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“Brain–Computer Interface: Trend, Challenges, and Threats”

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CERTIFICATE

Certified that the Technical Seminar work entitled **"Brain–computer interface: trend, challenges, and threats"** carried out by Ms **Bhoomika G R** bearing USN **1JB21CS026** is a bonafide student of **SJB Institute of Technology** in partial fulfilment for 8^{th} semester of **BACHELOR OF ENGINEERING** in **COMPUTER SCIENCE AND ENGINEERING** of the **Visvesvaraya Technological University**, **Belagavi** during the academic year **2024-25.** It is certified that all corrections/suggestions indicated for Internal Assessment have been incorporated in the Report deposited in the Departmental library. The technical seminar report has been approved as it satisfies the academic requirements in respect of Technical Seminar prescribed for the said Degree.

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ABSTRACT

Brain–Computer Interface (BCI) technology, which enables direct communication between the human brain and external devices, has gained significant traction across various research and industrial domains. It holds transformative potential in assisting individuals with physical disabilities, thereby enhancing their independence and overall quality of life. Beyond healthcare, BCI has made inroads into multiple sectors such as entertainment, gaming, automation, education, neuromarketing, and neuroergonomics. Despite its wide array of applications, the global progression and adoption trends of BCI have not been thoroughly explored in existing literature. Recognizing this gap, researchers conducted an extensive bibliometric analysis of 25,336 BCI-related publications sourced from Scopus. The study revealed a significant surge in publications from China starting in 2019, which even surpassed the output from the United States—previously a global leader in the field—whose contributions have shown a declining trend during the same period.

This shift in research output indicates a broader change in global BCI research dynamics, potentially driven by increased government investment, academic collaboration, and technological advancement in China. The study delves into possible reasons behind this pattern, including national strategic priorities and research funding trends. However, as BCI moves closer to practical and commercial deployment, significant challenges remain. Key concerns include the privacy and security of neural data, which, if not adequately addressed, could hinder the widespread acceptance of the technology. To tackle these concerns, a conceptual BCI architecture has been proposed that integrates robust security mechanisms and privacy safeguards. Such advancements are essential for ensuring that BCI systems are not only effective but also trusted and embraced by society for real-world applications.

TABLE OF CONTENTS

LIST OF FIGURES

CHAPTER 1

A Comprehensive Review on Brain Computer Interface System

1.1 Introduction

Humans typically rely on their peripheral nervous system and muscles to interact with the physical world—performing tasks like moving, speaking, or perceiving their surroundings. However, individuals suffering from severe neurological conditions such as amyotrophic lateral sclerosis (ALS) or brainstem stroke often lose the ability to control these motor functions, making them dependent on others for basic interactions. To address this limitation, researchers have developed Brain–Computer Interface (BCI) technology, which allows direct communication between the brain and external devices, bypassing the need for muscles or nerves. Also known as brain–machine interface, BCI interprets brain signals and translates them into commands to control devices like robotic limbs, wheelchairs, or computers. Since its inception by Jacques Vidal in 1973, BCI research has grown significantly, yielding numerous successful applications that enhance the capabilities of individuals with disabilities, including those with neurological and psychiatric disorders. The technology has found use in diverse sectors such as healthcare, gaming, education, marketing, and neuroergonomics, making it a promising field with the potential to augment human abilities in both therapeutic and everyday contexts.

Despite its immense potential, the future of BCI technology is still under-explored, particularly in terms of its ethical, medical, and security-related implications. The integration of BCIs into human life raises significant concerns around data privacy, medical safety, and the ethics of brain data manipulation. The human brain's complex and not fully understood nature further complicates the safe and reliable implementation of BCI systems. This study highlights the need for greater focus on the short- and long-term impacts of BCI on human health and well-being. It encourages the scientific community to engage in proactive discussions around responsible innovation, especially as BCI transitions from the lab to real-world applications. Moreover, the analysis of 25,336 metadata entries from Scopus reveals an exponential surge in BCI-related publications from 2019 onward, with China emerging as a global leader in BCI research, followed by the United States. This trend not only underscores the growing interest and investment in the field but also emphasizes the urgency to address the accompanying threats to ensure the development of safe, ethical, and beneficial BCI solutions.

1.2 The Importance of BCI System

The importance and excitement for BCI System could be established through the following facts mentioned below:

- **Restores Abilities**: Helps individuals with neurological disorders regain control over devices, improving independence.
- **Direct Brain Communication**: Enables brain-to-device interaction without muscles or nerves for faster control.
- **Multi-Industry Use**: Applicable in healthcare, gaming, education, marketing, and more.
- **Drives Innovation**: Advances research in neuroscience, AI, and human-computer interaction.
- **Global Research Growth**: Rapid increase in BCI studies, especially in China and the U.S.
- **Enhances Human Potential**: Can improve cognitive and physical abilities even in healthy individuals.
- **Raises Ethical Focus**: Promotes discussions on privacy, safety, and ethical use of brain data.

1.3 Motivation For This Study

The motivation behind Brain–Computer Interface (BCI) technology stems from the need to empower individuals with severe neurological disorders who are unable to control external devices through traditional muscle or nerve activity. By enabling direct communication between the brain and machines, BCI offers a transformative solution that restores independence and improves quality of life. Additionally, its broad applicability across various fields such as healthcare, entertainment, education, and marketing highlights its potential to revolutionize human interaction with technology. The exponential growth in global research, especially in countries like China and the United States, further emphasizes the increasing interest and investment in this field. Motivated by these promising opportunities, researchers aim to overcome existing challenges—such as privacy, ethics, and medical safety—to develop safe, effective, and widely accessible BCI systems.

1.4 Advantages and Benefits of BCI System

Here are the **advantages and benefits** of the BCI (Brain–Computer Interface) system:

- **Restores Motor and Communication Abilities**
  BCI helps individuals with severe neurological conditions (e.g., ALS, brainstem stroke) regain control over external devices, enabling communication and movement without using muscles or nerves.
- **Improves Independence and Quality of Life**
  By enabling users to perform tasks without physical assistance, BCI reduces reliance on caregivers and enhances daily living for people with disabilities.
- **Direct Brain-to-Device Interaction**
  BCI provides a non-muscular communication channel, allowing fast, intuitive control over computers, prosthetics, or robotic limbs directly from brain signals.
- **Wide Application Across Industries**
  BCI is used in various sectors including healthcare, entertainment, education, marketing, neuroergonomics, and security, making it a highly versatile technology.
- **Supports Scientific and Technological Innovation**
  Continuous research in BCI drives progress in neuroscience, artificial intelligence, and human–machine interaction, opening new frontiers in technology.
- **Potential to Enhance Human Capabilities**
  Beyond assisting the disabled, BCI may be used to boost cognitive functions and performance in healthy individuals, offering new possibilities in human augmentation.

