Humanities & Social Sciences Communications

ARTICLE

https://doi.org/10.1057/s41599-023-02419-x OPEN

The functional differentiation of brain-computer interfaces (BCIs) and its ethical implications

Xiao-yu Sun[1] & Bin Ye[2]✉

The growth of research and applications of brain–computer interfaces (BCIs) has spurred extensive discussion about their ethical implications. However, most existing research has primarily examined ethical issues related to BCIs from a general perspective, with little attention paid to the specific functions of the technology. This has resulted in a mismatch between governance and ethical issues, due to the lack of differentiation between write-in and read-out BCIs. By providing detailed descriptions of the functions and technical approaches of both write-in and read-out BCIs, we argue that ethical governance of BCIs should follow the principle of precise governance and develop refined governance strategies for different functional types of BCIs.

[1] Department of Philosophy and Science, Southeast University, 211189 Nanjing, China. [2] Department of Philosophy (Zhuhai), Sun Yat-sen University, 519082 Zhuhai, China. ✉email: yebin8@mail.sysu.edu.cn

Introduction

Since its inception, brain–computer interface (BCI) technology has sparked significant interest and debate regarding its ethical implications. Concerns have been raised that the use of BCI technology may infringe upon users' rights to safety, privacy, and informed consent. For instance, Tamara Bonaci has asserted that despite claims of performance, reliability, and security guarantees by current engineering practices for BCI technologies, they still pose significant risks to physical safety and privacy, due to the lack of standards and guarantees (Bonaci et al., 2014). Eran Klein has similarly warned that BCI may compromise the privacy and security of patients' brain information (Klein et al., 2015), while other studies have shown through a BCI game (Flappy Whale) that BCI technology can be used to collect users' private and sensitive data, leading to potential violations of privacy and a hindrance to users' right to informed consent (Ienca et al., 2018).

In addition to the risks associated with BCI technology, many studies have shown that it raises significant ethical issues regarding personal identity, responsibility, and social justice/fairness. For example, a qualitative study conducted by Erika Versalovic et al. found that BCI devices can impact users' self-conceptions and how others perceive them (Versalovic et al., 2020). Similarly, Schmid et al. discovered through an online survey that there is widespread support among the public for holding BCI users accountable for the consequences of their behavior and that users cannot avoid taking responsibility (Schmid et al., 2021). Sasha Burwell et al. have identified personal identity, responsibility, and fairness as the most important ethical issues arising from BCI technology, but note a lack of concrete proposals to address them (Burwell et al., 2017). Emily Postan has conducted research on the influence of neurotechnologies like BCIs on identity and has presented a normative framework regarding identity to assist in crafting narratives that constitute identity (Postan, 2016; 2020). The impact of BCI technology on patient autonomy and agency has been a key concern for many scholars. For instance, Michael Abbott and Steven Peck suggest that patients with total locked-in syndrome, who entirely rely on BCI-related functions and lose voluntary muscle control, may face ethical issues related to the technology replacing patients' own decision-making abilities (Abbott and Peck, 2017). Likewise, Frederic Gilbert et al. have highlighted concerns regarding the potential for BCIs to alter patients' agency (Gilbert et al., 2019).

However, the above-mentioned studies have not considered the way the technology is implemented, i.e., most of them ignore the fact that different functional types of BCI technologies rely on different technological approaches. Because of the differences in their approaches, it results in different ethical consequences, i.e., the ethical issues and implications arising from write-in and read-out BCIs are different (Mazurek and Schieber, 2021), and thus a universal or general strategy of governance may not be applicable to all types of BCIs and may even hinder the further development of BCIs.

This paper provides in the second section an overview of two functional types of BCIs: read-out BCIs and write-in BCIs, outlining their current state of development, with a specific focus on highlighting the differences between the two technologies. In the third section, we investigate the ethical challenges associated with both read-out and write-in BCI technologies. To address these challenges, we argue that a precise governance approach is required, and we further propose the need to refine the current governance model. Based on these established governance measures, the paper concludes by offering recommendations and countermeasures for the technical and ethical issues faced by the two types of BCIs.

Write-in and read-out BCIs

BCI is defined uniformly in current studies. Stephen Scott regards BCI as a mechanism that deciphers our thoughts into action, providing brain-damaged patients with an opportunity for direct communication with the external environment (Scott, 2006). John Donoghue believes that BCI permits interaction between external devices and the brain by decoding appropriate neural signal characteristics, which controls external devices (Donoghue, 2008). A standard BCI framework consists of an acquisition system, a signal processing system, and an effector. The acquisition system aims to obtain and record brain signals through electrode arrays. The signal processing system extracts features of brain signals and translates these feature signals into various intentions - for instance, speech, movement, and cognition. The effector is responsible for converting and implementing various intentional actions of the users (Bonaci et al., 2014; Santhanam et al., 2006).

