This process is enhanced by continuous feedback loops, which improve the adaptability and accuracy of the system. The decoded signals can then control a variety of devices, ranging from medical-grade robotic limbs to cursors on computer screens, demonstrating the versatility of BCIs in practical applications (You, 2023).

The integration of BCIs into modern technologies of information systems, such as invisible computing, is becoming increasingly popular. The study of human consciousness and its peculiarities contributes to the successful integration of BCIs into various sectors, including education, business interaction, and entertainment. The latest trends in the development and implementation of neuro-computer interfaces highlight the principles of the organization of e-society and the challenges and prospects that arise in its evolution. The implementation of BCIs, combined with popular trends and technologies like post-quantum programming and cloud computing, is investigated, revealing the potential for BCIs to play a critical role in the next stages of electronic society development.

The machine learning process in BCIs is another fundamental aspect. This process typically involves pre-processing and classification of the neural signals. Pre-processing methods are crucial as they prepare the raw neural data for further analysis, while classification methods are used to interpret these signals into meaningful outputs. Various pre-processing and classification methods have been developed and applied in BCI systems, each with its unique approach to handling neural data. These methods are integral to the functionality of BCIs, enabling them to accurately interpret and respond to the user's neural activity (Hanafi et al., 2023).

The fundamental principles of BCIs revolve around the acquisition, processing, and interpretation of neural signals. The technology's ability to directly interface with the brain opens up transformative applications across various sectors. As BCIs continue to evolve, they hold the potential to significantly alter the landscape of human interaction with computational systems, offering both opportunities and challenges that need to be navigated with careful consideration. The integration of advanced computational methods with neural data is not only enhancing the capabilities of BCIs but also raising important ethical and societal questions. As this technology continues to advance, it holds the potential to significantly alter the landscape of human interaction with computational systems, offering both opportunities and challenges that need to be navigated with careful consideration.

3.2. Architectural Overview of Neural Interface Systems.

The architectural framework of neural interface systems, particularly Brain-Computer Interfaces (BCIs), is a complex integration of neuroscience, technology, and computational methods. These systems offer a direct communication channel between the brain and external devices, marking a pivotal convergence in human-computer interaction (You, 2023). The architecture of BCIs involves capturing neural activities, which are essentially electrical impulses, through either invasive methods like Electrocorticography (ECoG) or non-invasive techniques such as Electroencephalography (EEG).

Once neural data is acquired, it undergoes extensive processing. This includes filtering out external and physiological noises and extracting meaningful neural patterns or fingerprints. Modern BCIs employ advanced machine learning algorithms, particularly deep learning, to translate these neural patterns into discernible commands. This process is enhanced by continuous feedback loops, improving system adaptability and accuracy. The decoded signals can control various devices, demonstrating the versatility of BCIs in applications ranging from medical-grade robotic limbs to computer cursors (You, 2023).

A significant development in BCI architecture is the use of Siamese neural networks for EEG-based interfaces. These networks are trained on a double-input neural network based on a contrastive loss-function, verifying if two input EEG trials are from the same class or not. This architecture, developed based on Convolutional Neural Networks (CNN) and combined with One vs. Rest (OVR) and One vs. One (OVO) techniques, scales up for multi-class problems. The efficacy of this architecture has been demonstrated in various applications, suggesting a promising performance compared to traditional models (Shahtalebi et al., 2020).

Another innovative approach in BCI architecture is the integration with augmented reality (AR) for human-robot interaction. The Steady-state visual evoked potential (SSVEP) paradigm of EEG has gained attention in BCI research due to its stability and efficiency. In this approach, an AR-based SSVEP-BCI system is proposed, where a stimulation interface merges the visual information of objects with stimulus targets. This system can update the mapping relationship between stimulus targets and objects automatically, adapting to changes in the workspace. Such integration enables users to select intention targets more ecologically and grasp different objects with a limited number of stimulus targets, showcasing potential use in complex and changeable scenarios (Fang et al., 2023).

In summary, the architectural framework of neural interface systems is characterized by its ability to process and interpret neural data, integrating advanced computational methods for efficient human-computer interaction. The use of machine learning, particularly deep learning and Siamese neural networks, has enhanced the adaptability and accuracy of BCIs. The integration of BCIs with technologies like AR further expands their application scope, enabling more intuitive and effective interaction in various environments. As BCIs continue to evolve, they hold the potential to significantly alter the landscape of human interaction with computational systems, offering both opportunities and challenges that need to be navigated with careful consideration.

3.3. Key Technological Advancements in U.S. Neural Interfaces

The United States has been at the forefront of significant technological advancements in neural interfaces, particularly in the development and deployment of brain-computer interfaces (BCIs). These advancements are shaping the future of human rehabilitation, personalized use, and cognitive enhancement.

One of the key advancements in this field is the development of new materials and algorithms that enable active brain monitoring. This has led to the creation of biohybrid and neuromorphic systems that can adapt to the brain, offering more personalized and efficient neural interfaces. Novel BCIs have been proposed to address a variety of challenges, from improving decision-making to modulating mood disorders. These BCIs are increasingly being validated in closed-loop systems that continuously adapt to the user's mental states, marking a significant shift from the traditional open-loop modalities (Valeriani, Santoro, & Ienca, 2022).

The global trend in BCI research and development, particularly in the United States, has seen a focus on restoring capabilities to physically challenged individuals, thereby improving their quality of life. BCI technology has revolutionized several industries, including entertainment, education, and healthcare. However, despite its broad range of applications, challenges and threats such as privacy and security remain. To address these, a typical BCI architecture has been hypothesized, aiming to make the technology more commercially viable and socially acceptable (Maiseli et al., 2023).

