Literature Review on The Future of Brain-Computer Interfaces: Are We Ready for the Next Stage of Human-Computer Interaction?

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I. Introduction

In January 2024, Neuralink reached a significant milestone by implanting its N1 chip in a quadriplegic patient, Noland Arbaugh, which allowed him to control digital devices with only his thoughts [?]. Brain-Computer Interfaces (BCIs) are rapidly transforming the field of Human-Computer Interaction (HCI), enabling direct communication between the brain and external devices. These advances hold significant promise, particularly in healthcare care, where BCIs can restore mobility and communication for people with neurological disorders. Recent developments, such as Neuralink's successful implantation of its N1 chip into a quadriplegic patient, illustrate the increasing viability of BCIs in both medical and consumer applications. However, as this technology progresses, it raises important ethical, societal, and psychological questions: are we ready for a world where thoughts can control machines? What risks accompany the widespread adoption of BCIs? Should the development of BCIs be regulated or limited?

This literature review examines the future of BCIs by evaluating their current state, societal readiness, cognitive and psychological implications, and ethical concerns. The review is based on a selection of articles, conference papers, industry reports, and reputable news sources. The sources were chosen for their relevance to key themes, including medical applications, social perception, technological advancements, and regulatory challenges. Certain limitations should be noted. First, this review focuses on both non-invasive and invasive BCIs in medical and consumer applications but does not explore speculative or purely theoretical discussions of BCI technology. Additionally, while it examines ethical and legal challenges, it does not provide a detailed legal analysis. Instead, it highlights key debates and emerging regulatory frameworks. By reviewing and evaluating existing research, this review aims to determine whether society is truly prepared for this next stage of human-computer interaction.

II. Review

My review structure is [**Thematic**]

A. The Evolution and Current State of Brain-Computer Interfaces

1) A Brief History of BCI Development: The origins of brain-computer interfaces (BCIs) date back to Hans Berger's 1929 discovery of brain electrical activity using electroencephalography (EEG) [?]. However, BCIs as we know them today began to emerge in the 1970s, when Jacques Vidal in 1973 [?] demonstrated real-time EEG signal processing, laying the foundation for non-invasive BCIs.

By the 1990s, BCIs were applied in medicine, particularly for patients with ALS and locked-in syndrome. Early systems allowed users to spell words using P300 brainwave responses, offering a breakthrough in communication for paralyzed individuals [?].

Invasive BCIs gained attention in the 2000s, as studies showed that implanted electrodes could enable direct brain control of robotic limbs [?]. The BrainGate system [?] was a major milestone that allowed paralysis patients to move a cursor and control prosthetic devices using only neural activity. Non-invasive BCIs continued to advance, integrating functional near-infrared spectroscopy (fNIRS) to improve signal accuracy and reliability [?]. However, early BCI systems faced challenges such as low signal resolution, slow processing speeds, and limited real-world use.

2) Current Advancements in BCI: In medical applications, modern BCIs are revolutionizing neuroprosthetics, enabling individuals with paralysis to control robotic limbs and computers [?]. Systems like BrainGate allow direct thought-based control, while wireless implants reduce surgical risks. BCIs also support epilepsy treatment through closed-loop neurostimulation, helping prevent seizures. Stroke rehabilitation BCIs promote neuroplasticity, aiding in long-lasting arm motor recovery [?].

In consumer and industry applications, beyond medicine, BCIs are entering gaming, smart home control, and workplace productivity. EEG-based systems enable hands-free device interaction, while military research explores brain-controlled drones and cognitive enhancement. However, there are some ethical concerns related to this, including privacy risks and cognitive enhancement [?].

Some challenges and limitations of BCI applications are that they may access and extract sensitive neural information without the explicit consent of users, raising significant privacy issues [?]. Additionally, implantable BCIs require long-lasting power sources, but the brain's environment can cause battery performance to decline over time.

Although BCI technology is advancing rapidly, key challenges remain in accuracy and real-world usability. Addressing these issues will be vital for safe and widespread adoption.

B. The Future of BCI in Society: Are We Ready?

Beyond technical challenges, the success of BCIs will also depend on public perception and social readiness. While researchers continue to improve BCI accuracy and usability, societal acceptance remains a crucial factor.