However, such a definition of BCI focuses solely on the read-out aspect. This could be due to the mature technology of read-out BCIs, which offers a broad range of benefits, allowing patients to control robotic arms, wheelchairs, and use voice synthesis devices and word processors as tools to communicate with the outside world (Chaudhary et al., 2016; Anumanchipalli et al., 2019; Mudgal et al., 2020). Yet based on BCIs' different technical approaches and functions, they can be classified into write-in and read-out BCIs.

Write-in BCIs. Write-in BCIs are those that send signals to neural tissue through electrical or optical stimulation. For example, Deep brain stimulation (DBS), which is an invasive brain stimulation method that entails the implantation of electrode arrays under the deep cortex of the brain to stimulate certain target sites, with stimulation parameters controllable by external devices to treat symptoms such as Parkinson's disease, tremor, or other refractory disorders (Kringelbach et al., 2007; Lyons and Pahwa, 2008; Volkmann, 2004).

Write-in BCIs are designed to manipulate brain activity with the aim of either stimulating or inhibiting specific responses (Rafferty, 2021). These BCIs find extensive application, primarily in therapeutic contexts. For example, the cochlear prosthesis, an artificial implant, restores auditory function by stimulating auditory nerves, enabling individuals with hearing impairments to regain their ability to hear (Andersen, 2019). DBS offers therapeutic possibilities for a range of neurological conditions and disabilities, including Parkinson's disease (Limousin and Foltynie, 2019; Weaver et al., 2012; Fasano et al., 2012; Pal et al., 2022), tremors (Lozano, 2000; Bekar et al., 2007), and dystonia (Anderson and Lenz, 2006), among other movement disorders. Additionally, DBS is utilized in the management of specific psychiatric conditions, such as Alzheimer's disease (Laxton et al., 2010; Sankar et al., 2015), treatment-resistant depression (Bewernick et al., 2010; Schlaepfer et al., 2014), and severe obsessive-compulsive disorder (Greenberg et al., 2006; Visser-Vandewalle et al., 2022).

From a technical perspective, there are certain issues associated with write-in BCIs. First, there are safety concerns related to write-in BCIs. Implanting electrode arrays often requires craniotomy, which can cause a range of issues, such as hardware infection and damage to adjacent brain structures, such as intracranial hemorrhage (Volkmann, 2004). Additionally, electrode array stimulation parameters, such as frequency and voltage, are often generalized based on animal studies, rendering safety uncertain and human application highly risky (Bjånes and Moritz, 2019; Kim et al., 2015; Negi et al., 2010). Optimal electrode array size must be selected to improve signal accuracy in write-in BCI devices (Negi et al., 2010). Prolonged stimulation times on write-in BCIs can degrade brain signal quality and potentially alter the responsiveness of nerves to electrical stimulation, thereby elevating safety risks to brain nerves (Hughes et al., 2021; Tehovnik and Slocum, 2009; DeYoe et al., 2005).

Second, the exact mechanism of write-in BCIs is not well understood, and further investigation is needed to fully comprehend it. There is no way to predict which brain tissues will be affected by electrical stimulation or to what extent it will be damaged (Benabid, 2015; Gershon et al., 2003). Moreover, it is difficult to determine the precise target location for electrode array implantation and which areas of the brain can be used to "write" information (Mazurek and Schieber, 2021).

Third, the feasibility of BCIs is a critical concern that warrants investigation. The implantation of BCI electrodes in the cerebral cortex leads to a range of inflammatory reactions and gliosis, which raises long-term feasibility concerns (Lee and Fried, 2017; Davis et al., 2012). Furthermore, the reliability and flexibility of current write-in BCIs are considerably limited (Buller, 2021). Of utmost significance, patients may need to rely on write-in BCIs for extended periods, yet the impact of long-term use of this technology on the brain remains unclear. As such, the capacity of write-in BCIs to meet the users' needs is questionable, calling into question their technical feasibility (Bensmaia and Miller, 2014).

Read-out BCIs. Read-out BCIs receive and record brain signals, decode them using algorithms and decoders, and convert them to various representations of intentional activities that can be used to control effectors such as prostheses or wheelchairs (Andersen, 2019). Electroencephalogram (EEG) and functional magnetic resonance imaging (fMRI) are technologies that "read" brain signals. Among these, EEG-based BCI technology is more advanced and involves recording brain signals using an array of electrodes placed on the scalp. (McFarland and Wolpaw, 2017) These signals can then be used to control external robotic arms and other devices for the detection of brain function and diseases such as sleep disorders (Demene et al., 2017; Stevner et al., 2019).