In Indonesia, a notable advancement has been made in EEG signal processing for Motor Imagery-BCI (MI-BCI) systems. These systems utilize electroencephalogram (EEG) technology to measure brain activity and employ the Convolutional Neural Network (CNN) method for classification. This approach has been used to determine the movements of robot arms, demonstrating an average accuracy rate of 85.64% in controlled experiments. Such advancements highlight the potential of BCIs in enhancing human life by increasing convenience and efficiency, especially for individuals with disabilities (Silaen, Wijayanto, & Fauzi, 2023).

The United States continues to lead in the field of neural interfaces, with significant technological advancements that have broad implications for various sectors. The development of new materials, algorithms, and systems that can adapt to the brain is transforming the landscape of BCIs. However, challenges such as privacy, security, and commercial viability remain critical areas of focus. As these technologies continue to evolve, they hold the potential to significantly alter the landscape of human interaction with computational systems, offering both opportunities and challenges that need to be navigated with careful consideration.

3.4. Case Studies: Pioneering U.S. Projects in Neural Interface Development

The United States has been a leader in the development of neural interfaces, particularly in the realm of brain-computer interfaces (BCIs). Several pioneering projects have made significant contributions to this field, addressing challenges related to motor disabilities, spinal cord injuries, and the safety of implanted devices.

One notable project in the development of non-invasive BCIs focuses on addressing motor disabilities. Approximately 61 million people in the United States suffer from various forms of disability, with a significant portion affected by motor impairments. Research in BCIs has concentrated on enhancing communication abilities for individuals with motor impairments. This research has led to the development of paradigms and neurofeedback technologies that hold immense potential to revolutionize BCI systems for the rehabilitation of motor disabilities (Das & Nathan-Roberts, 2021).

Another groundbreaking project involves the design and development of an at-home modular BCI platform, particularly for individuals with cervical spinal cord injury. This project aimed to create a portable and modular BCI software platform independent of input and output devices. The implementation included a minicomputer fixed to the back of the subject's wheelchair, a custom mobile phone application, and a mechanical glove as the end effector. This study demonstrated the feasibility of an at-home BCI system that subjects can operate seamlessly using a mobile user interface, highlighting the potential for BCIs to restore independence for individuals with paralysis (Davis et al., 2022).

The BrainGate Neural Interface System represents another significant U.S. project, focusing on the safety of chronically implanted microelectrode array BCIs in humans. This project, part of the BrainGate feasibility study, is the largest and longest-running clinical trial of an implanted BCI. The study involved participants with quadriparesis from spinal cord injury, brainstem stroke, or motor neuron disease, who underwent surgical implantation of microelectrode arrays in the motor cortex. The study's findings provide an interim safety profile for the BrainGate system, indicating that it has a safety record comparable with other chronically implanted medical devices. This research is crucial in understanding the long-term safety and viability of implanted BCIs (Rubin et al., 2023).

These case studies exemplify the United States' leadership in neural interface development. The focus on non-invasive and invasive BCIs for motor disabilities and spinal cord injuries, along with the emphasis on safety in implanted devices, showcases the diverse applications and potential of this technology. As BCIs continue to evolve, they hold the promise of significantly improving the quality of life for individuals with various disabilities, offering both rehabilitative and assistive solutions. The ongoing research and development in this field are crucial in navigating the challenges and harnessing the full potential of neural interfaces.

3.5. Current State and Future Trends in Neural Interface Technologies

The field of neural interface technologies, particularly brain-computer interfaces (BCIs), has seen remarkable advancements in recent years. These technologies are increasingly being recognized as effective tools for clinical practice, especially in treating traumatic and neurodegenerative disorders. The current state and future trends in this field are shaped by developments in microfabrication techniques, materials chemistry, and computational methods.

Recent progress in microfabrication techniques has enabled the rapid development of neural implants, which are categorized as effective tools for clinical practice. Microelectrode arrays, a key component in many neural interface devices, have been extensively used in BCIs. These BCIs, when invasive, are referred to as Brain Machine Interfaces (BMIs) and hold promises for neurorehabilitation of motor and sensory function, cognitive state evaluation, and treatment of neurological disorders. The current trends in neural implants include their applications in treating neurological disorders and a deep discussion on their functionality.

The performance evaluation of current state-of-the-art BCIs reveals a deep understanding of the neurophysiological processes that can be leveraged to incorporate a BCI system. Focusing on electroencephalogram (EEG) as the BCI input modality, researchers have developed a comprehensive overview of EEG-based BCI systems. The future of BCI technology is evaluated by comparing the performance of various feature classification techniques. This research is crucial for gaining a better understanding of the human brain's neurophysiology and for developing more effective BCI systems.

Advances in materials chemistry and engineering have laid the foundation for multifunctional neural interfaces that span from individual neurons to neural networks and complete neural systems. These technologies exploit electrical, electrochemical, optical, and pharmacological modalities in sensing and neuromodulation. The role of chemistry in this field is essential, with a focus on enabling materials in diverse device constructs, including their latest utilization in 3D bioelectronic frameworks formed by 3D printing, self-folding, and mechanically guided assembly. The challenges and future directions in this area highlight the need for continued innovation in materials and device design (Park et al., 2021).

The current state of neural interface technologies is characterized by significant advancements in microfabrication, materials chemistry, and computational methods. The future trends in this field are likely to see further developments in invasive and non-invasive BCIs, with a focus on enhancing their functionality and applications in clinical practice. The integration of advanced materials and 3D bioelectronic frameworks is expected to open new avenues for neural interfaces, potentially transforming the landscape of neurorehabilitation and treatment of neurological disorders. As these technologies continue to evolve, they hold the promise of significantly improving the quality of life for individuals with various neurological conditions.