1) Public Perception and Social Readiness: Public sentiment toward brain-computer interfaces is complex, balancing optimism with apprehension. A decade-long analysis of social media discussions on Twitter found that 59.38% of posts about BCIs were neutral, 32.75% were positive, and only 7.85% were negative. Notably, anticipation (20.56%), trust (17.59%), and fear (13.98%) were the dominant emotions expressed in these discussions [**?**]. While this suggests a generally balanced public perception, the methodology of the study should be scrutinized. The reliance on Twitter data introduces potential biases, as social media does not necessarily represent the views of the broader population. Additionally, sentiment analysis tools may misinterpret cultural context and nuanced opinions, affecting the accuracy of results. Future studies using survey-based or qualitative methods may provide a more comprehensive understanding of public sentiment toward BCIs.

Cultural and philosophical beliefs significantly influence public opinions on BCI technology, leading to variations in acceptance across different regions. A study focusing on the Chinese general public identified key factors affecting BCI acceptance, including age, health, socioeconomic status, social support, and learning ability. Notably, younger individuals with higher socioeconomic status and better health showed greater acceptance of BCIs, highlighting the impact of cultural and demographic variables on technology adoption [**?**].

Ethical debates surrounding BCIs focus on their potential use in enhancing intelligence, memory, and focus, which could create unfair advantages in education, business, and military applications. Public trust in BCIs is significantly influenced by their intended use, with medical applications being more widely accepted than non-therapeutic cognitive enhancements. A February 2025 survey of 806 participants found strong interest in BCIs for medical purposes, such as stroke rehabilitation and paralysis treatment, but also high ethical concerns [**?**]. Notably, 98% of respondents expressed concerns about implantation risks, and 92% were worried about costs, highlighting fears that BCI technology could exacerbate social inequalities. These findings align with earlier research conducted in China, which showed that socioeconomic status and health conditions play a key role in BCI acceptance [**?**]. Together, these studies suggest a global trend where BCIs are embraced for medical interventions but face resistance when associated with cognitive enhancement or commercial applications. Future research should explore whether these attitudes shift as the technology becomes more mainstream.

These findings emphasize the need for clear regulatory frameworks and educational initiatives to improve public understanding and ensure that BCI development aligns with societal values and expectations.

2) The Digital Divide and Accessibility: The advancement of BCI technology prompts concerns about increasing societal inequalities. Economic disparities may lead to a scenario where only wealthier individuals can afford cognitive enhancements, potentially widening existing social gaps. Moreover, geopolitical variations in BCI development could result in unequal access across different regions. For example, individuals who live in rural or remote areas may not have access to the necessary infrastructure or resources to support the technology, creating a geographical divide [**?**].

Addressing these challenges requires collaborative efforts among policymakers, technologists, and ethicists to ensure equitable access and to prevent the deepening of the digital divide between people as BCI technologies evolve.

C. The Psychological and Cognitive Impacts of BCI

1) Effects of Long-Term BCI Use on the Brain: BCIs have the potential to enhance neuroplasticity, allowing the brain to reorganize and form new connections. Studies indicate that BCI applications can lead to functional improvements, particularly after strokes, by altering neurophysiological parameters [**?**]. This suggests that BCIs may support rehabilitation by helping the brain naturally rewire itself after neurological damage.

However, despite these benefits, BCIs also present challenges; direct neural control facilitated by BCIs may raise concerns about cognitive overload and mental fatigue. Users may experience psychological harm when their intentions are not accurately realized by the BCI system, leading to frustration and mental strain.

Due to factors such as ethical considerations, technical challenges, and the relatively recent development of the technology, research on the long-term effects of BCI use is ongoing. Some studies show that BCIs can cause immediate changes in the brain after short-term use [**?**]. However, there is little data on their long-term effects. More research is needed to understand how prolonged BCI use might impact brain perception and cognition.

2) Mental Privacy & Psychological Risks: BCIs pose significant ethical concerns regarding mental privacy. The potential for decoding, manipulating, and unauthorized access to an individual's thoughts raises questions about cognitive liberty and the right to mental self-determination. As BCIs become more advanced, the risk of "brain hacking" or external influence over brain activity becomes a greater issue. According to experts, society is not yet equipped with the legal and ethical regulation needed to fully protect individuals from these risks [**?**]. The lack of clear regulations on neural data ownership and security raises concerns about whether users can maintain autonomy over their own thoughts. While neurotechnology offers promising advancements in medical and assistive applications, public trust in BCI adoption when it comes to mental privacy will likely depend on robust policies ensuring consent and protection against potential exploitation.