CHAPTER 2

LITERATURE SURVEY

Research Papers

- **Brain-Computer Interface (BCI) technology represents a cutting-edge field that establishes a direct communication link between the brain and external devices, offering new possibilities for interaction and control.** -BCI systems bypass traditional pathways of communication, such as peripheral nerves and muscles, by directly interpreting brain activity. This allows for a novel form of interaction where thoughts and intentions can be translated into actions in the external world. This technology holds the potential to revolutionize how humans interact with technology and the environment around them.
- **A primary motivation for BCI research lies in its potential to restore lost functions in individuals with physical impairments, such as those with severe neurological diseases, thereby enhancing their autonomy and overall quality of life-** BCI offers a lifeline to individuals suffering from paralysis, stroke, or neurodegenerative diseases like ALS, who may have lost the ability to move or communicate. By providing a means to control assistive devices like wheelchairs, prosthetic limbs, or communication aids through brain signals, BCI can significantly improve their independence and enable them to engage more fully with the world.
- **BCI technology demonstrates versatility across various industries, including entertainment and gaming for enhanced user experiences, automation and control for improved human-machine interaction, education for innovative learning methods, neuromarketing for understanding consumer behavior, and neuroergonomics for optimizing workplace environments-** Beyond medical applications, BCI is finding applications in diverse fields. In entertainment, it can offer immersive gaming experiences. In automation, it can streamline control systems. In education, it can personalize learning. Neuromarketing utilizes BCI to gain insights into consumer responses, while neuroergonomics focuses on designing work environments that align with brain activity patterns for increased efficiency and safety.
- **Despite its wide-ranging potential, the existing literature provides limited discussion**

on the future trajectory of BCI technology and the associated challenges and threats, indicating a need for more in-depth exploration in this area- While the field of BCI is rapidly advancing, a comprehensive analysis of its future direction, including potential obstacles and risks, is lacking. This gap in the literature underscores the importance of research that not only explores the technological advancements but also critically examines the broader implications of BCI technology for society.

- **A bibliometric analysis of over 25,000 BCI publications reveals an upward trend in research output, with China experiencing a notable surge in publications since 2019, signaling a shift in global research contributions-** The quantitative analysis of BCI publications provides valuable insights into the growth and geographical distribution of research efforts. The significant increase in publications from China indicates a growing focus and investment in BCI research in that country, potentially reshaping the global landscape of BCI development.
- **The increase in China's BCI publications may be attributed to substantial research funding and strategic government initiatives aimed at fostering technological innovation and establishing the country as a leader in this advanced field**- Government support and funding play a crucial role in driving scientific advancements. China's focused approach to BCI research, through increased financial support and strategic planning, has likely contributed to its rapid growth in publications and its emergence as a key player in the BCI field.
- **While the United States has historically been a leading country in BCI research, its publication output has shown a decline from 2019 onwards, prompting investigations into the factors influencing this trend and potential strategies to revitalize its contributions-** The observed decline in BCI publications from the United States raises questions about potential shifts in research priorities, funding allocations, or other factors affecting its research output. Understanding these influences is essential for maintaining a leading role in BCI innovation.
- **The fundamental components of a BCI system include signal acquisition, which involves capturing brain activity; signal processing, which extracts and translates relevant features; and application, which utilizes these translated signals to control external devices or provide feedback-** These three components form the core of any

BCI system. Signal acquisition captures brain activity using sensors; signal processing extracts meaningful information from this activity; and the application utilizes this information to control a device or provide feedback to the user. Each component is critical to the BCI system's overall functionality.

- **Signal acquisition is a critical stage where brain signals, such as electrophysiological signals, are captured using electrodes, with the quality of these signals significantly impacting the overall performance and reliability of the BCI system**- The accuracy and fidelity of the acquired brain signals are paramount for the BCI system to function effectively. Factors such as the type of electrodes used, their placement, and the presence of noise can all influence the quality of the signal and, consequently, the performance of the BCI.
- **BCI systems can be broadly classified into invasive, involving electrodes implanted directly into the brain for higher signal accuracy, and non-invasive, using electrodes placed on the scalp, offering a less invasive but potentially less precise approach**- Invasive BCI systems offer the advantage of higher signal quality and spatial resolution, but they require surgical procedures, posing risks. Non-invasive BCI systems are safer and easier to implement but may suffer from lower signal quality due to interference from the scalp and skull.
- **Signal processing involves feature extraction to identify relevant patterns in brain signals, classification to interpret these patterns, and translation to convert them into commands that can be used by external devices** - Feature extraction identifies specific characteristics in the brain signals that correlate with different mental states or intentions. Classification algorithms then interpret these features to determine the user's intent. Finally, translation converts this intent into commands that can control an external device.
- **BCI technology holds the potential for decoding thoughts, which could revolutionize fields such as criminology by enhancing lie detection methods and contribute to a deeper understanding of cognitive processes**- Decoding thoughts, while still in its early stages, has the potential to transform various fields. In criminology, it could potentially improve the accuracy of lie detection. More broadly, it could provide insights into cognitive processes, memory, and consciousness.

- **The concept of extending human memory using BCI raises intriguing possibilities for augmenting human cognitive capabilities, allowing for quicker processing, retrieval, and transmission of information** - BCI could potentially be used to enhance memory by directly interfacing with brain regions involved in memory storage and retrieval. This could lead to technologies that assist in learning, memory recall, and even the transfer of information.
- **BCI research is exploring innovative concepts such as brain energy harvesting, where energy from the brain could be utilized to power external devices, presenting new avenues for sustainable technology**- The brain consumes a significant amount of energy, and BCI research is investigating the feasibility of harvesting some of this energy to power low-energy devices. This could lead to self-powered BCI systems and other applications in sustainable energy.

CHAPTER 3

PROBLEM STATEMENT

“A fundamental problem within the rapidly evolving field of Brain-Computer Interface (BCI) technology lies in the increasing disparity between the swift advancements in technological capabilities and the comparatively underdeveloped comprehensive analysis of the technology's broader implications; specifically, while BCI research is generating increasingly sophisticated applications spanning diverse sectors—from healthcare and assistive technologies to entertainment and industrial automation—there exists a significant and critical lack of thorough, nuanced, and interdisciplinary investigation and discourse concerning its long-term future direction (including optimal development pathways, potential for convergence with other technologies, and societal integration strategies), the multifaceted challenges that currently impede its progress and wider adoption (encompassing inherent technical limitations in signal acquisition and processing, significant inter- and intra-individual variability in brain signals, usability and accessibility constraints for diverse user populations, and the need for robust validation and standardization protocols), and the potential threats it poses to individuals and society (including profound ethical dilemmas related to autonomy and identity, serious privacy violations stemming from the extraction and misuse of sensitive neural data, security vulnerabilities that could expose BCI systems to malicious attacks, and safety concerns associated with both invasive and non-invasive BCI techniques), which is absolutely crucial for ensuring responsible and ethical development, facilitating effective translation of research into robust and reliable real-world solutions, fostering public trust and acceptance of this transformative technology, and proactively mitigating potential harms before they materialize”.