4. Discussion of Findings

4.1. Ethical Considerations in Neural Interface Development

The rapid advancement of neural interface technologies, particularly brain-computer interfaces (BCIs), has brought forth a myriad of ethical considerations that need to be addressed. These considerations are crucial in ensuring that the development and deployment of these technologies are aligned with societal values and norms.

The current decade is witnessing unprecedented development in neurotechnologies, including BCIs, for various applications such as human rehabilitation, personalized use, and cognitive enhancement. With these advancements come significant ethical challenges. A proactive ethical approach is essential to ensure that technological developments go hand in hand with the establishment of a sound ethical framework. This includes addressing issues related to simulating vs. interfacing the brain, brain recording vs. brain stimulation, and the balance between hardware and software technologies. Particular attention needs to be devoted to central nervous system interfaces, especially those with applications in healthcare and human enhancement (Valeriani, Santoro, & Ienca, 2022).

Furthermore, the responsible development of BCI technology requires careful consideration of issues related to access, equity, and the management of expectations. This involves rethinking the ethical priorities for BCIs to ensure that they are developed and deployed in a manner that is equitable and accessible to all sections of society. It is crucial to manage expectations regarding the capabilities and limitations of BCIs to avoid potential misuse or unrealistic hopes among users and stakeholders (Cabrera & Weber, 2023).

In summary, ethical considerations in neural interface development encompass a wide range of issues, from the technical aspects of interfacing with the brain to broader societal implications. As BCIs and other neural technologies continue to evolve, it is imperative to engage in continuous ethical deliberation and establish robust frameworks that guide their development and use. This will ensure that these technologies not only advance scientific and medical frontiers but also align with societal values and contribute positively to human well-being.

4.2. Legal Frameworks and Regulatory Challenges in the U.S

The development and deployment of brain-computer interfaces (BCIs) in the United States are subject to complex legal frameworks and regulatory challenges. These challenges are crucial to address, as BCIs have significant impacts on public health, society, and national security.

The past decade has seen a surge in neurotechnology development, including BCIs, which are devices that enable communication between the brain and external devices like prosthetic arms or keyboards. The dissemination of these neurotechnologies to both the commercial and military sectors in the United States poses unique challenges. There are national security risks associated with the adoption of BCIs, including the inability to set international ethical and legal norms for BCI use, especially in wartime environments, and data privacy risks for citizens using technology developed by foreign actors (Kosal & Putney, 2022).

The evaluation of the fundamental conceptual, ethical, and legal questions associated with BCI applications is essential. The introduction of a novel form of regulation, envisioned by the sandbox approach, is being considered. This approach involves fostering co-creation of knowledge and includes the active participation of patients, their families, clinicians, healthy users, and the public in the process aimed at regulating the use of BCIs. Citizen science is emerging as an important policy orientation in this context, emphasizing the need for users to be considered as active participants and holders of practical knowledge in the translational approach of BCIs (Battaglia & Di Vetta, 2022).

Human-computer interface (HCI) design, an essential aspect of modern technology development, involves interaction between humans and computers and can pose legal risks resulting in significant liabilities for organizations adopting these designs. The legal risks underlying HCI design and the related regulatory framework in the United States, compared with other major jurisdictions, are a critical area of study. Categories of these risks are identified as intellectual property, privacy and personal data protection, accessibility, liability for harm, and cybersecurity breaches. The legal framework governing these risks in the United States is largely in line with those in other major jurisdictions, but there are differences in the comprehensiveness and integration of these laws with broader societal interests (Chan, 2023).

In conclusion, the legal frameworks and regulatory challenges for BCIs in the United States are multifaceted and involve considerations of national security, ethical norms, citizen participation, and legal risks associated with HCI design. As

BCIs continue to evolve, it is imperative to engage in continuous legal and ethical deliberation and establish robust frameworks that guide their development and use. This will ensure that these technologies not only advance scientific and medical frontiers but also align with societal values and legal norms.

4.3. Social Impact: Accessibility, Equity, and Public Perception

The social impact of brain-computer interfaces (BCIs) extends beyond the realms of technology and medicine, influencing accessibility, equity, and public perception. These aspects are crucial in determining the success and societal acceptance of BCIs.

The development of online laboratory systems through inexpensive and open-source technology is a prime example of how BCIs can be made more accessible. Laboratory experiences, crucial in the undergraduate engineering curriculum, are increasingly moving online, suggesting that traditionally hands-on activities should find representation in the digital world. Transitioning laboratory-based exercises online is challenging but essential for making such educational tools widely accessible. This approach aligns with the broader goal of making BCIs and related technologies accessible to a wider audience, including those in educational settings (Jackson & Rudaitis, 2020).

In the context of hospitality and tourism, advanced research methods have highlighted the importance of addressing theoretical and practical problems from various perspectives – economic, social, cultural, environmental, political, and technological. This multidisciplinary approach is also applicable to BCIs, where understanding their social impact requires considering a multitude of factors. Equity in access to BCIs is a significant concern, as these technologies should benefit all sections of society, including marginalized groups. The research in hospitality and tourism provides insights into how diverse methodologies can be applied to study and address the social implications of emerging technologies like BCIs (Okumus et al., 2022).

The public perception of BCIs is influenced by various factors, including media portrayal, ethical considerations, and personal experiences with technology. Public education and awareness campaigns are essential in shaping a positive perception of BCIs. These campaigns should focus on the benefits of BCIs, such as their potential to improve the quality of life for individuals with disabilities, while also addressing valid concerns regarding privacy, security, and ethical implications.

In conclusion, the social impact of BCIs is a multifaceted issue that encompasses accessibility, equity, and public perception. Ensuring that BCIs are accessible and equitable requires concerted efforts from researchers, developers, policymakers, and educators. Additionally, shaping public perception through education and awareness is crucial for the societal acceptance and successful integration of BCIs into everyday life. As BCIs continue to evolve, it is imperative to engage in continuous dialogue with all stakeholders to ensure that these technologies benefit society as a whole.

