Edited Book

Green Frontiers

Emerging Technologies for a Sustainable Future

Editors

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Dr. Sayantan Sil

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Preface

In an age marked by rapid scientific progress and increasing global challenges, the integration of knowledge across disciplines has become essential for meaningful innovation and sustainable development. *Green Frontiers: Emerging Technologies for a Sustainable Future* is conceived as a comprehensive academic work that brings together diverse fields of study to present a unified perspective on contemporary scientific and technological advancements. The book seeks to highlight how evolving knowledge systems can address pressing environmental concerns, enhance technological capabilities, and contribute to the betterment of society.

The primary purpose of this volume is to provide a balanced understanding of both foundational concepts and emerging trends across multiple domains. It explores critical issues such as environmental degradation, renewable energy development, advanced materials, and intelligent systems, emphasizing their interconnected nature.

The scope of the book is intentionally broad, encompassing insights from environmental science, physics, engineering, biotechnology, and applied sciences. It reflects the growing need to move beyond isolated disciplinary frameworks and adopt integrated perspectives that foster innovation.

This volume is designed to serve as a valuable resource for students, researchers, and professionals alike. Students will find it particularly useful in building conceptual clarity and gaining exposure to emerging areas of study.

The relevance of *Green Frontiers: Emerging Technologies for a Sustainable Future* lies in its focus on the dynamic relationship between scientific advancement and societal needs. As the world faces challenges such as climate change, resource scarcity, and technological disruption, there is an increasing demand for knowledge that is both comprehensive and applicable. It is hoped that this work will encourage critical thinking, inspire innovation, and enable readers to contribute effectively to a sustainable and technologically advanced future.

— Editorial Board

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"Innovation and sustainability are not opposites—they are partners in shaping the future."

— Paul Polman

Former CEO, Unilever; Sustainability Leader

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CHAPTER 4

A BRIEF REVIEW OF BRAIN-COMPUTER INTERFACES AND THEIR APPLICATIONS

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Abstract:

As we have seen from the rapid advancements and growth in Knowledge Transfer technologies, the use of Brain-computer Interfaces (BCI) or Brain Machine Interfaces (BMI) has become a significant focus for research in the past several years. One key area of the application of this technology is to provide a means for people with disabilities to communicate with others and control their prosthetic limbs through BCI technology. Therefore, researchers are investigating several functions of BCIs relating to the field of Media & Communications as these generate significant areas of potential use. Additionally, BCI's have shown promise as they demonstrate the ability to allow BCI's to provide mental health recovery for individuals who have lost their ability due to conditions such as schizophrenia. Although there is a significant amount of potential use for BCI's, there is still a lack of research regarding the future direction of this technology. Furthermore, there are perceived risks associated with the use of BCI's such as medical safety, privacy, ethical, and secure use issues. This paper provides a summary of the important areas related to the study of Brain-Computer Interfaces (BCI) that have been established in existing literature. Different technologies that are used for BCIs include EEG, ECoG and fNIRS, and examples of BCI applications include rehabilitation, prosthetics and cognitive research. Furthermore, the paper also provides a discussion on the roles of Neurofeedback and Communication systems for individuals with disabilities, as well as discussing the practical challenges to be faced, Ethical concerns for BCIs, and possible future trajectories of BCI Research.

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Keywords: brain-computer interface, Signal processing, Neurofeedback, Ethical issues

Introduction:

As a product of recent advancements in science and technology, the Brain Computer Interface (BCI) is an innovative communication system, using the brain's activity as an input to the interface and the interface as a direct connection between a human being's brain and their computer (or other electronic devices). Initially developed by Jacques Vidal at the University of California, Los Angeles (UCLA), funded by the National Science Foundation in the 1970's BCIs have continued to evolve and improve. In addition to being able to extract and process data for research purposes, Scopus has allowed researchers to identify 25,336 BCI related articles and examine the patterns and trends in the field of BCI research.

