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Reflections on the Applicability of Fundamental Bioethical Principles in Affective Brain-Computer Interfaces

Yumeng Yin

School of Philosophy, Beijing Normal University, Beijing, China
Email: y1nyumeng@163.com

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Abstract

In recent years, the research, development, and application of Affective Brain-Computer Interfaces (aBCIs) have advanced rapidly, demonstrating broad prospects across diverse domains. This paper examines how aBCI challenges informed consent, autonomy, privacy, non-maleficence, beneficence, and justice in clinical and consumer settings. It also considers the allocation of responsibility among users, clinicians, developers, manufacturers, and institutions when computational systems participate in affective inference or intervention. By examining the technical characteristics and potential effects of aBCI, the paper clarifies the contexts, functions, and limitations of applying fundamental bioethical principles to this field.

Keywords

Affective Brain-Computer Interface, Bioethical Principles, Implementation Difficulties

1. Introduction

Affective Brain-Computer Interface (aBCI) is a neurotechnology that establishes a direct communication pathway between the brain and external devices, enabling the detection, regulation, and intervention of affective states in subjects. It is being investigated in medical contexts, including experimental neuromodulation for treatment-resistant depression. However, aBCI technology also gives rise to a series of ethical issues, including: neural data security and personal privacy protection; the specificity of obtaining informed consent; and the potential impact of neuromodulation on subjective autonomy. Employing a bioethical analytical framework, this study systematically examines the potential risks in the applica-

tion of aBCI technology, with a particular focus on the challenges it poses to fundamental bioethical principles, thereby providing a theoretical basis for the establishment of a comprehensive ethical review mechanism and regulatory system for aBCI.

This paper distinguishes affective-recognition systems, neurofeedback, and invasive DBS, while including other neuromodulation methods only when neural sensing is connected to feedback or adaptive stimulation. Recognition systems remain largely experimental, the effects of neurofeedback vary across protocols and conditions, and psychiatric DBS remains investigational. These differences in maturity and invasiveness shape the ethical analysis that follows (Wu et al., 2023; Sobstyl et al., 2022).

2. Current Applications of Affective Brain-Computer Interfaces

At present, the clinical assessment of affective disorders such as depression relies primarily on self-rating and observer-rating scales. These assessments are subjective and provide limited temporal information. aBCI research explores whether EEG, fNIRS, or intracranial recordings can supply supplementary physiological information by identifying neural patterns associated with affective states. Current systems can classify such patterns under particular experimental conditions, but their accuracy varies across individuals, recording environments, emotion models, and validation procedures. They therefore remain experimental adjuncts rather than precise stand-alone mood monitors. At the application level, the functions of aBCI can be broadly summarised as affective recognition and affective modulation (Wu et al., 2023).

Affective recognition involves the identification of an individual's affective state by decoding neural activity patterns associated with emotions. Its research methodology is based on the classification of emotion labelling, establishing mapping relationships between specific affective states and neural signals (Koelstra et al., 2011). For example, the DEAP (Database for Emotion Analysis Using Physiological Signals) dataset developed by Koelstra et al. presents subjects with specific stimuli (such as audio clips) while simultaneously collecting their neural signals, subsequently constructing associative models. Through these correspondences, researchers can utilise neural activity signals to identify users' affective states. This recognition technology provides a novel avenue for emotional expression: for patients with severe motor impairments such as amyotrophic lateral sclerosis, the loss of speech and motor functions severely limits traditional channels of emotional expression (e.g., facial expressions, gestures, or language). In such clinical scenarios, Abci-based affective recognition technology can offer patients an alternative affective communication channel. Furthermore, affective recognition has demonstrated considerable potential in entertainment and consumer electronics. By integrating real-time emotion classification algorithms, researchers have developed interactive entertainment systems capable of dynamically adapting to users' affective states.

Affective modulation can be divided into neurofeedback and direct neuromod-

ulation. Neurofeedback presents users with information derived from neural activity and supports learned self-regulation. Direct neuromodulation, including Deep Brain Stimulation (DBS), applies stimulation to selected neural targets. A systematic review of subcallosal cingulate DBS for treatment-resistant depression reported promising but highly variable outcomes from a small and heterogeneous evidence base (Sobstyl et al., 2022). Personalised closed-loop stimulation has also produced a sustained response in one patient, a finding that requires replication in larger studies (Scangos et al., 2021). Psychiatric DBS therefore remains an investigational intervention rather than an established treatment for several psychiatric conditions.