The primary function of a read-out BCI is to retrieve neural data generated by the brain, assess and analyze brain activity, with the aim of deducing alterations in intentions, behaviors, perceptions, and cognitive states based on brief data snapshots (Rieger et al., 2008; Schicktanz et al., 2015). Additionally, it can transmit or report neural data for various purposes (Rafferty, 2021). Read-out BCIs designed to restore motor and language functions serve as common examples (Rieger et al., 2008; Schicktanz et al., 2015). For instance, through direct transmission of mental commands to relevant devices, monkeys can manipulate limb movements through their thoughts (Ifft et al., 2013). These devices are similarly employed for individuals with severe paralysis, where electrode signals can decode their motor intentions (Aflalo et al., 2015), allowing them to control robotic arms for tasks such as bringing a bottle to their mouth and drinking through a straw (Hochberg et al., 2012). Furthermore, read-out BCIs have applications in real-time language translation and mood detection for individuals who have lost their speech and communication abilities (Moses et al., 2019; Wu et al., 2017). Moreover, some scholars speculate that these BCIs may eventually find application in lie detection, deception detection, and even in uncovering intricate and potentially subconscious or concealed brain information (Roelfsema et al., 2018).

From a technical perspective, there are also certain issues associated with read-out BCIs. Firstly, read-out BCIs are generally non-invasive, less costly and pose fewer safety risks compared to write-in BCIs (Volkova et al., 2019; Van Steen and Kristo, 2014). Secondly, the mechanism of read-out BCIs is easy to comprehend. Signals generated by intentional brain activity are recorded with scalp electrode arrays, and specialized algorithms decipher these signals into recognizable representations. Thirdly, these representations are converted into external actions via dedicated devices. Technically, read-out BCIs require only minimal apparatus attached to the scalp, which enhances the feasibility of utilizing them for 24-hour periods or extended periods (Bensmaia and Miller, 2014). Lastly, the efficiency of read-out BCIs is limited by some challenges. The EEG-based technology has some limitations, as it is subject to interference from tissue layers such as the scalp and skull (Nicolas-Alonso and Gomez-Gil, 2012; Lebedev and Nicolelis, 2006). Consequently, the accuracy of signals and the transmission rate is relatively low, compromising the ability to translate the user's intentions into external activities. Moreover, it is impossible to extract signals generated by individual fascicles, which contributes to errors in decoding the neurological activity resulting in incorrect external activity outcomes (Xu et al., 2018). This might negatively impact users, and in severe cases, may lead to harm. There is also the danger of malicious attackers exploiting vulnerabilities, potentially compromising the confidentiality of brain information (Xu et al., 2018).

From the previous description of read-out and write-in BCIs, we can identify the differences between these two technologies. Firstly, read-out BCIs interpret the users' intentional activity and translate it into actual actions where the users take control of these activities. On the other hand, write-in BCIs input intended action into users, and stimulate them to generate intentional action brain signals, whereby the device is the initiator of the intention-generating activity, not the users. Secondly, while read-out BCIs involve electrode arrays on the users' scalp to record and analyze brain activity, write-in BCIs require implanting an electrode array in the brain to electrically stimulate a target site, generating cognitive, verbal, or motor intentions in the users, controlled by an external device based on their needs or medical condition. While some write-in BCIs function by stimulating specific areas of the scalp using induced currents, the accuracy, and achievement of all the desired outcomes may be minimal. In conclusion, while both read-out and write-in BCIs can convert user intentions into actual activities, the former is a self-generated activity by the users, while the latter is a device-initiated activity that raises technical challenges and ethical considerations that differ from those of read-out BCIs.

Ethical challenges of write-in and read-out BCIs

According to the technical differences and different functions between write-in and read-out BCIs, the ethical issues posed by each are distinct. While there may be some common concerns, the impact of these ethical issues varies significantly. Therefore, it is necessary to distinguish between ethical issues caused by these two types of BCIs in order to fully comprehend the ethical implications of each. A comparison of the ethical issues present in write-in and read-out BCIs, the need for differentiation, and the varying levels of impact are provided in Table 1 below.

Table 1 highlights the distinct ethical challenges associated with write-in BCIs and read-out BCIs. This paper summarizes these challenges into seven key aspects: safety, privacy, identity, autonomy and agency, responsibility, fairness, and informed consent. Below, this paper provides a detailed analysis of the ethical issues and implications of write-in and read-out BCIs.

Ethical challenges of write-in BCIs

Safety. As can be seen from the second section: the safety of users is a primary concern with the implementation of write-in BCIs.

Table 1 A comparison of ethical challenges of write-in and read-out BCIs.

Ethical issues	Write-in BCIs			Read-out BCIs		
	Yes/no	Distinction	Degree of impact	Yes/no	Distinction	Degree of impact
Safety	Yes	Yes	Large	Yes, but slight	Yes	Slight
Privacy	Yes, but slightly	Yes	Slight	Yes	Yes	Large
Identity	Yes	Yes	Large	No	Yes	Slight
Autonomy & agency	Yes	Yes	Large	Yes, but slight	Yes	Slight
Responsibility	Yes	No	Large	Yes	No	Large
Fairness	Yes	No	Large	Yes	No	Slight
Informed consent	Yes	No	Same	Yes	No	Same

Technical uncertainties surrounding the devices and their lack of a reliable mechanism may result in harm to the user's body (Benabid, 2015; Gershon et al., 2003). Unavoidable risks from surgery and electrical stimulation can also create damage to brain tissues, and unexpected situations may lead to risks to the user's life.