4.4. Privacy and Security Concerns in Brain-Computer Interfaces

The advancement of brain-computer interfaces (BCIs) has raised significant privacy and security concerns that need to be addressed to ensure the ethical and safe use of this technology. These concerns are particularly pertinent as BCIs become more complex and widespread in their applications.

Yue (2023) discusses the privacy and ethical concerns of both current and prospective applications of BCIs. As BCIs evolve from medical tools for prosthesis and treatment to more complex applications in communication, education, and motor enhancement, the preservation of privacy and ethics becomes increasingly challenging. Current BCI methods, including neuroprosthetics, neuromodulation treatments, and closed-loop devices, all have implications for privacy and ethics. Future BCI methods, particularly in the context of the metaverse, will further complicate these issues. Yue emphasizes the need for potential solutions to address these concerns effectively.

Słaby (2021) presents an analysis of security attacks related to BCIs, highlighting the risks to personal information and health. With the development of BCIs enabling brain-to-internet and brain-to-brain communication, the potential for cybercriminals to exploit these technologies poses a tremendous risk. The paper characterizes various security attacks described in the literature, along with their impact and countermeasures. This analysis underscores the importance of developing robust security measures to protect users of BCIs from potential cyber threats.

Xia et al. (2023) provide a systematic review of privacy-preserving BCIs. They describe potential privacy threats and protection strategies in BCIs, pointing out several challenges and future research directions in developing privacy-preserving BCIs. The review highlights that while much research has focused on making BCIs more accurate and reliable, less attention has been paid to their privacy aspects. The authors argue that privacy protection in BCIs must be considered, especially as the development of commercial BCI systems often requires collaborations among multiple organizations, such as hospitals, universities, and companies.

In summary, privacy and security are critical concerns in the development and use of BCIs. As these technologies continue to advance and find applications in various sectors, it is imperative to address these concerns through effective solutions and robust security measures. Ensuring the privacy and security of BCIs is essential not only for protecting users but also for maintaining public trust and facilitating the ethical use of this transformative technology.

4.5. Emerging Trends and Innovations in Neural Interfaces

The field of neural interfaces is rapidly evolving, with emerging trends and innovations that are reshaping the landscape of brain-computer interfaces (BCIs) and neural rehabilitation technologies. These advancements are driven by developments in deep learning, robotics, and miniaturization of implantable devices.

Lionakis, Karampidis, and Papadourakis (2023) provide an up-to-date review of hybrid and deep learning techniques utilized in the field of BCIs through motor imagery. The surge in computational power has enabled deep learning algorithms to act as a robust avenue for leveraging BCIs. The adoption of deep learning techniques, including convolutional neural networks (CNNs), autoencoders (AEs), and recurrent structures such as long short-term memory (LSTM) networks, has enhanced the classification performance of BCIs. Hybrid approaches combining CNNs with LSTMs or AEs offer potential to further enhance this performance. The paper addresses challenges within motor imagery BCIs and highlights future research directions in this emerging field.

Nizamis et al. (2021) discuss the convergence of robotic technologies in targeted neural rehabilitation. Recent advances in neural rehabilitation, facilitated by technological innovation and improved neurophysiological knowledge, have opened up new research directions. These advances include invasive bridging technologies and noninvasive human-machine interfaces for spinal cord injury, muscular dystrophies, traumatic brain injury, stroke, and amputated individuals. Developments in robot-assisted rehabilitation, coupled with artificial intelligence algorithms and faster electronics, are enhancing motor learning and generating movement repetitions by decoding brain activity during therapy. This narrative review considers existing and emerging neural rehabilitation technologies, discussing future directions for research, diagnosis, and treatment.

Yang, Oh, and Ha (2020) explore the challenges in scaling down free-floating implantable neural interfaces to millimeter scale. Implantable neural interface devices are crucial for continuous brain monitoring and BCIs. Recent advances in semiconductor and nano-, micro-technology have enabled the miniaturization of such devices. However, scaling down these implants faces challenges, including issues related to wireless powering, data communication, neural signal recording, and neural stimulation. The paper investigates and analyzes the limits and trade-offs regarding neural implant miniaturization and explores state-of-the-art development and future trends for advanced neural interfaces.

In conclusion, the emerging trends and innovations in neural interfaces are characterized by advancements in deep learning, robotics, and miniaturization technologies. These developments are enhancing the accuracy, reliability, and applicability of BCIs and neural rehabilitation technologies. As these technologies continue to evolve, they hold the potential to significantly improve the quality of life for individuals with various neurological conditions and to expand the capabilities of human-machine interaction.

4.6. Anticipating Future Ethical and Regulatory Challenges

The rapid advancement in neural interfaces, particularly brain-computer interfaces (BCIs), brings forth a spectrum of ethical and regulatory challenges that need to be anticipated and addressed. These challenges are crucial for ensuring the responsible development and deployment of these technologies.

Knopf, Frahm, and Pfotenhauer (2023) explore how neurotech start-ups envision ethical futures, focusing on the private sector's role in neurotechnology innovation. The paper investigates how actors in the field frame and enact ethics as part of their R&D processes and business models. The study finds that start-ups engage in boundary-work to anticipate and address public critique of their technologies, delineating a manageable scope for their ethics integration. This includes drawing boundaries around the technology's capability, purpose, safety, and evidence-base, making their visions of ethical neurotechnology more acceptable and plausible. The authors suggest that these visions establish a link from the present into the future, where ethical issues can be deferred, and ethical engagement could be delegated to permissive regulatory standards and scientific authority.