3.1 Challenges

- **Ethical Problems:**BCI raises tricky questions about what's right and wrong .We need to figure out how to protect people's thoughts and information, keep BCI safe, and make sure everyone can use it fairly.
- **Privacy Worries:**BCI can read information directly from the brain .This means we have to be very careful about who can see that information and how it's used, because it's very personal.
- **Security Risks:**If BCI is connected to computers, it can be hacked.Hackers could mess

with BCI systems, which could be dangerous. So, we need to make BCI systems very secure.

- **Hard to Use:**BCI systems often need to be adjusted or retrained.This takes time and can be annoying for users, making BCI less practical for everyday use.

These challenges underscore the need for ethical and responsible implementation, which the problem statement aims to address.

3.2 Objectives of the Study

This study aims to:

- **Analyze the trend of BCI research:** The study examined 25,336 metadata from Scopus to identify patterns and growth in BCI publications, revealing an exponential increase particularly in China since 2019. This analysis aims to inform researchers and practitioners about the evolving landscape of BCI research and where to focus future efforts.
- **Discuss the challenges and threats limiting the exploitation of BCI capabilities**: The research provides an extensive discussion on the obstacles and potential dangers that impede the full utilization of BCI technology, including issues like privacy, security, and safety .

  This exploration seeks to foster scholarly discussion on addressing these challenges to promote responsible BCI development and adoption.
- **Propose a BCI architecture to address privacy and security concerns:** To enhance the commercial viability of BCI technology, the study proposes a typical BCI architecture designed to mitigate privacy and security vulnerabilities. This hypothetical architecture integrates components and processes aimed at protecting user data and ensuring secure BCI operation.
- **Provide recommendations for future research and development in the BCI field:** The study offers recommendations to guide the development of safe BCI products that benefit humanity and improve the quality of life. These recommendations emphasize the importance of considering the short-term and long-term impacts of BCI and addressing ethical considerations.

CHAPTER 4

METHODOLOGY

Bibliometric Analysis as the Core Approach: The study's fundamental methodology was a bibliometric analysis, a quantitative research technique used to analyze patterns in scholarly publications. This approach is well-suited for examining the evolution of a research field, identifying key trends, and assessing the impact of publications over time. In this context, it allowed the researchers to systematically investigate the growth and development of BCI research.

Scopus Database as the Primary Data Source: The researchers relied on the Scopus database as their main source of information. Scopus is a large and reputable abstract and citation database that indexes a vast amount of peer-reviewed literature, including scientific journals, conference proceedings, and books. Using Scopus ensured that the analysis was based on a comprehensive and high-quality collection of scholarly works related to BCI.

Precise Search Strategy for Data Retrieval: To retrieve relevant publications, the researchers employed a carefully designed search string. This search string included the term "brain computer interface" and its various alternative forms and related keywords. This ensured that the search captured a wide range of relevant studies while minimizing the inclusion of irrelevant material. The use of a precise search strategy is crucial in bibliometric analysis to obtain accurate and representative data.

Extensive Data Extraction from Publications: The researchers extracted metadata from a substantial number of BCI publications, totaling 25,336. Metadata refers to the descriptive information about each publication, such as authors, title, publication year, source, abstract, and keywords. Extracting this metadata allowed for quantitative analysis of various aspects of BCI research, such as publication trends, author collaborations, and geographical distribution.

Systematic Organization and Categorization of Data: The extracted metadata was systematically organized and categorized to facilitate meaningful comparisons. In particular, the publications were classified according to the continents, regions, and countries of the authors' affiliations. This geographical categorization enabled the researchers to analyze the distribution of BCI research activity across different parts of the world and identify regional trends.

Application of VOSviewer for Network Analysis: The researchers utilized the VOSviewer software, a specialized tool for constructing and visualizing bibliometric networks. VOSviewer allowed them to create visual representations of the relationships between publications, authors, and keywords. These network visualizations provided valuable insights into patterns of collaboration, emerging research areas, and the structure of the BCI knowledge domain.

Focus on Trend Identification and Analysis: A central focus of the methodology was to identify and analyze trends in BCI research. This involved examining how the number of publications has changed over time, identifying periods of rapid growth or stagnation, and determining the key factors that may have influenced these trends. Analyzing trends helps to understand the historical development of the field and predict future directions.

Emphasis on Quantitative Analysis and Statistical Support: The study relied heavily on quantitative analysis of the publication data. Statistical methods were used to calculate various metrics, such as publication counts, citation frequencies, and growth rates. These quantitative findings provided empirical evidence to support the researchers' interpretations and conclusions about the evolution of the BCI field.

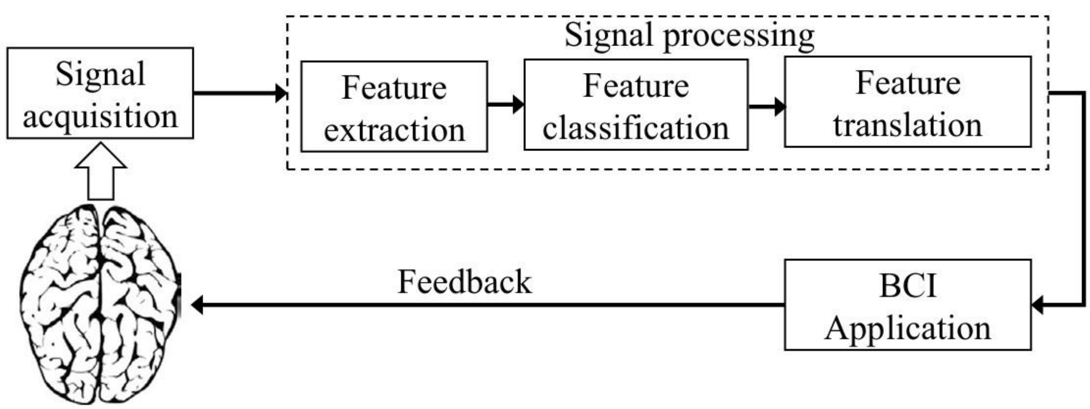


Fig. 1 Main components of the brain–computer interface (BCI) system

Figure 4.1: Main components of brain – computer interface(BCI) .