3. Cognitive Barriers and Authorisation Misalignment in Informed Consent

The principle of informed consent is one of the core requirements of modern medical ethics, emphasising that patients should autonomously decide whether to accept treatment based on a full understanding of the risks, benefits, and alternatives of medical interventions (Zhai & Qiu, 2005). However, the complex technical characteristics and unique application scenarios of aBCI pose severe challenges to the traditional informed consent model. These are elaborated below.

First, users often lack the cognitive capacity to comprehend complex technologies. The primary target population for aBCI includes patients with mood disorders such as depression and anxiety, whose cognitive functions are frequently impaired by the disease itself. Patients with major depressive disorder typically exhibit reduced prefrontal cortical activity, leading to deficits in executive function, working memory, and decision-making capacity. This cognitive impairment makes it difficult for patients to fully understand the technical principles, potential risks, and long-term effects of aBCI. More complex still, the technology itself presents formidable cognitive barriers. aBCI systems typically rely on deep learning algorithms for real-time decoding of neural signals, followed by closed-loop regulation to adjust activity in target brain regions. The mathematical modelling underlying this process far exceeds the comprehension of the average patient. Even when medical personnel employ plain language in their explanations, patients may still be unable to form substantive understanding due to the "technology black box" effect. This cognitive disconnect renders informed consent often perfunctory.

Second, aBCI involves significant information asymmetry, which can readily lead to misunderstandings. Science fiction often portrays neurotechnologies such as aBCI as seamlessly integrated, fully controllable "human-machine fusions," whereas in reality, aBCI still faces technical bottlenecks including signal noise, device drift, and iatrogenic injuries. Such misrepresentations can easily distort users' assessments of technological risks and benefits. In clinical practice, this information asymmetry is further exacerbated by threefold obstacles: first, the exploratory nature of neuroscience makes it difficult to accurately predict the long-term

effects of aBCI; second, professional barriers create serious cognitive gaps—there is a substantial disconnect between the focal concerns of neuroengineering (such as "signal-to-noise ratio optimisation," "feature extraction") and those of ordinary users (such as "emotional authenticity"); finally, the inherent uncertainty of the technology and the proliferation of commercial applications further intensify the difficulty of risk disclosure. Non-medical aBCI devices often enter the market as consumer electronics, where the informed consent process is reduced to clicking a "user agreement," utterly failing to meet ethical requirements. It is precisely these various forms of information asymmetry that prevent users from developing accurate understanding of the technological principles and associated risks.

Third, surrogate decision-making creates a distinctive problem when severe illness impairs decision-making capacity. A guardian may authorise an invasive procedure on the basis of expected therapeutic benefit, while the patient may later regain capacity and evaluate continued stimulation differently. DBS can be adjusted, switched off, or removed, although implantation, deactivation, and explantation each involve clinical risks and consequences. Advance preferences, periodic capacity assessment, and a clear exit plan should therefore address device deactivation, possible explantation, symptom recurrence, and access to follow-up care.

Fourth, dynamic intervention creates tension with static consent. Traditional informed consent commonly relies on one-time authorisation, whereas closed-loop systems may alter detection thresholds or stimulation parameters as new neural data are collected. Initial consent should specify the permitted range of adaptation, material uncertainties, data uses, conditions for clinical review, and procedures for pausing or ending stimulation. Periodic re-consent is appropriate after substantial parameter changes, software updates, changes in decision-making capacity, or emergent adverse effects.

These four core challenges constitute the principal implementation obstacles to the principle of informed consent in the clinical application of aBCI. However, China's current healthcare system has not yet established a standardised institutional framework adapted to the technical characteristics of aBCI, with two prominent deficiencies: on the one hand, the traditional one-time written consent model cannot accommodate the real-time adjustment of aBCI intervention parameters and the long-term evolution of neural effects, resulting in a temporal-spatial misalignment between the consent process and the actual intervention. On the other hand, existing informed consent procedures fail to adequately account for the differential risk profiles across various aBCI application scenarios and the individual variability in patients' cognitive capacities. This standardisation deficit leaves the disclosed content either too specialised to be comprehensible or overly simplified to the point of losing substantive meaning.

4. Reshaping and Erosion of Autonomy through Affective Modulation

The original research and development objective of many clinical aBCI systems is

to relieve symptoms and restore capacities impaired by affective disorders. Their effects on cognition, behaviour, and self-experience may also alter the conditions under which autonomy is exercised. According to the three-component account of autonomy proposed by Beauchamp and Childress (2022)—intentionality, understanding, and freedom from controlling influences—an intervention may support one component while placing pressure on another.