Human beings interact with one another and perform their desired actions using the muscles and peripheral nerves in their arms and legs. For individuals who have suffered from neuromuscular disabilities such as amyotrophic lateral sclerosis, cerebral palsy and stroke, BCI has the potential to replace current assistive technologies used for people with these disabilities and provide new options for interacting with their environments when assistance from other people is not possible. BCI provides five fundamental functions that support the operation of the BCI; signal capture, preprocessing, feature extraction, classification and control interface.

The capture of brain signals is accomplished through the processing of artifacts and the reduction of noise by identifying the key distinguishing characteristics of those signals through the extraction of features. However, due to the overlap of brain signals, the extraction of useful information is complicated, leading to the mix of signals or interference from aberrations such as EMG and EOG. The complexity of extracting useful features can be reduced through the use of a small feature vector that does not sacrifice significant data. Therefore, based on the features extracted from the brain signals, a classification step will interpret the user's intent, and the control interface will convert the classified signals into commands for various wearable technology devices.

Review of Literature:

History:

Developments in the field of BCIs are historically attributed to Hans Berger's discovery of Electric Activity in the Brain and subsequently to the growth of Electroencephalogram (EEG) technology. Using EEGs, Berger recognised the occurrence of oscillatory wave patterns like the alpha rhythm, and subsequently compared the variations in his own charts and graphs of EEG waveforms of different brain disorders. EEG technology opened up entirely new ways to research the workings of the brain, as the term BCI, which is referred to as a Brain-Computer Interface was originally coined by Vidal, who wrote the first peer-reviewed articles related to the area of BCIs, and many consider Vidal to have been the founder of this ability. One of the studies that Vidal published that brings forward the concept of the BCI Challenge using EEG Signals to control objects in earnest, specifically making use of Contingent Negative Variations (CNVs); he introduced this concept in his 1973 paper. One of the major portions of his 1973 article focused on the potential use of CNV brain potentials. Subsequently, researchers Kennedy and Bakay first employed human brain implants to provide better quality electrical signals to enable users to move quicker. Research performed in 2010 suggests that neural stimulation may lead to the recovery of functional connectivity and behavioral patterns through alteration of molecular pathways. Research on BCI has evolved over the past 25 years. 25 years ago, research on BCI was done in a few distant laboratories and was generally believed to be obscure. Now, BCI has become an area that continues to grow rapidly and is capturing the interest of the many researchers, engineers and clinicians that are around the world. These BCIs provide enable people who have physical disabilities (including autism) with communication, mobility, daily tasks and environmental control through the research community.

Types of BCI: There are 3 different types of BCI categorized by invasiveness: invasive, semi-invasive and non-invasive. The major asset of invasive BCIs is that operating room procedures allow insertion of electrodes into the skull and soft tissue in order to provide a better signal to send motor commands. The application of invasive BCI research has been to restore sight or to provide new capabilities to individuals with disabilities. The semi-invasive or partially invasive BCI use a combination of outside components as well

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as parts installed in the skull. ECoG devices are used to measure the electrical activity of the brain from beneath the skull, similar to EEG, with the use of electrodes attached to a flexible pad and implanted just below the dura mater. Non-invasive neuroimaging technologies provide methods for stimulating the computer with the brain's electrical components without actually penetrating the skull. There are five main technologies typically used in non-invasive BCIs: EEG, fMRI, MEG, NIRS and fTCD.

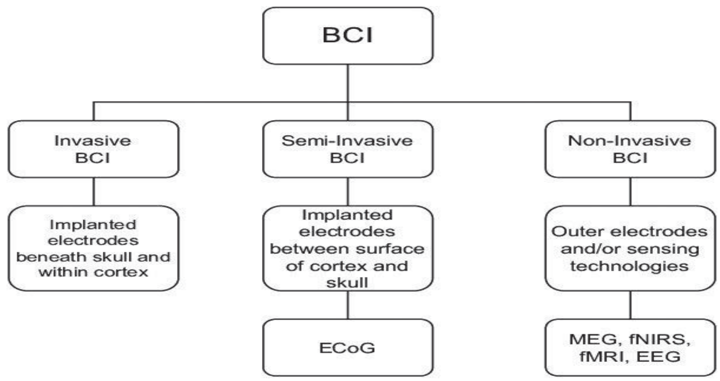

Figure 1: Three types of BCI: invasive BCI, semi-invasive BCI and non-invasive BCI [1]