CHAPTER 5

IMPLEMENTATION

5.1 An Overview Of BCI System

The BCI system comprises three fundamental components that serve specific roles: signal acquisition, signal processing, and application . These components are interconnected and work together to allow the flow of brain signals to the target BCI application (e.g., robotic arm). In particular situations, control signals from the BCI application may be sent back to the brain to stimu late some common human functionalities, such as vision and hearing.

Signal acquisition:

This component comprises an electronic device with electrodes for acquiring brain signals (oscillating electrical voltages caused by biological activities of the brain) that define its neurophysiological states. Signal acquisition involves capturing of electrophysiological signals that represent specific activities of the brain (e.g., movement, speech, hearing, and vision). Most BCI systems, including the commercial ones, deal with the following electrophysiological signals: electroencephalography, brain’s electrical activity measured with electrodes placed on the scalp electrocorticography , electroencephalographic signals measured directly with electrodes placed on the surgically exposed cerebral cortex; local field potential , electric potential measured around the neuron’s extra cellular space; and neuronal action potential , rapid and temporary change in the neuron’s membrane potential. Before being presented to the next BCI com ponent, the captured brain signals undergo filtering, amplification, and digitization . The overall performance of the BCI system depends heavily on the quality (signal-to-noise ratio) of the acquired brain signals. Depending on the signal acquisition method, BCI can broadly be categorized into two types: invasive (electrodes implanted under the scalp to record signals directly from the brain) and non-invasive (electrodes implanted on the scalp). Invasive BCI provides a more accurate reading of brain signals, but requires surgery; non-invasive BCI does not require surgery, but suffers from weak brain signals (poor signal-to-noise ratio) that require expensive amplification hardware and sophisticated signal processing techniques.

Signal processing:

Feature extraction:

In this stage, the BCI system extracts critical electrophysiological features from the acquired signals to define brain activities, and hence encoding of the user's intent . Similar to the previous stage, feature extraction should be executed accurately, ensuring that the features reflect high correlation with the user's intent to enhance the effectiveness and performance of the BCI system. Typical BCI systems employ time domain or frequency-domain features that take different characteristics: amplitude or latency of event-evoked potentials (e.g., P300), frequency power spectra (e.g., sensorimotor rhythms), or neuronal firing rates . Therefore, before designing the BCI system, the domain transform and characteristics of features should be established. Also, confounding artifacts contained in the features that can negatively impact the subsequent stages of the BCI system should be eliminated.

Feature classification:

The extracted features represent brain activities intended for desired actions. The classification process helps to recognize patterns of the features corresponding to these actions. For example, we can recognize features representing an instruction for moving a robotic arm. This component is usually implemented using machine learning and classification methods.

Feature translation:

In this signal processing stage, the classified features are translated and transformed into actual commands to operate an external device (BCI application). Examples of the outputs given after feature extraction include commands for cursor movement on the computer screen, volume control on the audio device, or text writing. One important attribute of an algorithm for feature trans lation is adaptability [55, 56]: ability of the translation algorithm to adaptively track changes of the features and generate an appropriate output.

BCI application:

Feature translation generates commands that can control external devices (BCI applications): cursor for letter and text selection on the computer screen , wheelchair , and robotic arm . For BCI restoration problems, the control signals from the BCI application may be transmitted to the brain or other body organs.

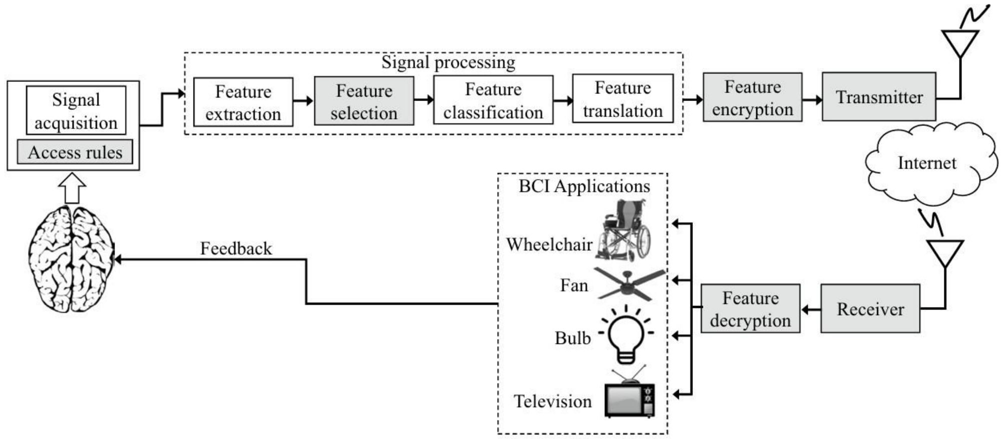


Fig. 6 Brain–computer interface (BCI) system with encryption and decryption components for enhancing privacy

FIGURE 5.1: Brain-computer interface system with encryption and decryption components

5.2 Trend of BCI research

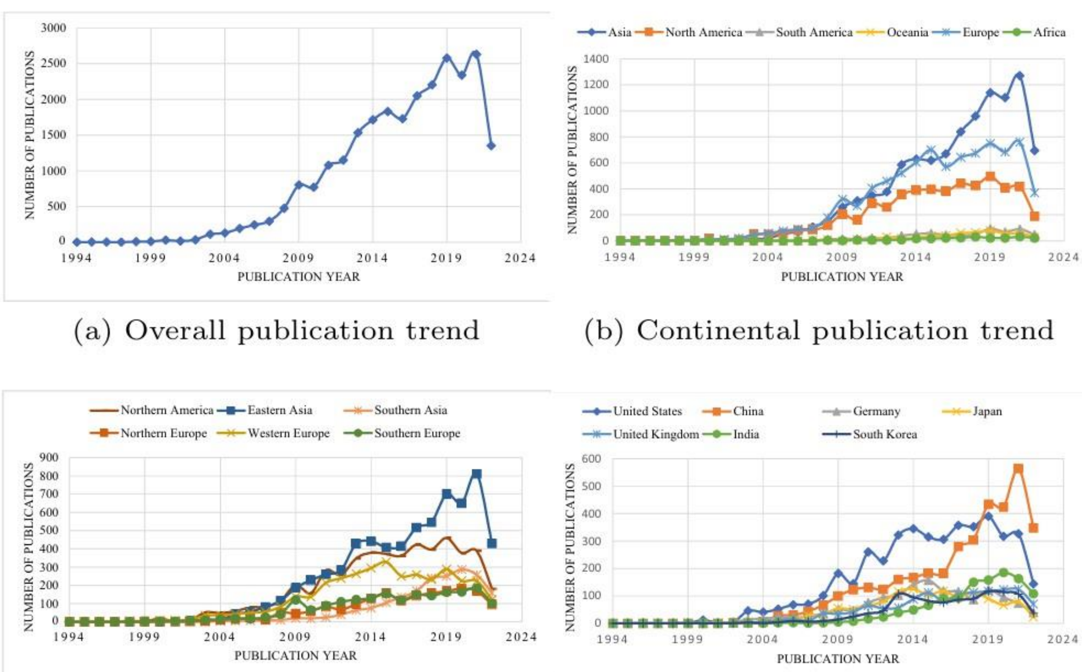
In analyzing the trend of BCI research, we, on 26 August 2022, extracted metadata of 25,336 publications from Scopus.1 The search string used was “brain computer interface” that, as per the Scopus research rules, includes other similar string variations: brain-machine interface; Brain Computer Interface; Brain-Computer Interfaces; Brain-computer Interface; Brain Machine Interface; Brain-computer Interface (BCI); Brain Computer Inter faces (BCIs); Brain-computer Interfaces; Brain-machine Interface; Brain Computer Interface (BCI); and Brain Computer Interface. Next, some publications incorrectly classified as related to BCI were omitted. In our extended dataset,2 all the extracted metadata were organized into continents, regions, and countries3 for analysis. The VOSviewer4 served a purpose of organizing and analyzing the bibliographic networks of the investigated BCI publications.