Identity. Identity refers to the enduring nature of a person's self, remaining stable over a period of time without transformation into a distinct persona. Scholars concur that specific criteria determine whether someone's identity has been modified. These are personality, beliefs, thoughts, perceptions, behaviors, emotions, and sense of self (Coleman and Williams, 2013; Postan, 2016; Pugh, 2020; Postan, 2020). The use of write-in BCIs may change users' cognition, behaviors, and self-perception, thereby affecting their identity (Gilbert et al., 2017). Researchers have delved into the connection between BCIs and identity, investigating the potential for BCIs to modify a user's identity and induce psychological changes, among various other factors (Tamburrini, 2009; Klein, 2015; Glannon, 2016; Gilbert et al., 2018; Aggarwal and Chugh, 2020).

According to a qualitative study by F. Gilbert et al., in which semi-structured interviews were applied to patients using write-in BCIs, patients perceived the devices as an extension of their bodies, materializing into a portion of themselves. These machines impacted their desired goals and improved daily activities (Gilbert et al., 2017). The change in identity can create varied effects: both positive and negative. For instance, if a write-in BCI encourages users to set proper ideal goals in life, it has a positive effect, users possess the capacity to comprehend their own selves, identify valuable aspects, strategize for and sustain enduring projects, commitments, and relationships (Postan, 2020). Conversely, when this leads to the embrace of erroneous values, detrimental consequences ensue.

Autonomy and agency. Autonomy and agency are vital for individuals' ability to control their daily activities spontaneously, particularly since this behavior is independent of the external environment's influence and manipulation (Buss and Westlund, 2018). Autonomous agents freely act as per their choices and plans (Schlosser, 2019). Agency's realization primarily relies on agents' autonomy, and this can only be possible with the ability of agents to decide independently about their activities (Schlosser, 2019). Write-in BCIs offer the potential to alter users' agency and autonomy. On the one hand, they can restore users' autonomy and agency, while on the other hand, they can impair them (Friedrich et al., 2018). A user with Locked-in syndrome (LIS), for instance, may use a write-in BCI to enhance her or his cognitive ability and decide and perform routine activities independently, thus restoring autonomy and agency (Fenton and Alpert, 2008; Vukov, 2017). However, if a user receives signals through write-in BCIs to perform behaviors that she or he cannot control, it erodes their autonomy and agency. As an illustration, BCIs could potentially find applications in interrogation contexts or even for the purpose of pacification, ultimately eroding the autonomy of individuals (Munyon, 2018).

Ethical challenges of read-out BCIs. Read-out BCIs pose fewer ethical concerns due to their functional and methodological differences. The most apparent ethical challenge that arises with read-out BCIs is privacy concerns. To illustrate, read-out BCIs have the capability to acquire not only the user's brain data but also various other data types, including physiological and behavioral information. Subsequently, these systems can formulate specific inferences about the user's brain activities or thoughts, individually or in combination, thereby presenting a potential risk to the privacy and security of the user (Postan, 2020). These concerns associated with read-out BCIs stem not only from the devices themselves but also from malware attacks like malicious algorithms, "brain spyware," among others (Bonaci et al., 2014). Attackers carefully design "brain spyware" malware to locate and tap into user's private data, including their financial and facial information, raising severe ethical concerns (Martinovic et al., 2012).

Users' privacy security could be seriously threatened when attackers misuse the private information generated by users' brains and predict their mental activities, intentions, beliefs, health information, and personality traits (Inzlicht et al., 2009; Chaudhary and Agrawal, 2018). Landau et al. (2020a, 2020b) illustrated that the collection of EEG data via BCI applications constitutes an encroachment upon privacy. Furthermore, they established that personality traits can be deduced from this EEG data.

Exploitation of such information could lead to users being manipulated or coerced into performing malicious behaviors. As BCI technology advances, the ability to monitor users' thoughts will continue to improve. For instance, researchers have developed a GPT-based language decoder that is similar to the ChatGPT model. This decoder records and decodes brain activity information using non-invasive fMRI, achieving an accuracy rate of up to 82% in speech perception (Tang et al., 2023; Reardon, 2023).

Users' raw and predicted private information could be exploited for commercial advertising and marketing purposes, or even to harm and manipulate them, posing a threat to their physical and mental well-being and overall safety (Bonaci et al., 2014). For instance, a malicious attacker might obtain private information about an individual with epilepsy and purposely send them unwanted messages with rapidly flashing, horrific, and hateful animated images designed to trigger seizures (Ertl, 2007; Poulsen, 2008). Users of read-out BCIs are often physically disabled, and access to their private information, coupled with inference and predictions of other information, could significantly threaten their physical and mental well-being, along with various other aspects of their lives.