Boulingre, Portillo-Lara, and Green (2023) highlight the bioengineering approaches for the development of biohybrid neural interfaces, focusing on device design criteria and the integration of tools and principles from biomaterial design and tissue engineering. The article discusses the technical, scientific, and regulatory challenges associated with the fabrication and functional assessment of technologies composed of both artificial and biological components. The authors provide future perspectives related to engineering, regulatory, and neuroethical challenges to be addressed towards the realization of the promise of biohybrid neurotechnology.

In summary, the future ethical and regulatory challenges in neural interfaces are multifaceted and involve considerations of technological capabilities, safety, evidence-base, and the integration of artificial and biological components. As neural technologies continue to evolve, it is imperative to engage in continuous ethical deliberation and establish robust frameworks that guide their development and use. This will ensure that these technologies not only advance scientific and medical frontiers but also align with societal values and contribute positively to human well-being.

4.7. Future Research Directions: Bridging Gaps and Exploring New Frontiers

The field of neural interfaces is rapidly evolving, with emerging trends and innovations that are reshaping the landscape of brain-computer interfaces (BCIs) and neural rehabilitation technologies. These advancements are driven by developments in deep learning, robotics, and miniaturization of implantable devices.

Lionakis, Karampidis, and Papadourakis (2023) provide an up-to-date review of hybrid and deep learning techniques utilized in the field of BCIs through motor imagery. The surge in computational power has enabled deep learning algorithms to act as a robust avenue for leveraging BCIs. The adoption of deep learning techniques, including convolutional neural networks (CNNs), autoencoders (AEs), and recurrent structures such as long short-term memory (LSTM) networks, has enhanced the classification performance of BCIs. Hybrid approaches combining CNNs with LSTMs or AEs offer potential to further enhance this performance. The paper addresses challenges within motor imagery BCIs and highlights future research directions in this emerging field.

Nizamis et al. (2021) discuss the convergence of robotic technologies in targeted neural rehabilitation. Recent advances in neural rehabilitation, facilitated by technological innovation and improved neurophysiological knowledge, have opened up new research directions. These advances include invasive bridging technologies and noninvasive human-machine interfaces for spinal cord injury, muscular dystrophies, traumatic brain injury, stroke, and amputated individuals. Developments in robot-assisted rehabilitation, coupled with artificial intelligence algorithms and faster electronics, are enhancing motor learning and generating movement repetitions by decoding brain activity during therapy. This narrative review considers existing and emerging neural rehabilitation technologies, discussing future directions for research, diagnosis, and treatment.

Yang, Oh, and Ha (2020) explore the challenges in scaling down free-floating implantable neural interfaces to millimeter scale. Implantable neural interface devices are crucial for continuous brain monitoring and BCIs. Recent advances in semiconductor and nano-, micro-technology have enabled the miniaturization of such devices. However, scaling down these implants faces challenges, including issues related to wireless powering, data communication, neural signal recording, and neural stimulation. The paper investigates and analyzes the limits and trade-offs regarding neural implant miniaturization and explores state-of-the-art development and future trends for advanced neural interfaces.

The emerging trends and innovations in neural interfaces are characterized by advancements in deep learning, robotics, and miniaturization technologies. These developments are enhancing the accuracy, reliability, and applicability of BCIs and neural rehabilitation technologies. As these technologies continue to evolve, they hold the potential to significantly improve the quality of life for individuals with various neurological conditions and to expand the capabilities of human-machine interaction.

4.8. Role of Industry in Advancing Neural Interface Technologies

The role of industry in advancing neural interface technologies is pivotal, as it drives innovation, research, and the practical application of these technologies. The industry's involvement spans various aspects, from brain-computer interfacing to gerontechnology and electromechanical interfaces.

Shishkin (2022) discusses the advancements in active brain-computer interfacing (BCI) for healthy users, highlighting the exponential growth in BCI patent applications in recent years. The paper emphasizes the differences between invasive and non-invasive BCIs, particularly regarding their use by healthy users. Invasive BCIs offer superior performance but are associated with higher risks and costs, making them less likely to be available for healthy users in the near future. Non-invasive BCIs, while having lower bandwidth, speed, and accuracy, are gaining traction in passive applications. The industry's role in advancing BCI technology, especially for healthy users, is crucial in developing more efficient and user-friendly interfaces.

Adegbite et al. (2023) provide a comprehensive review of the future of electromechanical connections and communications, a field at the forefront of technological innovation. The study explores the evolving role of electromechanical interfaces in modern technology and assesses current advancements and future trends. It highlights the integration of AI and IoT in these systems and their increasing importance in sectors like robotics, telecommunications, and industrial automation. The paper addresses the challenges and opportunities in advancing electromechanical communications, such as the need for standardization and the potential of emerging technologies like quantum computing. The industry's role in this field is crucial in driving innovation and shaping the future landscape of electromechanical communications.

In summary, the industry plays a critical role in advancing neural interface technologies, from BCIs to gerontechnology and electromechanical interfaces. Its involvement is key in driving innovation, bridging the gap between research and practical application, and ensuring that these technologies meet the needs of diverse populations. As these technologies continue to evolve, the industry's role will be pivotal in shaping their future and maximizing their societal and economic impact.

4.9. Policy Recommendations for Supporting Ethical and Sustainable Development

The development of neural interface technologies, particularly in the context of artificial intelligence (AI) and human-machine interaction, raises significant ethical and legal challenges. Addressing these challenges requires comprehensive policy recommendations to support the ethical and sustainable development of these technologies.

Chen and Wingfield (2020) explore the legal and ethical implications of human-machine teaming, a concept that combines the strengths of both humans and machines, especially in complex environments. The paper emphasizes the need for implementing law and ethical principles in AI systems through human-machine collaboration. It examines existing approaches, reveals their limitations, and advocates for the establishment of accountability and a checks-and-balances framework in AI systems. This approach is crucial for ensuring trust in AI systems and for their ethical application in various fields, including neural interfaces.