Our analysis reveals that the BCI field has constantly been evolving over the years, with publications ranging from theories and fundamental principals to practical applications. Studies demonstrate that BCI may significantly improve the quality of life for physically challenged people . Given its broad applications in many fields, researchers have invested more time to address practical challenges in BCI systems. Analyzing previous BCI studies, we have observed an exponential growth of the BCI field to date .Within a 5-year interval (between 2016 and 2021), for instance, the number of BCI publications increased steadily by approximately 1.5 times. This trend suggests an increasing demand of BCI to the scientific and general community, an indicator calling for a need to conduct advanced BCI research.

The Eastern region, has generated more BCI publications over the years. China demonstrates a steadily growing trend of the publications on brain–computer interface, topping other countries from 2019 onwards .This interesting trend may be caused by an increased research funding and support by the China government to undertake advanced research . In the Made in China 2025 strategy, China has established ambitious plans to become a leading superpower by 2049. The strategy, coupled with a higher population size and an increased number of academic and research institutions, could be a driving factor for China to achieve a remark able achievement in BCI research.The United States, however, remains a leading country in terms of the overall number of BCI publications .Given the higher technological and economical muscle of the United States, this observation would be expected. Perhaps an intriguing question for future inquiry would be on why the number of BCI publications for this country started to decline from 2019 onwards. One way that the United States may improve the trend of BCI publications is to promote co-authorship with Chinese universities and research institutions

Africa lags behind in BCI research , generating only 0.95% of all the BCI publications globally. This small proportion may be attributed to insufficient funding for supporting and advancing BCI research. Funding organizations may need to observe Africa as a potential continent for BCI research. With an estimatedmately three times that of Europeand with more than 2,000 universities and institutions,7 Africa can significantly contribute in BCI research. The methods and results from studies on BCI can improve the quality of life for millions of Africans. According to statistics from the United Nations, more than 80 million people in Africa are disabled, including those with severe mental health conditions and physical impairments that may be benefciaries from BCI results. Therefore, supported by funding organizations and governments, African researchers and innovators should exploit the capabilities of BCI technology to address the existing practical challenges in Africa. Another possible reason causing low number of BCI publications in Africa could be the inadequate level of technology to undertake BCI research that requires advanced equipment and complex infrastructure. Collaboration with the developed world, especially China and United States, in undertaking BCI research may be an effective and a feasible strategy for Africa to achieve the desirable output in BCI research.

Generally, the BCI research opens up several interesting problems that demand attention within the scholarly community. Our study discovered that countries address the BCI problem differently depending upon their local contexts. For example, while BCI studies from developed countries focus on the industrial applications of the technology, those from developing countries mostly deal with how the technology contributes in improving life quality of humans (e.g., increasing life expectancy). United States and China, which have shown significant advances in BCI research, provide promising prospects of BCI in the fourth industrial revolution with, however, a serious concern of the potential threats that the technology may impose if misused. These countries have, in fact, practically applied BCI in the real-world to advance humanity. Critically analyzing metadata of the 25,336 reviewed articles, we observed sophisticated BCI research laboratories that generates results with positive practical impacts. Developing countries, such as those in Africa, lack a support infrastructure for BCI research.



(a) Overall publication trend (b) Continental publication trend

(c) Regional publication trend (d) Publication trend per top countries

Fig. 2 Evolution of brain–computer interface publications. (Data collected from Scopus on 26 August 2022.)

FIGURE 5.2: Evolution if BCI Publication

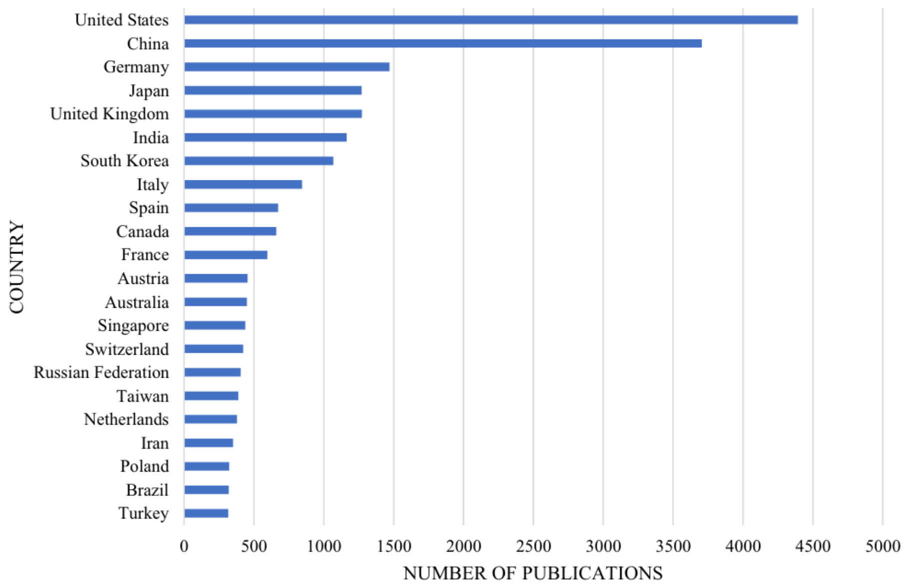


Fig. 3 Number of publications on brain–computer interface per country. (Data collected from Scopus on 26 August 2022.)