Fundamental Components: Brain-computer interfaces (BCIs) aim to identify and measure elements of brain signals related to one's mental intent and then translate the data from these elements into device control commands to perform the user's mental intent. BCIs are comprised of three primary components, each performing a function. The three components work together to capture the brain signal and apply them to target applications or wearable devices. In addition to providing control signals from the device to the user, BCIs can send control signals back to the user's brain that provides sensation stimulations (e.g., visual or auditory).

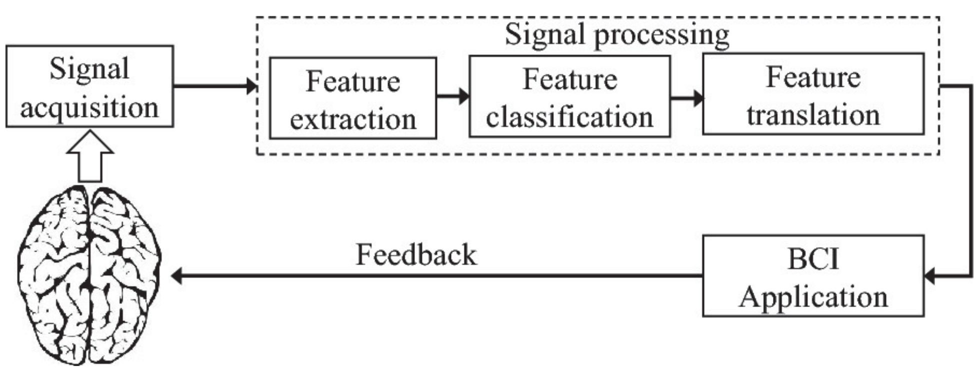

Figure 2: Main components of the brain–computer interface (BCI) system [2]

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Electrodes are used in signal acquisition to capture the brain signals that are created or generated by changes in electrical voltages from several biological processes in the brain through electroencephalography (EEG). These signals essentially represent the neurophysiological state of the individual, thus, to capture the best possible signal they are subjected to filtering, amplification and digitization before proceeding further.

A BCI (brain computer interface) breaks down the brain signal into three steps; feature extraction, classification and translation. The BCI translates the user's intent or desire by extracting, classifying and translating the characteristics of their brain signals into the command used by the BCI to control an external device. In the feature extraction stage, relevant signal patterns are extracted from the brain, in the classification phase machine learning methods are used to classify the brain signal into relevant groups or categories versus the rest of the brain signals that have no relationship to any action, and finally in the translation phase the commands are converted into commands that can be used by an external device to generate a movement such as selecting text on a computer screen, moving around a room in a wheelchair or maneuverings a robotic arm. In some cases, the signals can also be sent back to the brain or other parts of the body to facilitate recovery after an injury or illness.