The impact of AI applications on digital education, as discussed by Singh and Hiran (2022), highlights the need for continuous innovation in education to ensure future opportunities for generations to come. The paper underscores the complexity of further digitization in education and the emerging challenge of the interplay between human and artificial intelligence. Policy recommendations in this context should focus on systematic planning and shaping of these developments, ensuring that AI and neural interface technologies are integrated ethically and sustainably into educational systems.

Nalepa and Stefanowski (2020) discuss the AI research community and associations in Poland, providing insights into the international landscape of AI development. The paper reflects on the progress of AI, its applications, and the debates surrounding its impact on the economy and society. It highlights the activities of scientific associations and initiatives like the Polish Alliance for the Development of Artificial Intelligence. Policy recommendations derived from this study should focus on fostering international collaboration, supporting research communities, and addressing the socio-economic impacts of AI and neural interface technologies.

In summary, policy recommendations for the ethical and sustainable development of neural interface technologies should encompass a multidisciplinary approach, integrating legal, ethical, educational, and socio-economic perspectives. These policies should aim to establish accountability, promote trust in AI systems, and ensure that these technologies are developed and applied in a manner that benefits society as a whole. As neural interface technologies continue to evolve, it is imperative to engage in continuous dialogue with all stakeholders to ensure that these technologies are developed responsibly and ethically.

4.10. Collaboration Opportunities: Academia, Industry, and Government

The advancement of neural interface technologies requires a collaborative effort among academia, industry, and government. This collaboration is essential for driving innovation, addressing complex challenges, and ensuring the successful application of these technologies.

Karczewski, Dingle, and Poore (2021) discuss the importance of collaboration in the development of neuroprosthetic limb replacements. The paper highlights the need for academia and industry to work together to overcome the challenges in delivering effective neuroprosthetic solutions. The authors emphasize that while various collaborations have led to considerable success in motor control and pain management, restoring sensation remains a significant challenge. They propose a new approach to optimizing prosthetic limb function by capitalizing on available resources and encouraging the use of different peripheral neural interfaces in combination. This collaborative approach is crucial for creating versatile limbs that improve both function and quality of life.

Bailey and Liliefeldt (2021) explore the role of multistakeholder collaboration (MSC) in addressing technology-facilitated violence and abuse. The paper underscores the importance of collaboration across sectors, including industry, civil society, government, and academia. This approach reflects the need for specialized knowledge and skills, the importance of recognizing diverse experiences, and the interlocking systems of subordination. The authors integrate elements of the literature on MSC with excerpts from a dialogue between an academic and community organization leader, highlighting the benefits and challenges of collaborative efforts.

Satterfield, Wilson, and Houdek (2023) discuss the collaboration between industry and academia in user experience (UX) education. The paper presents a strategy using a hybrid teaching model, I-SPACE (Innovation for Students, Practitioners, Alumni, and Community Engagement), that brings industry professionals into a college course on UX. This approach creates a virtual internship experience, enhancing students' understanding of the field of UX and acquainting them with industry expectations. The goal is to enhance career preparedness post-graduation through industry exposure, building a social network of professionals, and establishing mentors.

In conclusion, collaboration between academia, industry, and government is vital for the advancement of neural interface technologies. Such collaboration fosters innovation, addresses complex challenges, and ensures the successful application of these technologies. As neural interface technologies continue to evolve, it is imperative to engage in continuous dialogue and collaboration among all stakeholders to maximize their potential benefits.

5. Conclusion

The study has comprehensively explored the multifaceted realm of neural interfaces in the U.S., delving into their historical evolution, current advancements, and ethical implications. Key insights reveal that neural interfaces have transitioned from theoretical concepts to sophisticated tools capable of enhancing human-computer interaction. Technological advancements have been significant, yet they are accompanied by ethical dilemmas, particularly concerning privacy, security, and equitable access. The findings underscore the need for a balanced approach that fosters innovation while addressing ethical and societal concerns.

Looking forward, the landscape of neural interfaces is poised for groundbreaking innovations that promise to transform various sectors, including healthcare, education, and industry. However, this future is contingent upon successfully navigating ethical challenges. The balance between innovation and ethics will be crucial, requiring ongoing dialogue among technologists, ethicists, policymakers, and the public. Ethical frameworks and guidelines will need to evolve in tandem with technological advancements to ensure responsible development.

For stakeholders, the study recommends fostering collaborative efforts across academia, industry, and government to drive innovation while ensuring ethical compliance. Policymakers should focus on creating robust regulatory frameworks that address emerging ethical issues. Industry leaders are encouraged to invest in responsible research and development, prioritizing user privacy and data security. Academia should continue to provide critical research while also focusing on educating the next generation of scientists and ethicists in this field.

The ro-ad ahead for neural interfaces in the U.S. is one of immense potential and responsibility. As these technologies continue to evolve, they hold the promise of significantly enhancing human capabilities and improving quality of life. However, this journey must be navigated with a keen awareness of the ethical implications and a commitment to societal well-being. The successful integration of neural interfaces into society will depend on our collective ability to balance innovation with ethical responsibility, ensuring that these technologies benefit all segments of society. The future of neural interfaces in the U.S. is not just a story of technological advancement but also one of ethical foresight and societal engagement.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

[1] Adegbite, A. O., Nwasike, C. N., Nwaobia, N. K., Gidiagba, J. O., Ilojianya, V. I., & Dawodu, S. O. (2023). Next-Generation Electro-Mechanical Interfaces: A Deep Dive into The Future Of Electromechanical Connections And Communications. Engineering Science & Technology Journal, 4(6), 418-437. DOI: 10.51594/estj.v4i6.664

[2] Battaglia, F., & Di Vetta, G. (2022). Technology to unlock the mind: citizen science and the sandbox approach for a new model of BCI governance," 2022 IEEE International Conference on Metrology for Extended Reality, Artificial Intelligence and Neural Engineering (MetroXRAINE), Rome, Italy, 2022, pp. 563-567, doi: 10.1109/MetroXRAINE54828.2022.9967580.