FIGURE 5.3: Number of Publication on BCI per country

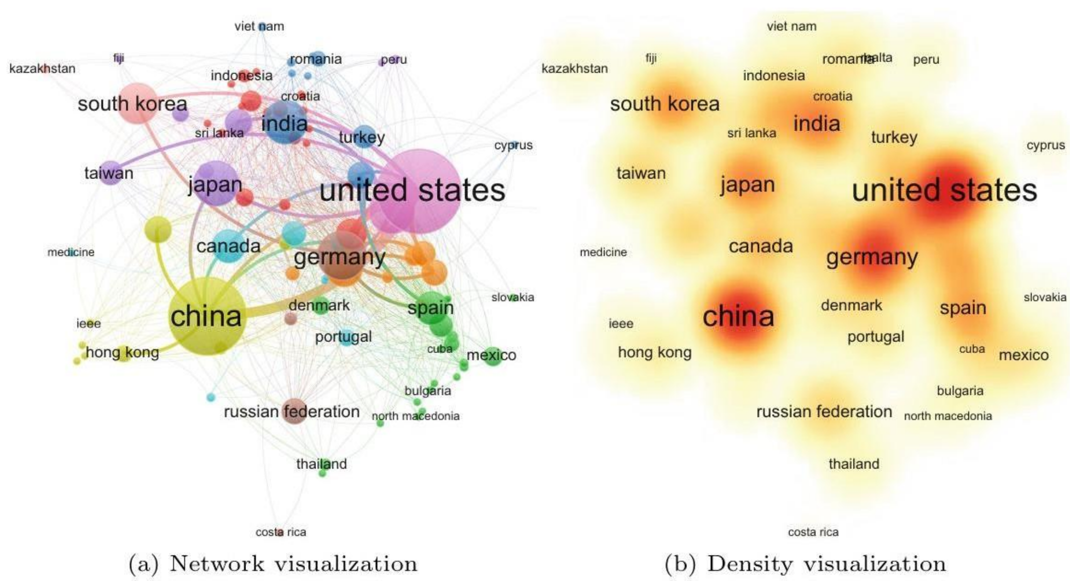
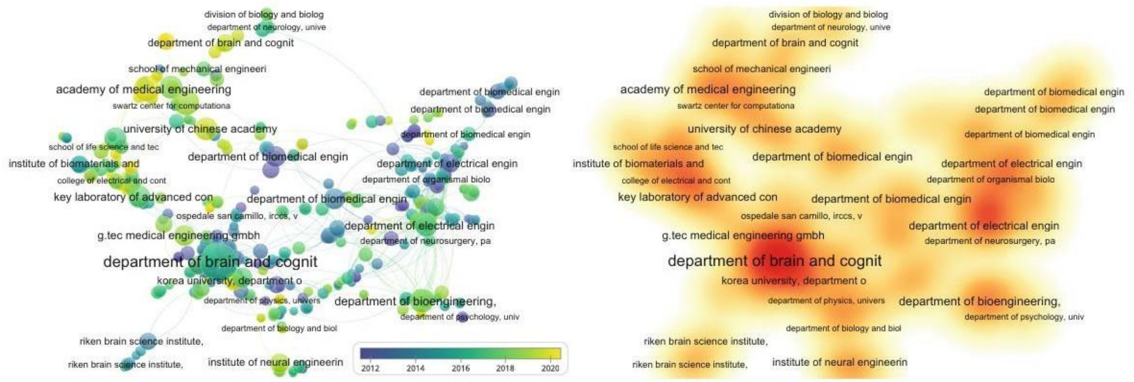


Fig. 4 Collaboration network among countries based on publications in brain–computer interface

FIGURE 5.4: Collaboration network among countries based on publication in BCI



(a) Network visualization (b) Density visualization

Fig. 5 Collaboration network of organizations supporting research on brain–computer interface. (Data collected from Scopus on 26 August 2022.)

FIGURE 5.5: Collaboration network of organization supporting research on BCI interface

5.3 Challenges and potential threats of brain computer interface

The BCI technology, despite its broad applications, poses threats to humans that need to be addressed. As we strive to make the technology friendly and useful, researchers should develop BCI applications that resonate with the standard principles of humanity. In essence, a better technology should enhance our lives while considering human factors, including convenience, ease-of-use, privacy, security, and safety . Before adopting the BCI technology for use by the community, researchers and practitioners are obliged to engage users and ensure that the technology has passed predefined quality standards.

- **Privacy :**The discussion emphasizes the privacy challenges in Brain-Computer Interface (BCI) technology, highlighting the absence of specific development standards, which leads to BCI applications potentially accessing and extracting sensitive user information without their awareness. To address these concerns, the authors propose establishing standards for acquisition methods, access control, and encryption techniques, and they also hypothesize a functional BCI model that incorporates privacy and security measures. This model includes predefined access rules, feature selection to retain relevant information, encryption of control commands for network transmission, and a feature decryption block, aiming to prevent unauthorized access and protect user safety.
- **Security:** The field of BCI has made a significant progress in the development of medical applications and products to improve the patients’ quality of life (e.g., restoration of damaged sight or hearing) . However, given the increasing demand for BCI-internet

communications, security concerns have emerged . The advancement of brain–computer interface creates opportunities for cyber attackers to intervene in the normal operations of the BCI application . The attackers may alter commands derived from the feature translation component and cause adverse effects to the target subject. Therefore, researchers should investigate security threats and vulnerable BCI components that can be easily attacked, then find robust solutions.

- **Safety**: Safety concerns can generally be observed in invasive BCI types. Because of being implanted into the brain tis sue, invasive BCI can damage nerve cells and blood vessels, hence increasing the risk of infection. Additionally, the natural defence system of the body may reject the implant, treating it as a foreign entity (biocompatibility concern). Another safety concern of invasive BCI is the possible formation of scar tissue after surgery, a consequence that may gradually degrade the quality of the acquired brain signals. Addressing this challenge requiresa comprehensive knowledge on how the human body works and interacts with foreign matters. The knowledge should be used by BCI scientists and engineers to develop safe and quality BCI applications. This knowledge should, in addition, equip neurosurgeons with more accurate information on specific brain regions to implant BCI electrodes.
- **Ethical, legal, and social concerns:**The BCI research raises a number of ethical, legal, and social concerns on privacy, security, safety, accountability, and accessibility [118]. The society would prefer the BCI technology that addresses their questions. For example, should people be concerned by privacy and security of the BCI applications? Does the technology guarantee safety? Does the society get equal access to the technology? In a situation of negative technological or technical impacts, who will be accountable and what are the legal implications? These questions require careful considerations and further research before administering this technology to the society.
- **Convenience and flexibility:** Most BCI applications require calibration data to reverse undesirable changes caused by neural plasticity or micro movements of the electrode arrays . This necessity calls for frequent decoder retraining, an inconvenient and time-consuming process that unnecessarily burdens the user. Willett et al. highlight the challenge in their seminal work on brain-to-text communication through handwriting. Despite the promising performance achieved by the authors' model, daily decoder

retraining was unavoidable. Future studies may investigate more effective techniques for decoder training without physically engaging the user. In essence, the BCI applicationshould operate adaptively with respect to the stochastic changes in the neural activities of the brain. Automatic self-calibration approaches may be employed to update operation of the BCI application accordingly, hence promoting convenience and flexibility.