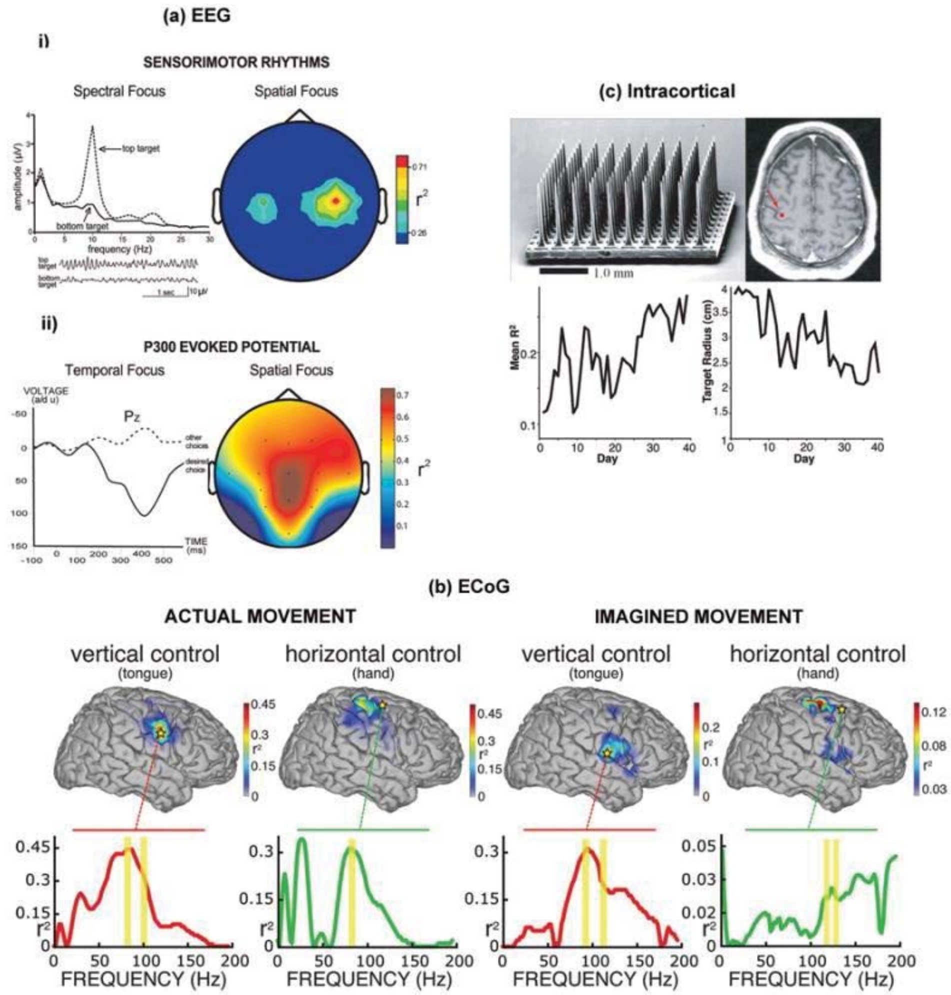

Figure 3: EEG-based and ECoG-based BCI systems [3]

Electroencephalography (EEG)-based BCIs:

EEG is an abbreviation for electroencephalograph, which is a medical device used to detect brain activity through the measurement of the electrical current that passes through the brain when a team of neutrons is synaptically excited at the dendrites of those neurons.

EEG electrodes which are used to obtain electrical signals from the scalp are non-invasive recording modalities that provide very low quality (compared to those of invasive modalities) of EEG raw data as they must travel through numerous layers of the brain including the skull.

The structure of a recorded EEG system generally consists of electrodes, amplifiers,

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analogue to digital converters (ADCs) and recording devices. Each of these has an important and specific role to play in the acquisition of an EEG signal, with the electrodes being responsible for detecting electrical activity originating at the scalp, amplifiers for capturing and processing the analogue signal, and ADCs for converting analogue signals into digital format.

The amplitude of the electrical bio signal is measured in microvolts, which makes it extremely susceptible to electronic noise. Other common types of electronic noise are generated externally by things like background noise, thermal noise, short noise, flicker noise, and many other electronic sources; therefore, these design considerations try to minimize these effects to the extent possible.

The electrical signals from the EEG consist of several different types of signals that are classified according to the frequency. The most commonly used frequency ranges are described by their respective distributions across the scalp and their respective biological significance, and they are often referred to as delta (highest frequency) through to gamma (lowest frequency).

The Electroencephalogram or EEG is conducted by placing electrodes over the patients head via a standardized system developed by the American Electroencephalographic Society. The placement of the electrodes is based on markings on the skull indicating plane intervals of 10% and 20% (as shown in the figure below).