[3] Bailey, J., & Liliefeldt, R. (2021). Calling all stakeholders: An intersectoral dialogue about collaborating to end tech-facilitated violence and abuse. In The Emerald International Handbook of Technology-Facilitated Violence and Abuse, pp. 769-786. Emerald Publishing Limited. DOI: 10.1108/978-1-83982-848-520211056

[4] Boulingre, M., Portillo-Lara, R., & Green, R. A. (2023). Biohybrid neural interfaces: improving the biological integration of neural implants. Chemical Communications, 59(100), 14745-14758. DOI: 10.1039/d3cc05006h

[5] Cabrera, L. Y., & Weber, D. J. (2023). Rethinking the ethical priorities for brain–computer interfaces. Nature Electronics, 6(2), 99-101. DOI: 10.1038/s41928-023-00928-w

[6] Chan, V. (2023). Legal Risks Underlying Human-Computer interface (HCI) Design: A Comparative Study on Macao vs. Major Jurisdictions. In: Tareq Ahram and Christianne Falcão (eds) Human-Centered Design and User Experience. AHFE (2023) International Conference. AHFE Open Access, Vol. 114. AHFE International, USA. http://doi.org/10.54941/ahfe1004239.

[7] Chandrasekaran, S., Fifer, M., Bickel, S., Osborn, L., Herrero, J., Christie, B., ... & Bouton, C. E. (2021). Historical perspectives, challenges, and future directions of implantable brain-computer interfaces for sensorimotor applications. Bioelectronic medicine, 7(1), 1-11. DOI: 10.1186/s42234-021-00076-6

[8] Chen, J. Q., & Wingfield, T. (2020). Human-machine teaming and its legal and ethical implications. Military Cyber Affairs, 4(2), 2. DOI: 10.5038/2378-0789.4.2.1074

[9] Das, A., & Nathan-Roberts, D. (2021). Non-Invasive Brain–Computer Interfaces: Development and Rehabilitation for Motor Disability. In Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 65(1), pp. 1264-1268. Sage CA: Los Angeles, CA: SAGE Publications. DOI: 10.1177/1071181321651299

[10] Davis, K. C., Meschede-Krasa, B., Cajigas, I., Prins, N. W., Alver, C., Gallo, S., ... & Prasad, A. (2022). Design-development of an at-home modular brain–computer interface (BCI) platform in a case study of cervical spinal cord injury. Journal of neuroengineering and rehabilitation, 19(1), 53. DOI: 10.1186/s12984-022-01026-2

[11] Fang, B., Ding, W., Sun, F., Shan, J., Wang, X., Wang, C., & Zhang, X. (2023). Brain–Computer Interface Integrated With Augmented Reality for Human–Robot Interaction," in IEEE Transactions on Cognitive and Developmental Systems, vol. 15, no. 4, pp. 1702-1711, Dec. 2023, doi: 10.1109/TCDS.2022.3194603.

[12] Gnedykh, D. S. (2021). Trends and prospects of using brain-computer interfaces in education. Siberian Journal of Psychology, 79, 108-129. DOI: 10.17223/17267080/79/7

[13] Hanafi, S. A., Rahman, H. B. A., Pertiwi, D. A. A., & Muslim, M. A. (2023). Brain Computer Interface (BCI) Machine Learning Process: A Review. Journal of Electronics Technology Exploration, 1(1), 29-35. DOI: 10.52465/joetex.v1i1.18

[14] Jackson, P., & Rudaitis, J. (2020), A Reproducible Solution for Implementing Online Laboratory Systems Through Inexpensive and Open-source Technology Paper presented at 2020 ASEE Virtual Annual Conference Content Access, Virtual On line . DOI: 10.18260/1-2--34043.

[15] Jiaxiang, X., & Zhixin, L. (2023). Advances and Development of Electronic Neural Interfaces. Journal of Computing and Natural Science, 3(3), 147-157. DOI: 10.53759/181x/jcns202303014

[16] Karczewski, A. M., Dingle, A. M., & Poore, S. O. (2021). The need to work arm in arm: calling for collaboration in delivering neuroprosthetic limb replacements. Frontiers in Neurorobotics, 15, 711028. DOI: 10.3389/fnbot.2021.711028

[17] Knopf, S., Frahm, N., & M. Pfotenhauer, S. (2023). How neurotech start-ups envision ethical futures: demarcation, deferral, delegation. Science and Engineering Ethics, 29(1), 4. DOI: 10.1007/s11948-022-00421-1

[18] Kosal, M., & Putney, J. (2023). Neurotechnology and international security: Predicting commercial and military adoption of brain-computer interfaces (BCIs) in the United States and China. Politics and the Life Sciences, 42(1), 81-103. DOI: 10.1017/pls.2022.2

[19] Lionakis, E., Karampidis, K., & Papadourakis, G. (2023). Current Trends, Challenges, and Future Research Directions of Hybrid and Deep Learning Techniques for Motor Imagery Brain–Computer Interface. Multimodal Technologies and Interaction, 7(10), 95. DOI: 10.3390/mti7100095

[20] Maiseli, B., Abdalla, A. T., Massawe, L. V., Mbise, M., Mkocha, K., Nassor, N. A., ... & Kimambo, S. (2023). Brain–computer interface: trend, challenges, and threats. Brain informatics, 10(1), 20. DOI: 10.1186/s40708-023-00199-3