First, aBCI can influence, obscure, or even alter the user's intentions. Intentionality, as a core element of autonomous action, requires that the actor's actions align with their subjective conceptions (Beauchamp & Childress, 2022). Affective states, as important modulators of cognitive activity, directly influence an individual's information processing efficiency, attentional allocation, and judgment and decision-making capacities. By modulating these emotion-related neural mechanisms, aBCI indirectly influences users' intentionality and ultimately participates in the shaping of user intentions.

From a technical implementation perspective, current aBCI emotion recognition systems face significant theoretical limitations; their quantitative representations of emotion are inadequate for precisely accommodating the complex and dynamic nature of human affective states. Mainstream recognition models primarily adopt two paradigms: first, discrete models based on Paul Ekman's basic emotion theory, categorising emotions into a limited set of classes (Koelstra et al., 2011); second, dimensional models based on a two-dimensional valence-arousal space. However, human emotional experience is characterised by a high degree of complexity and dynamism, encompassing both mixed basic emotions and modulation by cultural and individual differences. Empirical studies have demonstrated that, due to significant individual differences, the same stimulus can evoke different emotional responses across different subjects. More critically, emotion-related neural signals often overlap with non-affective neural activity, and establishing causal relationships with specific stimuli remains difficult. Such inaccuracies can compromise the fidelity of affective representation (Wu et al., 2023). When an aBCI system cannot achieve precise emotion recognition, a chain reaction ensues: the recognition bias propagates through the "emotion-cognition-decision" pathway, ultimately affecting the quality of users' autonomous decisions.

Second, aBCI may affect the subject's capacity for understanding. Patients with severe affective disorders can experience fluctuations in attention, memory, executive function, and decision-making capacity. Neurofeedback or stimulation may produce additional effects that vary by modality, target, parameters, illness, and individual response. Acute confusion, mood elevation, impulsivity, or other neuropsychiatric effects have been observed in some DBS settings. Current evidence supports repeated, person-specific assessment while leaving the possibility of durable cognitive or personality change unsettled (Sobstyl et al., 2022; Alemany et al., 2023).

Furthermore, long-term device use may create several forms of dependence. Users may become functionally reliant on stimulation for symptom control, insti-

tutionally reliant on specialist programming and maintenance, or psychologically reliant on the device as a means of emotional regulation. Interviews with psychiatric DBS recipients describe both restored agency and difficult adjustment (de Haan et al., 2015). Qualitative research with people living with DBS for Parkinson's disease also documents the practical importance of continued stimulation and specialist support (Hariz et al., 2016). Although this population differs from psychiatric aBCI users, the findings identify forms of device-related reliance that long-term follow-up should assess.

Third, aBCI can exert controlling influences over the subject. The degree of influence varies across modalities: affect recognition provides information, neurofeedback structures self-regulation, and DBS directly changes neural activity through stimulation. Its ethical significance depends on the intensity and predictability of the effect, the user's capacity to recognise it, the clinician's control over settings, and the possibility of interruption or revision. Qualitative evidence has documented stimulation-related neuropsychiatric symptoms in some DBS recipients, including changes in impulsivity and behaviour (Mosley et al., 2021). Such findings warrant monitoring, while the available evidence does not establish personality transformation as a general effect of aBCI (Gilbert et al., 2018; Sobstyl et al., 2022).

With respect to internal control, the modulatory effects of aBCI are more complex. Subjects who have been in extreme emotional states over prolonged periods cannot fully control their own emotional changes and bodily movements. Emotional changes lead to alterations in physical states, including the musculoskeletal, neuroendocrine, and autonomic nervous systems (Levenson, 2003). Neuroendocrine research has shown that prolonged extreme emotional states cause abnormalities in stress hormone levels such as cortisol; these physiological changes can induce various pathological behaviours, including non-suicidal self-injury (Zhang, 2023) and cognitive dysfunction (Chen et al., 2023). Moreover, aBCI interventions may disrupt pre-existing emotional regulatory balances, generating new internal controlling factors. Although aBCI was originally developed to eliminate the detrimental effects of extreme emotions, its use may also induce extreme emotions, thereby weakening users' control over themselves.

The principle of respect for autonomy remains applicable to aBCI, but its implementation requires modality-specific and longitudinal assessment. Ethical review should distinguish affective recognition from modulation, evaluate changes in decision-making capacity, document how algorithmic outputs influence choices, and preserve meaningful options to pause, revise, or discontinue use. Mental privacy and psychological continuity can supplement this analysis by identifying interests that conventional consent procedures may overlook.