Integrating machines into the human brain, such as through Deep Brain Stimulation (DBS), can profoundly impact personal identity. Users might experience changes in self-perception, leading to feelings of self-estrangement or alterations in personality. For instance, a study published in Bioethics discusses how DBS, designed to improve motor, mood, and behavioral pathology, presents unique challenges to our understanding of identity, agency, and free will [?]. The study shows that these devices can have visible effects on individuals' physical and psychological properties, potentially leading to significant implications for personal identity. These findings underscore the complex relationship between neurotechnological interventions and personal identity, highlighting the need for careful ethical considerations in the future of BCI technologies.

There is also a concern that users could develop psychological dependence on BCIs, leading to potential "addiction" to neural control. The reliance on BCI technology for cognitive enhancement and daily functioning may result in diminished autonomy and increased vulnerability.

D. Ethical Concerns and the Need for Regulation

1) Key Ethical Issues in BCI Development: The integration of brain-computer interfaces raises significant concerns regarding cognitive surveillance and potential privacy violations. Unauthorized access to neural data could lead to unprecedented interference and alterations of individuals' mental thoughts. This necessitates robust legal frameworks to protect mental privacy.

BCIs blur the line between human autonomy and AI-driven decisions. As these interfaces become more integrated into daily life, ensuring that AI augmentation does not compromise individual autonomy is crucial. The Institute for Ethics in AI at the University of Oxford emphasizes the importance of ethical frameworks that preserve human agency in the face of advancing AI technologies.

2) Should We Regulate or Limit BCIs?: One of the primary arguments for stricter regulation of brain-computer interfaces is the need to prevent brain hacking and unauthorized neural manipulation. With the rise of neurotechnology, there is a significant risk that individuals' cognitive data could be accessed, altered, or even hijacked. Furthermore, the protection of mental privacy and personal identity is another critical reason for regulating BCIs. As neurotechnology advances, the potential for breaches of mental privacy becomes more pressing. BCIs could be used to not only access brain activity but also to alter an individual's thoughts and perceptions, which could then lead to a loss of self-identity. The European Parliament has highlighted these concerns in its reports, advocating for clear legal measures to safeguard citizens' neural data [?]. These regulations would help mitigate the risk of personal identity alteration and ensure that neurodata is handled with the utmost privacy and respect.

Additionally, implementing ethical and equitable regulations ensures that BCIs are used responsibly and fairly. Without them, neurotechnological advancements could increase existing social inequalities, making access to BCIs available only to certain privileged groups. Comprehensive policies can promote the equitable deployment of BCIs, ensuring that they benefit society as a whole.

Some argue that heavy regulation of BCIs could hinder innovation, particularly in the medical field. Overregulation may delay or even prevent the development of BCIs that could cure neurological diseases and enhance quality of life for individuals with disabilities. Supporters of decentralized governance believe that industry self-regulation would provide more flexible and specialized management, making it easier to adapt to new challenges. The Institute for Ethics in AI at Oxford University has suggested that collaboration between industry players, ethicists, and stakeholders could help develop effective self-regulatory frameworks [?].

III. Conclusion

Brain-computer interfaces represent a major leap forward in human-computer interaction, offering groundbreaking possibilities in medicine, communication, and cognitive enhancement. However, despite rapid technological advancements, society is not yet fully prepared for their widespread adoption. This review highlights critical concerns—including ethical dilemmas, regulatory gaps, psychological risks, and accessibility disparities—that must be addressed before BCIs can be safely integrated into everyday life. While public perception is generally optimistic about medical applications, fears of monitoring of thoughts, identity alteration, and socioeconomic inequality still exist. Additionally, current legal and ethical frameworks struggle to keep pace with these innovations. Moving forward, ensuring that BCI technology develops responsibly will require interdisciplinary collaboration among researchers, policymakers, ethicists, and industry leaders. Without regulation and public education, BCIs may make existing societal inequalities worse rather than serve as a beneficial tool for society. The future of BCIs is promising, but whether society is truly ready for this next stage of human-computer interaction depends on how effectively we address these ethical and societal concerns.

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