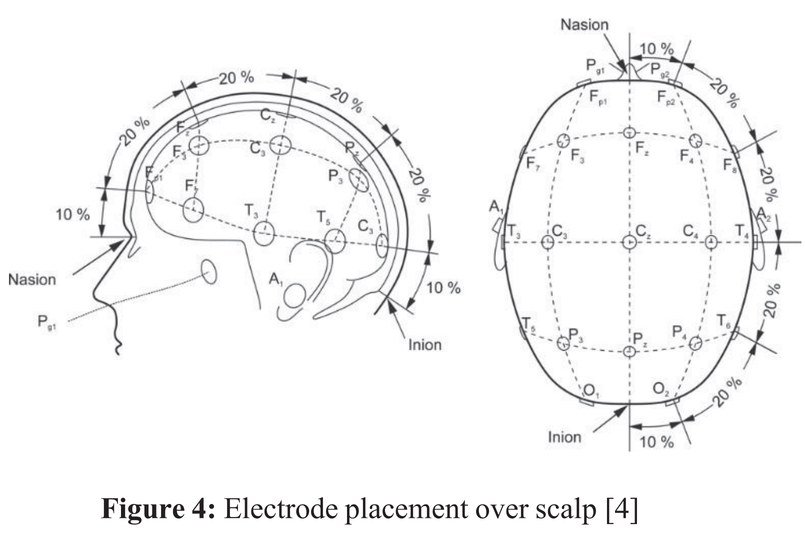

Figure 4: Electrode placement over scalp [4]

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Electrocorticography (ECoG)-based BCIs: Electrocorticography (ECoG) is a form of brain mapping that utilizes electrodes that directly contact the cerebral cortex in order to monitor brain electrical activity. Compared to other forms of monitoring such as electroencephalography (EEG), ECoG offers higher resolution both temporally and spatially, higher amplitudes, and less impact from artifacts due to eye movement or blinking. However, the implanting of electrodes through a craniotomy means the ECoG method has inherent risks to human health and safety. As a result, ECoG studies began with animal subjects, with early studies determining the long-term stability of ECoG signals from the brain and confirming that subdural electrodes yield stable and reliable ECoG signals over time.

Humans have used the electroencephalogram (E Co G) to study how alpha, beta and gamma waves are produced during voluntary motor actions. In terms of using an ECoG as part of a Brain Computer Interface (BCI), a BCI that classifies motor actions was developed by identifying the event-related potentials produced by motor actions. Leuthardt and others demonstrated at a conference that an ECoG-based BCI could provide sufficient information for the control of a cursor in one dimension. Several years later, XYZ presented an even more sophisticated ECoG-based BCI which allowed a user to manipulate, or control, a cursor in two-dimensional space.

Functional Near-Infrared Spectroscopy (fNIRS)-based BCIs: fNIRS systems measure the amount of oxygenated blood in the brain's cortex using infrared light. The fNIRS approach involves using near-infrared light that passes through the skull and is reflected back from the brain. The amount of reflected light is used to derive the level of oxygenation occurring in different brain regions that are engaged in cognitive tasks.

In regards to comfort and portability, fNIRS systems offer many advantages over both EEG and ECoG systems and can be utilized in a broader array of circumstances. In addition, fNIRS has slower response times as well as limited spatial resolution, thus decreasing the confidence when controlling precision. However, fNIRS can be utilized mainly for research purposes related to rehabilitation, assistive technologies, and cognitive load assessments.

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Applications Of BCIs: A key application of brain-computer interfaces (BCIs) is in medicine, where scientists and engineers are using BCIs to enhance the quality of life for people with certain disabilities by enabling them to use their thoughts to control devices integrated with BCIs and interact with their environment, thereby increasing their level of independence. The development of BCIs is a collaborative effort between scientists and engineers due to the multidisciplinary nature of the field, and recent developments in the education and mining industries have demonstrated that BCIs have industrial applications beyond medicine. BCIs have great potential to affect the fields of neurophysiology and robotics when coupled with the Fourth Industrial Revolution. Some interesting examples of BCI applications include the ability to decipher thoughts, extend memory capacity, conduct telepathic communication between individuals, and provide therapies targeting specific bodily injuries.