Common ethical challenges of write-in and read-out BCIs

Responsibility. BCI technology, both write-in and read-out, is faced with ethical issues concerning responsibility (Rainey et al., 2020); however, write-in BCIs have more significant implications. The use of write-in BCIs may cause the user's personal identity to change, resulting in altered personality, emotions, and perceptions before and after usage - a transformation into a different person (Jebari and Hansson, 2012). However, the responsibility for any unethical or illegal actions is controversial, since the user is not the same person as before using the write-in BCI. It becomes challenging to determine who should be responsible, especially if the user behaves wrongly due to being a different person or acquiring a nervous disorder. Consequently, owing to the convergence of identity and responsibility, the ethical responsibility linked to the actions of BCIs becomes notably intricate (Klein et al., 2015).

Furthermore, alterations in users' autonomy and agency can diminish their capacity to exercise autonomy independently, thereby introducing further complexities in ascertaining accountability. Moreover, BCIs can respond to users' subconscious thoughts, an arena where users possess neither consciousness nor control (O'Brolchain and Gordijn, 2014). In light of this scenario, the pivotal query emerges: whether users should assume complete responsibility for all consequences produced by the BCIs (Klein et al., 2015).

Privacy violations caused by read-out BCIs create a responsibility problem. If a user's privacy is breached, and they are manipulated or forced to commit illegal activities or suffer harm due to leakage (Bonaci et al., 2014), attributing responsibility for any wrongdoing and harm caused by manipulation becomes challenging. Furthermore, this responsibility issue for read-out BCIs extends beyond identifying the responsible party and involves determining how to hold the user accountable while also identifying the party responsible for privacy violations. As a result, multiple parties may be involved, necessitating more effective ways of attributing responsibility.

Social Fairness. The issue of social fairness is critical for both types of BCIs but has various implications. Write-in BCIs may use electrical stimulation to enhance users' cognitive abilities, actions, and other functions, creating social inequality (Khan and Aziz, 2019). Low affordability of write-in BCI devices to a large number of people can create differences in abilities between those who use and those who do not use them, leading to more class antagonism and social division (Vlek et al., 2012). In contrast, read-out BCIs have a relatively low social impact since they mainly focus on restoring hearing, speech, motor functions, etc., although they could still create some social inequalities. To illustrate, in the case of a BCI gaming, the input comprises EEG scan data obtained from users. Simultaneously, hospitals and healthcare institutions house vast datasets of patient EEG scan data and associated personal information. In a concerning scenario, if malicious actors were to gain access to both the EEG scan data from the gaming environment and hospital records, they could conduct comparative analyses to extract intricate user details. This, in turn, has the potential to result in discriminatory practices against specific populations, with implications for fairness (Landau et al., 2020a, 2020b).

Informed consent. The concept of informed consent is an important ethical concern in both types of BCIs and numerous other research domains (Grübler et al., 2013; Versalovic et al., 2020). It is crucial to obtain and provide consent from BCI users before utilizing it and ensure that they comprehend all potential consequences. Nevertheless, acquiring informed consent may be complicated for people lacking the ability to make autonomous decisions. In these circumstances, it is essential to brief their guardians on all the information so that they can make an informed decision.

Write-in BCIs raise ethical issues concerning user security, personal identity, autonomy, and agency, whereas read-out BCIs primarily concern privacy. Both categories pose challenges regarding responsibility, social equitability, and informed consent. It is crucial to differentiate personal identity, autonomy, and agency, and privacy for each type of BCIs. While responsibility and social equity issues have different impacts on users and society, they need not be distinguished since they arise from similar causes and require the same governance measures. Informed consent issues do not demand differentiation as they have comparable impacts on users and society. Although write-in BCI technologies are still in their nascent stages, current research on ethical concerns in BCI technologies prioritizes write-in BCIs. Neglecting to distinguish between the two categories of BCIs may cause unwarranted concerns about read-out BCI products currently in use, emphasizing the need for precise governance of ethical issues concerning BCIs. Although current research has put forth many governance measures and ethical principles concerning BCIs, it has yet to establish a distinct differentiation between write-in BCIs and read-out BCIs, thereby imposing certain constraints. Consequently, there exists a demand for precise governance to augment and fine-tune ongoing research pertaining to the ethical governance of BCIs.

Suggestions for governance

The current approaches for the ethical governance of BCIs. This article, following a comprehensive review of pertinent literature, identifies that the current approaches to governance concerning ethical aspects in BCIs can be broadly classified into two levels: ethical and legal.