- **Multidisciplinarity:** The BCI field involves multiple disciplines that should be linked to establish advanced principles and more effective BCI applications. In our analysis from Scopus, we observed that some important disciplines have not been adequately engaged in the BCI research . For example, only 1% of the BCI-related publications originate from psychology, a discipline dealing with study of human mind and behavior. Psychology, when combined with other disciplines, may provide a milestone to develop even better and practical BCI systems that can revolutionize humanity positively. Establishing research teams from varied disciplines may require strategic plans and funding, but such multidisciplinary teams are important to fully harness the BCI promising capabilities.
- **Big data:** The brain stores an enormous amount of information serving different human tasks. In addition, this central body organ generates a vast amount of electrical signals that control, monitor, and regulate human activities. Evidently, BCI raises a big data problem that needs sophisticated techniques to address. Unfortunately, because of insufficient knowledge on the brain working principles, BCI researchers may not have collected and utilized all the brain data and signals. Researchers need to understand key neurological features, including neuroplasticity that flexibly allows re-organization of neurons in learning or injury recovery . In non-invasive BCI, researchers should determine resolution of the electrode network on the scalp for optimal collection of brain signals. Similarly,invasive BCI requires electrodes optimally positioned under the scalp.
- **Availability of participants for clinical trials:** The passage discusses the challenges of deploying Brain-Computer Interface (BCI) technology, particularly in developing countries where awareness of its benefits and drawbacks is limited, potentially hindering clinical trials due to difficulties in recruiting participants who can provide informed consent. While some progress has been made with clinical trial approvals and ongoing

initiatives, the number of participants remains insufficient for global generalization. The authors advocate for diversifying clinical trials across different countries, considering cultural factors, and emphasize the need for studies examining societal acceptance of BCI technology, urging developers to incorporate human behavioral factors into the design of these devices.

- **Battery lifetime:** Implantable BCIs require materials that can sustainably operate over longer periods of time, preferably decades, without deterioration . The warm aqueous nature of our brains, however, affects the power retention capability of the implants. Water (cerebrospinal f luid), being a powerful solvent, gradually corrodes the insulating materials of the electrodes. Over time, short circuits may be created, increasing crosstalks between electrodes. This challenge reduces battery lifetime and limits the amount of signals collected by electrodes. Researchers need to study different insulating materials to understand how they interact with the brain relative to the BCIs battery lifetime. In addition, computation ally efficient algorithms should be developed to ensure optimum utilization of battery power. Even more importantly, alternative energy sources (e.g., micromovements inside the brain) for powering implantable BCIs should be investigated.
- **Affordability and portability:** Commercially available BCI devices can hardly be afforded by the general public because of their prohibitively high costs , perhaps due to their sophisti cation and construction materials. Also, the current BCI systems are complex and bulkier, making them suitable only in laboratory and industrial settings. Researchers should develop cost-effective and portable BCI systems for ordinary people, potential users of the technology. This solution will be more useful for people in developing countries.

CHAPTER 6

RESULTS

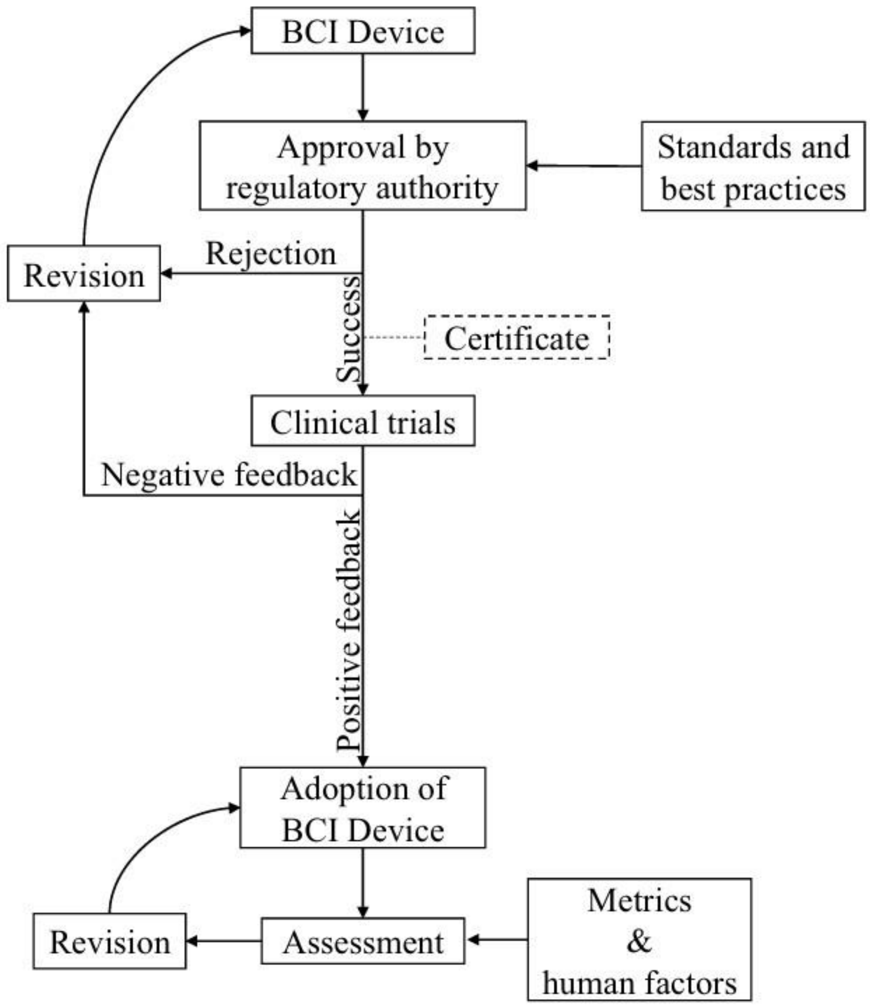


Fig. 8 Proposed procedures for practical administration of brain–computer interface devices