Prosthetics and Assistive Technologies with BCIs: Brain-computer interfaces are revolutionizing prosthetic technology by allowing people to use their thoughts and direct movements via analysis of their brain activity. An advantage to this development is that BCIs, as technology, make this possible by translating brain activity into a useful signal. The results from Lebedev and Nicolelis's experiments showed that monkeys can control robotic arms using brain signals. The studies by Hochberg and his colleagues have demonstrated that patients who have lost some function can also use robotic arms to grasp and manipulate objects, increasing their independence. In recent publications, Birbaumer and colleagues demonstrated that BCIs can also benefit individuals with severe physical disability when interacting with various technologies used to communicate, allowing both individuals with severe physical disabilities use communication devices as well as provide individuals a means to be more fully engaged and have greater interaction with their surroundings.

Rehabilitation and Therapeutic Applications of BCIs: Rehabilitation represents one of the more prominent areas of research where BCI applications can be found. These interfaces will enhance the effectiveness of conventional rehabilitation methodologies because they enable participants to receive real-time feedback and facilitate the user's participation in their rehabilitation.

Tedesco et al.'s group conducted a study showing that combining motor imagery training with BCI technology, it is possible to enhance recovery from stroke more effectively than traditional practices with the use of BCI technology.

There has been research exploring the potential for BCIs to assist in treating a variety of mental health conditions, including anxiety and depression. Research conducted by Hengameh et al. has indicated that BCIs that use neurofeedback may assist individuals in controlling their anxiety or depression by controlling their own brain activities.

Pain management is another area of research where BCIs have considerable promise. In research conducted by Zich et al., individuals suffering from chronic pain clearly did have the potential to manage their symptoms through regulated brain activity. The study offered evidence demonstrating how BCIs may provide a novel approach to controlling pain sensation.

Gaming and Entertainment with Brain-Computer Interfaces: More and more gaming companies are developing games that employ BCIs to allow players to be more engaged with their gaming experience than ever before, and to provide gamers with a more individualized experience by utilizing real-time brain activity. Researchers are studying how BCIs can be used to create gamer-specific rulesets and make gaming experiences a one-of-a-kind or personalized gaming experience.

A prime example of a game utilizing BCIs would be a game capable of determining a player's focus level in real time and then adapting the difficulty of the game in accordance with their attention level. According to findings published by Chavarriaga et al., utilizing BCIs has created an additional layer of immersion within a game because BCIs allow the game to adapt the level of difficulty based on the cognitive effort required by the player.

BCIs have also inspired the development of new forms of creativity and artistic expression. Kasyanov et al. revealed that, through the application of BCIs, the brain will generate dynamic pieces of artwork that vary based on the emotional response of the observer, helping to create truly interactive art experiences.

Neurofeedback and Neuroplasticity in BCIs: Neurofeedback allows individuals to train themselves in self-regulation of their brainwaves by using a real-time EEG signal to monitor brain activity and promote neuroplasticity through BCIs. Enriquez-Geppert et al. (2019) demonstrated that through a customized protocol, participants have demonstrated improved attention and increased working memory by increasing theta and alpha wave amplitudes. Customized neurofeedback protocols created specifically for individuals with cognitive deficits associated with ADHD, such as executive function skills and improved attention control can enhance the user's ability to regulate their brain. Neuroplasticity and BCIs for cognitive enhancement are hot topics in the literature and have been subject to a lot of recent research.

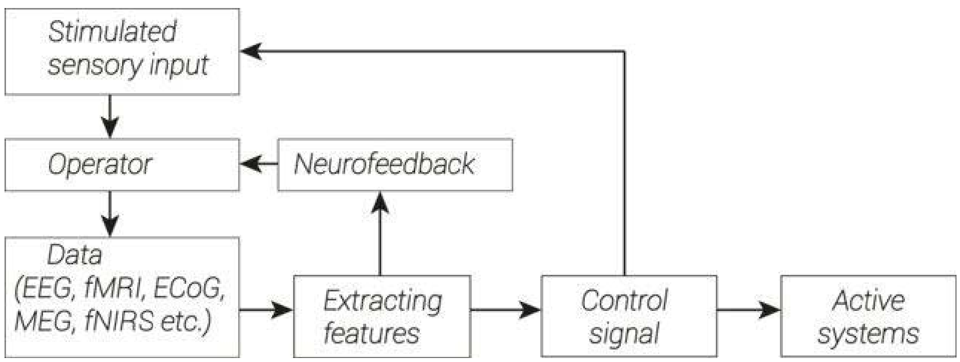

Figure 5: General scheme of implementation of biofeedback system in BCI [5]