Ethical level. The application of BCI technology has given rise to a multitude of ethical challenges with significant implications. Certain scholars contend that established ethical guidelines, such as the *Declaration of Helsinki* and the *Belmont Report*, may not offer adequate solutions to contemporary ethical dilemmas (Yuste et al., 2017). In response to the ethical quandaries stemming from BCI technology, numerous international organizations, and governmental bodies have implemented pertinent ethical initiatives and governance measures. As an illustration, UNESCO has published the "Report on Ethical Issues of Neurotechnology," which advocates for responsible innovation (International Bioethics Committee (IBC), 2022). Remarkably, China has introduced, for the first time within the BCI domain, a proposal emphasizing that BCI development should align not only with the principles of respecting, non-harming, benefiting, and justice in bioethics to preventing harm to users, but also with the principles of non-harming, respecting autonomy, protecting privacy, ensuring transparency, and upholding fairness and justice (Chinanews, 2023). Additionally, several scholars have proposed a range of recommendations pertaining to ethical issues in BCIs. These recommendations encompass the establishment of rights such as "neurofreedom" and "neuroprivacy," enhancements in informed consent procedures, regulation of brain data collection, constraints on brain data sharing, the recognition and mitigation of biases, and the advancement of fairness in neurotechnology (McCullagh et al., 2014; Goering et al., 2021; Doya et al., 2022).

Legal level. At the legal level, it is noteworthy that only a limited number of countries have enacted legislation and regulations aimed at safeguarding the integrity of the human mind or have incorporated neural data into their personal data protection laws (UNESCO, 2023). For instance, Chile's constitutional amendments have paved the way for the safeguarding of citizens' mental privacy and their freedom of will (Guzmán, 2022). Spain has introduced the "Digital Rights Charter," which mandates that the utilization of neural technology must ensure each individual's control over their identity, sovereignty, and self-determination, while also guaranteeing the security and confidentiality of acquired neural data. Moreover, it regulates the deployment of technologies that may impact physical or mental integrity (AOC blog, 2021). France, among others, has issued a "Charter for the responsible development of neurotechnologies."

In summary, while some governance approaches have been established, the research on the governance of ethical issues related to BCIs remains incomplete due to the ongoing development of BCI technology. Existing governance approaches exhibit certain limitations. Besides potential delays in the legal domain and the abstract nature of ethical aspects (Mittelstadt, 2019), a pivotal concern arises from the fact that current governance measures do not distinguish between write-in BCIs and read-out BCIs. Instead, they address ethical issues in BCIs at a macroscopic level. This approach may lead to confusion in practical applications, potentially governing non-existent ethical issues while overlooking genuine ethical concerns.

To effectively manage ethical challenges encountered by the aforementioned BCI types, precisely targeted recommendations and governance measures are necessary for specific ethical dilemmas unique to each type of BCIs. Precision governance (PG) is an approach that incorporates the preferences and contexts of individuals and collectives into policy decision-making. This governance method also includes the potential preferences and needs arising from specific circumstances and experiences, thereby enhancing the precision and personalization of decision-making (Hondula et al., 2018). Write-in BCIs and read-out BCIs face distinct challenges at ethical and technical levels. Ethical concerns regarding write-in BCIs encompass user safety, identity, autonomy, and agency, while read-out BCIs primarily entail significant privacy risks. On the technical level, write-in BCIs primarily confront issues of feasibility and uncertainty in operational mechanisms, whereas the effectiveness of the technology represents the primary concern for read-out BCIs. Therefore, ethical and technological governance diverge. Ethical governance primarily addresses the ethical challenges associated with BCIs, encompassing specific social and societal values, whereas technological governance primarily concentrates on the technical obstacles encountered by BCIs, encompassing practical rules in design, development, and deployment. Consequently, the general governance strategy mentioned earlier is inappropriate for addressing the multifaceted issues stemming from BCIs. Instead, precise governance is imperative, offering distinct governance measures tailored to the specific issues of write-in BCIs and read-out BCIs, meeting unique preferences and needs, achieving fine-grained and personalized governance, and compensating for the shortcomings of the general governance approach.

The approach of precise governance. To effectively govern ethical issues of BCI technology, it is imperative to apply precise governance principles by pinpointing specific issues and tailoring recommendations and governance measures for the unique ethical considerations of write-in and read-out BCIs. Problem-targeted governance measures should address key ethical issues, including security for write-in BCI and performance for read-out BCI. Governance measures should restrict write-in BCI use until establishing high levels of security and promoting use only after achieving the highest security standards. To deploy effective governance measures, implementing PG whereby ethical issues are classified, and effectively resolved is necessary. Current governance measures may lead to impractical solutions, misguided guidance, and improper resource deployment, impeding further BCI technology development and improvement.

PG for write-in BCIs

Technology governance: The safety of BCI technology is crucial, particularly for write-in BCIs that are still in their early stages of scientific and clinical development. Uncertainty about the safety, feasibility, and effectiveness of write-in BCIs exists, and prolonged use may be required to maintain their intended functions and effects, posing further concerns about their long-term impact on the brain. Additionally, the level of medical care significantly affects the use of write-in BCIs, making it necessary not only to enhance the quality of medical care but also to utilize write-in BCI technologies reasonably. Improving their safety is essential to protect the lives of users and promote the development and advancement of BCI technology.