5. The Deep Nature of Neural Data and the Breach of Privacy Boundaries

The principle of privacy protection stipulates that information holders shall nei-

ther disclose individuals' personal information nor improperly alter such information without the explicit consent of the information subject (Zhai & Qiu, 2005). However, aBCI technology poses unprecedented challenges to privacy protection. Unlike traditional medical data, neural data collected via aBCI possesses three distinctive attributes: the deep nature of raw data directly reflecting brain activity; the comprehensiveness of simultaneously containing both physiological and psychological information; and the predictivity of enabling algorithmic inference of potential psychological states. It is precisely this specificity that renders neural data collected through aBCI reflective of users' intentions, thoughts, and physical conditions—including elements that users may be unwilling to share with the outside world (Steinert et al., 2020). This data characteristic requires technology developers to establish rigorous data protection mechanisms. However, the current brain-computer interface research community has yet to develop a comprehensive privacy protection normative framework: researchers lack clear standards for the types of neural data to be collected, nor do they have uniform regulations regarding data storage duration; equally lacking are clear ethical guidelines concerning data preservation purposes and the scope of academic sharing (Rao, 2016).

The first concern is neural-data inference. Neural signals do not carry a self-evident emotional meaning; algorithms generate probabilistic labels by relating recorded features to training data and contextual assumptions. Such inferences may concern affective states, preferences, routines, or relationships. Their ethical significance depends on validity, bias, purpose, and the authority assigned to the result. Systems used in clinical, employment, educational, insurance, or consumer settings should therefore disclose uncertainty, validate performance in the relevant population, and provide a means of contesting consequential inferences.

The second concern is disclosure. Raw signals, affective labels, confidence scores, behavioural context, and longitudinal profiles may be shared with clinicians, researchers, relatives, platforms, employers, advertisers, or data processors. Clinical sharing may support care, whereas secondary commercial use may enable profiling, behavioural targeting, or discrimination. Data minimisation, role-based access, retention limits, restrictions on onward transfer, and separate permission for clinical, research, and commercial uses are therefore required.

The third concern is active affective modulation. When an inferred state triggers neurofeedback or stimulation, the system moves from processing information to acting upon the user's affective life. An inaccurate classification may prompt an unnecessary intervention, while an accurate classification may still support manipulation when the goal is selected without adequate authority. Ethical safeguards should include an agreed therapeutic or user-defined purpose, limits on automatic intervention, accessible records of triggers and parameter changes, and a practicable means of pausing the function. Consent to recording should not automatically authorise inference, disclosure, and modulation; each operation requires separate justification and permission.

6. Delayed Risks and Context-Dependent Benefits of Neural Intervention

The principle of non-maleficence requires avoiding and minimising unjustified harm, while the principle of beneficence requires promoting welfare and balancing prospective benefits against burdens and risks (Beauchamp & Childress, 2022). In bioethical practice, these principles are commonly considered together as the basis of risk-benefit assessment. Their application to aBCI depends on the modality, indication, and stage of technical development.

The first source of difficulty lies in uncertain and potentially delayed outcomes. Surgical and hardware complications of DBS can be monitored through established clinical procedures, while psychiatric outcomes and stimulation-related mood changes require extended observation. A multisite sham-controlled trial of subcallosal cingulate DBS did not demonstrate a significant antidepressant effect during the blinded phase (Holtzheimer et al., 2017). A later long-term cohort reported sustained improvement alongside adverse events and two suicides occurring long after surgery (Alemany et al., 2023). These findings support continuing psychiatric care and prospective monitoring of mood, cognition, impulsivity, self-experience, device function, and social adaptation.

Accompanying delayed harm is a more fundamental challenge: the blurring of the boundary between therapy and enhancement, leading to drift in risk standards. The effective application of non-maleficence and beneficence presupposes clear definitions of what constitutes "disease," what is "normal," and what is "enhancement." Yet aBCI straddles all three domains: at the therapeutic end, it is used to restore emotional function in patients with major depressive disorder, bipolar disorder, and other conditions that deviate from normal ranges; at the enhancement end, the same (or highly similar) technology can be employed to improve attention, stress tolerance, or social-emotional perception in healthy populations. Since the distribution of emotional and cognitive capacities is biologically continuous, there is no clear demarcation line between them. This ambiguity directly leads to inappropriate drift in risk-benefit assessment standards. In therapeutic contexts, when facing suicide risk or loss of social function due to severe affective disorders, the overall benefits of intervention may still outweigh the risks even when possible cognitive side effects and uncertain long-term neural effects must be considered. However, when the same technology is applied to subclinical populations or entirely healthy consumers, risk levels that were previously acceptable suddenly become unacceptable. Yet in commercial promotion practices, this boundary is frequently deliberately blurred, with efficacy for pathological conditions being marketed as capacity-enhancement solutions for the general public, exposing consumers to unnecessary neural interventions that have not undergone adequate risk assessment. In this context, the non-maleficence principle loses an important line of defence; it cannot function independently and must rely on clear technology use classification and regulatory labelling to regain operability.