Neuroscience and Cognitive Research with BCIs: The Brain-Computer Interface (BCI) has become a vital resource for Neuroscientists who are interested in deepening their understanding regarding the many complex ways that the Human Brain works. Neuroscientists and other researchers are studying Decision-Making and other processes within the brain, by observing what occurs within the brain while it performs these processes.

Researchers can use BCIs to observe and characterize the Neural Mechanisms that perform the function of Decision Making. The BCI provides insight into how the Brain processes Information, as well as providing neural maps of various brain structures. Further, the ability to create these neural maps allows us to understand the Origin of conditions such as Stroke and Epilepsy.

The therapeutic value of BCIs is another area deserving of continued investigation.

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Through research done by Dr. Sitaram and colleagues, utilizing Neuro-Feedback using BCIs, clinical intervention with patients having suffered from Craniocerebral Trauma has shown clinical validity when used in conjunction with a Cognitive Rehabilitation program.

BCI Technology Ethical Issues: Major ethical issues surrounding BCI technology include the potential for privacy violations and dissemination of private cognitive data without informed consent, as well as misuse, or the use of BCI data for illegal purposes. Because BCIs access and record brain activity, there is a substantial risk that BCIs could collect and analyze individual's Intimate cognitive data without their permission, hack into that data or, misuse it for nefarious reasons. In the context of medical applications, there are ethical concerns regarding the requirement of informed consent and the vulnerability of those being treated. The use of cognitive data will also require regulatory oversight and statutes to ensure the protection of individuals' intimacy as BCIs will acquire this data and analyze behaviors/thoughts/emotions. The potential to alter human behavior through neurostimulation present considerable ethical ramifications as well, especially in terms of military and/or security applications.

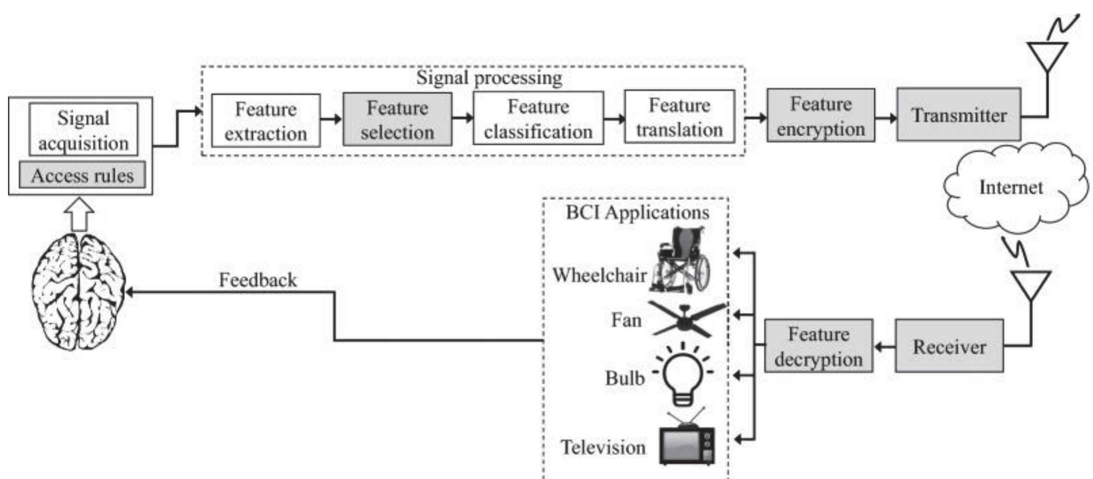

Figure 6: Brain-computer interface (BCI) system with encryption and decryption components for enhancing privacy [2]