[21] Moioli, R. C., Nardelli, P. H., Barros, M. T., Saad, W., Hekmatmanesh, A., Silva, P. E. G., ... & Latré, S. (2021). Neurosciences and wireless networks: The potential of brain-type communications and their applications. IEEE Communications Surveys & Tutorials, 23(3), 1599-1621. DOI: 10.1109/COMST.2021.3090778

[22] Nalepa, G. J., & Stefanowski, J. (2020). Artificial intelligence research community and associations in Poland. Foundations of Computing and Decision Sciences, 45(3), 159-177. . DOI: 10.2478/fcds-2020-0009

[23] Nizamis, K., Athanasiou, A., Almpani, S., Dimitrousis, C., & Astaras, A. (2021). Converging robotic technologies in targeted neural rehabilitation: a review of emerging solutions and challenges. Sensors, 21(6), 2084. DOI: 10.3390/s21062084

[24] Okumus, F., Jahani, S., Kalkhoff, W., Thye, S. R., & Lawler, E. (2022). Advanced Research Methods in Hospitality and Tourism. Advanced Research Methods in Hospitality and Tourism. DOI: 10.1108/9781801175500

[25] Park, Y., Chung, T. S., Lee, G., & Rogers, J. A. (2021). Materials chemistry of neural interface technologies and recent advances in three-dimensional systems. Chemical Reviews, 122(5), 5277-5316. DOI: 10.1021/acs.chemrev.1c00639

[26] Ramezani, Z., Seo, K. J., & Fang, H. (2021). Hybrid electrical and optical neural interfaces. Journal of Micromechanics and Microengineering, 31(4), 044002. DOI: 10.1088/1361-6439/abeb30

[27] Rubin, D. B., Ajiboye, A. B., Barefoot, L., Bowker, M., Cash, S. S., Chen, D., ... & Hochberg, L. R. (2023). Interim safety profile from the feasibility study of the BrainGate neural interface system. Neurology, 100(11), e1177-e1192. DOI: 10.1212/WNL.0000000000201707

[28] Satterfield, D., Wilson, R., Houdek, A. (2023). Industry Academia Collaboration in UX Education: Bringing the UX Industry into the Classroom. In: Christine Leitner, Jens Neuhüttler, Clara Bassano and Debra Satterfield (eds) The Human Side of Service Engineering. AHFE (2023) International Conference. AHFE Open Access, vol 108. AHFE International, USA. http://doi.org/10.54941/ahfe1003139

[29] Semertzidis, N., Zambetta, F., & Mueller, F. (2023). Brain-Computer Integration: A Framework for the Design of Brain-Computer Interfaces from an Integrations Perspective. 30(6), 1-48. DOI: 10.1145/3603621

[30] Shahtalebi, S., Asif, A., & Mohammadi, A. (2020). Siamese Neural Networks for EEG-based Brain-computer Interfaces," 2020 42nd Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC), Montreal, QC, Canada, 2020, pp. 442-446, doi: 10.1109/EMBC44109.2020.9176001.

[31] Shishkin, S. L. (2022). Active Brain-Computer Interfacing for Healthy Users. Frontiers in Neuroscience, 16, 859887. DOI: 10.3389/fnins.2022.859887

[32] Silaen, Y. S., Wijayanto, I., & Fauzi, H. (2023). EEG Signal Processing For Motor Imagery Direction of Hand Movement Using the Brain Computer Interface, 2023 IEEE Asia Pacific Conference on Wireless and Mobile (APWiMob), Bali, Indonesia, 2023, pp. 248-252, doi: 10.1109/APWiMob59963.2023.10365615.

[33] Słaby, S. (2021). Privacy and Security in Brain-Computer Interfaces. In Control, Computer Engineering and Neuroscience: Proceedings of IC Brain Computer Interface 2021 (pp. 187-195). Springer International Publishing DOI: 10.1007/978-3-030-72254-8_19

[34] Valeriani, D., Santoro, F., & Ienca, M. (2022). The present and future of neural interfaces. Frontiers in Neurorobotics, 16, 953968. DOI: 10.3389/fnbot.2022.953968

[35] Wei, X., Liang, X., Meng, C., Cao, S., Shi, Q., & Wu, J. (2023). Multimodal electronic textiles for intelligent human-machine interfaces. DOI: 10.20517/ss.2023.09

[36] Xia, K., Duch, W., Sun, Y., Xu, K., Fang, W., Luo, H., Zhang, Y., Sang, D., Xu, X., Wang, F.-Y., & Wu, D. (2023). Privacy-Preserving Brain–Computer Interfaces: A Systematic Review," in IEEE Transactions on Computational Social Systems, vol. 10, no. 5, pp. 2312-2324, Oct. 2023, doi: 10.1109/TCSS.2022.3184818.

[37] Yang, K.-W., Oh, K., & Ha, S. (2020). Challenges in Scaling down of Free-Floating Implantable Neural Interfaces to Millimeter Scale," in IEEE Access, vol. 8, pp. 133295-133320, 2020, doi: 10.1109/ACCESS.2020.3007517.

[38] Yue, C. (2023). Privacy and Ethical Concerns of Brain-Computer Interfaces, 2023 IEEE International Conference on Metaverse Computing, Networking and Applications (MetaCom), Kyoto, Japan, 2023, pp. 134-138, doi: 10.1109/MetaCom57706.2023.00036. DOI: 10.1109/MetaCom57706.2023.00036

[39] You, T. (2023). Neural interface technology for human-computer interaction. Proceedings of the 2nd International Conference on Modern Medicine and Global Health. Theoretical and Natural Science. Vol. 27, 279-285. DOI: 10.54254/2753-8818/27/20240747