Beneficence also requires attention to the patient's overall welfare. Symptom

reduction should be assessed alongside functioning, relationships, cognitive capacities, self-experience, and the burdens of device maintenance. Interviews with psychiatric DBS recipients describe both gains in agency and difficult adjustment (de Haan et al., 2015). Patient-centred outcome measures and long-term psychosocial follow-up should therefore accompany clinical symptom scales. Care plans should also address psychotherapy, social support, continued programming, replacement, and explantation.

Taken together, the core difficulties faced by non-maleficence and beneficence in the aBCI context can be reduced to one central point: potential harms may emerge over years, while evidence about lifetime effects remains limited; the measurement of benefit is blurred between therapy and enhancement; and the very manner in which "beneficence" is achieved may erode patients' longer-term, more fundamental well-being. The current risk-benefit assessment system, oriented toward short-term clinical endpoints, is no longer adequate for the ethical review tasks of aBCI. Future efforts should establish a dynamic risk assessment mechanism encompassing long-term neuroplasticity monitoring, cognitive function follow-up, and psychological dependence evaluation, and draw clear regulatory boundaries between therapeutic and enhancement uses, to prevent the beneficence principle from losing its normative force in the ambiguous space of commercialisation.

7. Justice, Access, and Commercial Disparities

The principle of justice concerns the distribution of the benefits, burdens, opportunities, and risks of aBCI. It applies from research design and participant selection through commercial deployment and long-term device support. Affective disorders, disability, income, geography, language, and digital literacy shape access to research and care. Justice, therefore, requires institutional arrangements that make participation and access meaningful.

Research justice concerns who bears experimental burdens and who benefits from the resulting knowledge. Participant selection should follow scientific criteria and include the populations for whom the system is intended. Supported decision-making, accessible materials, justified eligibility criteria, appropriate compensation, and advance disclosure of post-trial care can protect participants while improving the relevance of the evidence.

Justice also has an epistemic and distributive dimension. Models trained on narrow demographic, cultural, linguistic, or clinical samples may perform unevenly across populations. Developers should report dataset composition and subgroup performance, investigate sources of error, and limit deployment to validated settings. For systems requiring surgery, specialist programming, follow-up, replacement, or software support, fair implementation also requires transparent pricing, coverage planning, non-discriminatory allocation, and enforceable duties across the device lifecycle (Burwell et al., 2017; Goering et al., 2021).

Commercial aBCI creates an asymmetry between those who design emotional monitoring and those subjected to it. Workers, students, patients, and consumers

may have little practical opportunity to refuse monitoring tied to employment, education, care, or services. Justice supports necessity and proportionality tests, meaningful alternatives, limits on high-stakes uses, independent oversight, and remedies for discriminatory outcomes. It also directs attention to commercial incentives that favour profitable consumer markets over assistive and clinical applications.

8. Conclusion

Synthesising the foregoing analysis, the application of aBCI poses challenges to informed consent, autonomy, privacy, non-maleficence, beneficence, and justice. These challenges concern both traditional information protection and the integrity of affective and cognitive life. Neurorights—including mental privacy, mental integrity, cognitive liberty, and psychological continuity—can supplement conventional principles by identifying interests that require protection throughout the development and use of aBCI (Ienca & Andorno, 2017; Tong, 2024).

The allocation of responsibility should reflect the different roles of participants in an aBCI system. Users remain responsible for voluntary choices to the extent that they retain understanding and control. Clinicians are responsible for patient selection, disclosure, programming, monitoring, and responses to adverse effects. Developers and manufacturers are responsible for design choices, training data, validation, cybersecurity, foreseeable misuse, and post-market support, while research and healthcare institutions govern protocols, data access, maintenance, and long-term care. The algorithm has a causal and epistemic role but lacks the capacities required for independent moral agency. Responsibility should therefore be assigned according to each actor's knowledge, control, professional duties, and capacity to prevent harm, with shared responsibility applied where contributions overlap (Goering et al., 2021).

Ultimately, the development of aBCI concerns not only the technology itself but also fundamental questions regarding the nature of human emotions, cognitive patterns, and related issues. How to strike a balance between technological innovation and ethical constraints, and how to ensure that technology serves human well-being rather than alienating human nature, will remain key directions for future research. In confronting this challenge, interdisciplinary collaboration, dynamic governance mechanisms, and the establishment of social consensus are all indispensable. Only in this way can we safeguard the authenticity and freedom of human emotions while advancing technological progress.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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