Challenges of BCI Technology and Signal Processing: The implementation of brain-computer interface (BCI) technologies has created various challenges for scientists to work through. A major challenge is signal processing, which is essential

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to the operation of BCI technologies. When researchers analyze the electrical activity produced by the brain, there is a great deal of background noise present in the brain's electrical signals, making it difficult to interpret these signals reliably. One major difficulty for BCIs arises from the fact that most neural signal acquisition methods, such as electroencephalography (EEG), provide relatively low spatial resolution and suffer from a lot of interference from neighbouring areas of the brain, making it difficult to separate brain signals from other brain signals. In addition, the need for algorithms and specialised hardware to process brain signals in real-time has made BCI technology very expensive, and thus, not particularly cost-effective or convenient for the vast majority of users. Interpretations of brain signals vary from person to person based on the differences in individual biology and physiology; thus, it is impossible to create a single BCI application that is effective for all users.

Future Trends in BCI Rehabilitation and Applications: An anticipated advancement in the area of BCIs will be the result of not only advances in less invasive, more wearable forms of BCI devices, but also the concomitant development of enhanced signal processing algorithms. Together these two changes can provide BCIs with greater utility and practicality in the medical rehabilitation of individuals with motor disabilities and neurological disorders. BCI data processing developments (many of which include machine learning approaches) have resulted in increased signal quality (lower levels of distortion) and increased clarity regarding a user's intent. By using BCIs to provide greater control of prosthetic/assistive devices and their users' motor disabilities/neurological disorders, BCIs can enhance the quality of life for individuals with disabilities. Additionally, the enhanced neuroplasticity achieved through BCI training will contribute to improved recovery from stroke and traumatic injury as well as cognitive rehabilitation.

BCIs face numerous challenges, including ethical concerns; however, BCIs hold great promise in facilitating the transition of assistive technology toward a more integrated understanding of the brain-machine interface in both medical and non-medical applications.

Conclusion:

Over the last decade, there has been a rapid growth in BCI (Brain-Computer Interface) technology; this technology has had a variety of applications to improve the quality of every part of human life through cues (Assistive Technologies), rehabilitation, and rehabilitation of prosthetic arms and legs. The new advances in EEG (Electroencephalography), ECoG (Electrocorticography), and fNIRS (functional Near Infrared Spectroscopy) technology have increased the precision of the BCI System (brain-computer interface) through the inclusion of a wide variety of applications, including but not limited to, simple communications to more sophisticated rehabilitation programs, etc. BAI is faced with many challenges, including ethical issues, including the right to privacy, and the ability to protect personal safety; research is currently underway to identify and manage these risks through Data Security Methodologies (Data Security) and User Consent Methodologies (Ratio of User Consent) and, the possible Psychological Effects (Effects of Stress) associated with BCIs (Brain-Machine Interfaces).

Despite these obstacles, the future of BCI technology appears to be bright due to continual progress in the processing of signal processing technologies through Machine Learning (ML) and Robotic Technologies (RT). There is great potential for BCI technology to improve the quality of life of people with disabilities and to provide new ways of communication between humans and computers.

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Emerging Technologies for a Sustainable Future

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Dr. Tanay Pramanik is a Professor of Organic Chemistry with over 13 years of academic, research, and administrative experience at institutions such as the National University of Singapore, Lovely Professional University, and the University of Engineering and Management, Kolkata. A university silver medalist, he qualified CSIR-NET with SPM Fellowship nomination and secured top ranks in GATE and JAM. He earned his PhD from NUS and specializes in organic electronics, conjugated polymers, green synthesis, and sustainable water purification. He has over 55 SCI/Scopus publications, 20 patents, and several books and chapters. His work has received international recognition, including awards at the Geneva Inventions Exhibition. He has also held key leadership roles and contributed significantly to teaching, research mentoring, and academic development.

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