Ethical governance: The utmost importance must be given to safeguarding users' identity and autonomous decision-making rights when developing write-in BCI technology. Malicious attackers can exploit mind control over the user, generating impulsive or harmful thoughts and behaviors. Distinguishing the origin of such actions, either from the user or the attacker, can be challenging, leading to a loss of personal identity and autonomy. Therefore, write-in BCI technology must take into account user needs and values, tailoring the design accordingly while implementing relevant review standards and audit mechanisms to protect the user and others from harm.

PG for read-out BCIs

Technology governance: Enhancing the effectiveness of read-out BCI technologies is critical when considering interference or external environmental attacks. Although there is no immediate security risk, deviations from user-intended actions can occur, and the timeliness and accuracy of the device can be affected, ultimately harming the user. Therefore, additional improvements are necessary to ensure accurate and timely translation of user intention into an external device activity.

Ethical governance: Protecting user privacy is of paramount importance from an ethical standpoint. As read-out BCI technologies become more popular and mature, they become increasingly integrated into users' daily lives. However, over-involvement in users' lives poses a significant risk to privacy and security. Malicious access to, collection, and use of private information can cause harm to individuals and society, with potentially life-threatening results. Therefore, establishing technology specifications, enhancing and upgrading security mechanisms, and developing and updating privacy and security monitoring mechanisms in a timely manner becomes critical. It is vital to explain and prevent all possible harms resulting from read-out BCI technology and to establish privacy protection technologies. Supervising the product development process and enforcing ethical principles, laws, and regulations for privacy protection are of utmost importance to ensure user privacy.

PG for the common ethical issues of write-in BCIs and read-out BCIs

It is vital to improve relevant systems and regulations and reinforce policy protection: Responsibility attribution relies on clarification of the source of information driving the intentional behavior. If users generate it, they are responsible for any impulsive behavior. On the other hand, technical issues causing harm make the manufacturer accountable. The legal systems must be enhanced and policy protection strengthened to facilitate the market use of BCI technology. Specific mechanisms to handle recourse cases must be identified, and the right to informed consent protected. Furthermore, vendors must not obtain, store, or share user's personal privacy information without proper consent.

Enhancing social distribution systems is essential to promoting distributive justice: Generally, BCI products are costly, rendering them inaccessible to many patients, particularly those in impoverished areas where these products may be unavailable. Therefore, the state should allocate resources reasonably, and control BCI product prices. Additionally, pricing standards and allocation systems should be region and user-group-specific. It is worth noting that the development and utilization of BCIs may exhibit global variations, particularly in remote and resource-constrained areas. Thus, the governance of ethical issues related to BCIs in these regions should be adapted to their unique contexts. It is commonly recommended to engage local communities and researchers while fostering collaboration with other regions (Pickersgill, 2021; Shen et al., 2021). Furthermore, R&D and production companies should receive subsidies to develop BCI products, allowing them to forgo economic benefits while remaining profitable. These steps aim to ensure that everyone in society has an equal opportunity to access and utilize BCI technologies.

Conclusion remarks

BCIs bring about convenience and ethical concerns intrinsic to their function and mechanism. It is, therefore, necessary to differentiate BCI technologies by function and discuss technical and ethical issues separately. Write-only BCIs face technical safety, mechanism uncertainty, and low feasibility problems; technical effectiveness problems persist with read-out BCIs. Write-in BCIs give rise to problems in user security, personal identity, autonomy, and agency issues while privacy and security are chiefly problematic with read-out BCIs. Therefore, effective governance of ethical issues posed by BCIs requires precise governance measures for different technical and ethical problems to attain effectiveness and accuracy. The application of precise governance to the various technical and ethical concerns of BCIs will significantly enhance governance effectiveness in the field of BCIs. One limitation of this paper is in the definition of identity, which is a complex concept with multiple controversies in academia, thus relying on a general concept. In the future, BCIs will combine write-in and read-out techniques, emphasizing the need for increased research, clinical attention, and investment in this area.

Data availability

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

Received: 18 May 2023; Accepted: 16 November 2023;
Published online: 27 November 2023

References

Abbott MN, Peck SL (2017) Emerging ethical issues related to the use of brain-computer interfaces for patients with total locked-in syndrome. Neuroethics 10(2):235–242

Aflalo T, Kellis S, Klaes C et al. (2015) Decoding motor imagery from the posterior parietal cortex of a tetraplegic human. Science 348(6237):906–910

Aggarwal S, Chugh N (2020) Ethical implications of closed loop brain device: 10-year review. Minds Mach 30(1):145–170

Andersen R (2019) The intention machine. Sci Am 320(4):24–41

Anderson WS, Lenz FA (2006) Surgery insight: deep brain stimulation for movement disorders. Nat Clin Pract Neurol 2(6):310–320