FIGURE 6.1: Proposed procedures for BCI devices

6.1 Applications and future of brain–computer interface

In this contemporary society, scientists and engineers have been striving to apply advanced technologies in improving quality of human life [144]. Of the available technologies, BCI has gained considerable attention in medicine for its ability to restore emotional and physical strength of people with missing or damaged body parts.The BCI technology allows physically challenged people to control machines using their thoughts. This advantage gives such people arevealing experience to interact with the external environment and accomplish different activities without dependence from healthy people. The BCI field is moving fast with a number of promising outcomes that can significantly improve human lives. Researchers require regular updates to address challenges hindering further advancement of the BCI technology. More importantly, given the multidisciplinary nature of brain–computer interface, scientists and engineers should work together to develop new and advanced BCI applications. Recently, the technology has found numerous industrial merits in a range of fields, including mining and education. Combined with fourth industrial revolution, researchers have demonstrated that BCI may accelerate the evolution of robots and neurophysiological discoveries [98, 99, 150]. Other applications of the BCI technology include decoding of thoughts, extension of human memory, telepathy communication, automation and control, intelligence sharing, brain energy harvest ing, and optimized (targeted) treatment of damaged body parts.

- **Decoding of thoughts:** The development of BCI raises questions about its capacity to accurately translate thoughts into text, measure translation accuracy, map imagination into real objects, decode dreams, create wearable thought-monitoring devices, extract a dying person's will, and control devices like printers directly from the brain. The study anticipates future BCI developments that may enable direct mapping of human thoughts into physical objects and allow individuals, especially those with disabilities, to control machines remotely with their thoughts. However, this advancement necessitates addressing critical security and privacy issues through robust regulatory standards.
- **Extension of human memory:** The passage explores the potential of BCI to realize the concept of uploading the human mind, inspired by Stephen Hawking's theories, by investigating the extraction and decoding of memory signals for computer storage. It also discusses the possibility of BCI being used to harvest human behaviors and traits for research, emphasizing the need for strict ethical guidelines. Envisioning future applications, the text suggests the development of portable memory devices for BCI to extract or introduce information into the brain, highlighting the potential benefit for fields like counseling psychology, where detailed behavioral and trait information could enhance the effectiveness of advice and conclusions, but stresses the necessity of intensive multidisciplinary research to achieve these advancements.

- **Intelligence sharing:** Can the BCI, in conjunction with the CBI, help to repro gram the brain, hence allowing sharing of intelligence between individuals? Although it may be imagined as a fiction, the fundamental principles of the technology suggest that brains may be reprogrammed artificially. Achieving this milestone, however, requires solid under standing on the nature and functioning of our brains—a stage that has not been reached by the current state of knowledge.
- **Brain energy harvesting:** The human brain takes only 2% of the body's mass and, for an average adult in a normal state, consumes 20% of the whole body energy budget to execute its activities . This proportion of energy consumption makes it the third most energy-hungry body organ . We hypothesize that the BCI technology may be combined with other advanced technologies to harvest portion of this enormous amount of energy for powering low energy external devices. Studies are needed to realize the idea, investigating how much energy can a typical BCI system harvest from the brain.
- **Localized brain–computer interface**: In BCI, the process of brain signals acquisition is not discriminatory. Virtually, the electrodes acquire all the available signals within the vicinity of its location (under or on the scalp). Consequently, a huge amount of signals and noise are collected for a single intended task (e.g., movement of the artificial leg), making the processing of such signals rather difficult. We can, however, tap the specific signals intended to control a targeted body part by localizing the BCI system. For example, considering a person with speech problems, the BCI system may be placed in an area that directly receives speech control signals from the brain. This advancement may improve the performance of the BCI system and reduce its size.
- **Telepathy communication:** The passage discusses the potential of BCI, combined with computer-brain interface (CBI), to enable telepathy communication, allowing individuals to communicate without physical interaction. This integration forms the brain-brain interface, a field still in its nascent stages, with future research expected to explore applications in various scientific and engineering domains. The text suggests investigating how human brains could be interconnected via the Internet of Things (IoT) to enhance information exchange, acknowledging existing research on BCI-IoT interfacing but highlighting the need for further exploration of brain-IoT network integration, as well as the combination of BCI-IoT with other communication

modalities, all while emphasizing adherence to ethical principles.

- **Automation and control:** The promising developments in BCI suggests that the technology may be useful in automation and control industries . Currently, BCI has received a significant deal of attention in home automation and control . In this scenario, the technology assists physically challenged people to automate their daily home activities, making it possible for such people live independently. As the technology advances, we expect positive impacts of BCI in the industrial manufacturing processes. In essence, researchers may attempt to investigate the role of BCI in the fourth industrial revolution . For instance, the BCI application may be connected over a secure wireless network to automate processes in the manufacturing industry. Considering sophistication and rapid development in the sensor technology, BCI may be applied in non-contact control and automation industrial systems. This research direction requires intensive investigation to overcome inherent limitations of the BCI technology and ensure seamless interaction with intelligent sensors.

CONCLUSION

To fully harness the potential of Brain-Computer Interface (BCI) technology and maximize its usability across society, a concerted multidisciplinary effort is essential, requiring researchers and scientists to proactively address the inherent challenges and potential threats associated with its implementation. This collaborative approach necessitates integrating expertise from five key research directions: cognitive psychology, which provides the foundational understanding of brain function; medicine, which addresses the clinical applications and health implications of BCI; biomedical electronics, which focuses on developing advanced signal acquisition devices; signal processing, which creates algorithms for effective brain signal analysis; and engineering, which translates BCI principles into practical applications and establishes performance standards. Such interdisciplinary collaboration will enable researchers to effectively tackle the sub-challenges within each BCI component, ensuring a holistic and robust development process. The contributions from psychologists and medical doctors are crucial for elucidating the fundamental working principles of the brain, while scientists are responsible for creating effective signal acquisition technologies and algorithms for processing brain signals—encompassing extraction, classification, and translation of relevant features. Finally, engineers play a vital role in developing tangible BCI applications and establishing rigorous standards for their evaluation.

To maximize the benefits and usability of BCI technology, a multidisciplinary collaboration is crucial, integrating expertise from cognitive psychology, medicine, biomedical electronics, signal processing, and engineering to address potential threats and advance BCI components; this involves psychologists and medical doctors providing the foundational understanding of brain function, scientists developing effective signal acquisition technologies and algorithms for processing brain signals, and engineers creating practical BCI applications with rigorous evaluation standards. Despite BCI's promise, significant challenges and threats remain, including limited and undiversified clinical trial participants and a lack of global safety and quality standards, necessitating intensive and diverse research efforts before widespread societal adoption; therefore, future work, as outlined by the authors, will focus on developing computationally efficient algorithms and accuracy measures for the signal processing component, aiming to contribute to the establishment of universally acceptable evaluation standards for BCI applications.

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