Anumanchipalli GK, Chartier J, Chang EF (2019) Speech synthesis from neural decoding of spoken sentences. Nature 568(7753):493–498

AOC blog (2021) Digital rights charters to guarantee rights and freedoms. https://www.aoc.cat/en/blog/2021/cartes-drets-digitals/. Accessed 9 Sept 2023

Benabid AL (2015) Spotlight on deep-brain stimulation. Nature 519(7543):299–300

Bensmaia SJ, Miller LE (2014) Restoring sensorimotor function through intracortical interfaces: progress and looming challenges. Nat Rev Neurosci 15(5):313–325

Bjånes DA, Moritz CT (2019) A robust encoding scheme for delivering artificial sensory information via direct brain stimulation. IEEE Trans Neural Syst Rehabil Eng 27(10):1994–2004

Bekar L, Libionka W et al. (2007) Adenosine is crucial for deep brain stimulation–mediated attenuation of tremor. Nat Med 14(1):75–80

Bewernick BH, Hurlemann R, Matusch A et al. (2010) Nucleus accumbens deep brain stimulation decreases ratings of depression and anxiety in treatment-resistant depression. Biol Psychiatry 67(2):110–116

Bonaci T, Calo R, Chizeck H J (2014) App stores for the brain: privacy & security in brain-computer interfaces. https://ieeexplore.ieee.org/document/7128844. Accessed 9 Sept 2023

Buller T (2021) Brain-computer interfaces and the translation of thought into action. Neuroethics 14(2):155–165

Burwell S, Sample M, Racine E (2017) Ethical aspects of brain computer interfaces: a scoping review. BMC Med Ethics 18(1):1–11

Buss S, Westlund A (2018) Personal autonomy. https://plato.stanford.edu/archives/spr2018/entries/personal-autonomy. Accessed 3 Nov 2022

Chaudhary P, Agrawal R (2018) Emerging threats to security and privacy in brain computer interface. Int J Adv Stud Sci Res 3(12):340–344

Chaudhary U, Birbaumer N, Ramos-Murguialday A (2016) Brain–computer interfaces for communication and rehabilitation. Nat Rev Neurol 12(9):513–525

Chinanews (2023) China's first recommendation on ethical principles and governance in the field of brain-computer interface was released. https://www.tellerreport.com/business/2023-05-30-china-s-first-recommendation-on-ethical-principles-and-governance-in-the-field-of-brain-computer-interface-wasreleased.By7t3ZXLh.html. Accessed 9 Sept 2023

Coleman NV, Williams P (2013) Feeling like my self: Emotion profles and social identity. J Consum Res 40(2):203–222

Davis TS, Parker RA, House PA et al. (2012) Spatial and temporal characteristics of V1 microstimulation during chronic implantation of a microelectrode array in a behaving macaque. J Neural Eng 9(6):1–12

Demene C, Baranger J, Bernal M et al. (2017) Functional ultrasound imaging of brain activity in human newborns. Sci Transl Med 9(411):1–12

DeYoe EA, Lewine JD, Doty RW (2005) Laminar variation in threshold for detection of electrical excitation of striate cortex by macaques. J Neurophysiol 94(5):3443–3450

Donoghue JP (2008) Bridging the brain to the world: a perspective on neural interface systems. Neuron 60(3):511–521

Doya K, Ema A, Kitano H et al. (2022) Social impact and governance of AI and neurotechnologies. Neural Netw152:542–554

Ertl B (2007) Hooligans attack epilepsy patients during epilepsy awareness month. https://www.pr.com/press-release/60959. Accessed 26 May 2022

Fasano A, Daniele A, Albanese A (2012) Treatment of motor and non-motor features of Parkinson's disease with deep brain stimulation. Lancet Neurol 11(5):429–442

Fenton A, Alpert S (2008) Extending our view on using BCIs for locked-in syndrome. Neuroethics 1:119–132

Friedrich O, Racine E, Steinert S et al. (2018) An analysis of the impact of brain-computer interfaces on autonomy. Neuroethics 14(1):17–29

Gershon AA, Dannon PN, Grunhaus L (2003) Transcranial magnetic stimulation in the treatment of depression. Am J Psychiatry 160(5):835–845

Gilbert F, Brown T, Dasgupta I et al. (2019) An instrument to capture the phenomenology of implantable brain device use. Neuroethics 14(3):333–340

Gilbert F, Cook M, O'Brien T, Illes J (2017) Embodiment and estrangement: results from a first-in-human "intelligent BCI" trial. Sci Eng Ethics 25(1):83–96

Gilbert F, Viaña JNM, Ineichen C (2018) Defating the "DBS causes personality changes" bubble. Neuroethics 14(1):1–17

Glannon W (2016) Ethical issues in neuroprosthetics. J Neural Eng 13(2):021002

Goering S, Klein E, Specker Sullivan L et al. (2021) Recommendations for responsible development and application of neurotechnologies. Neuroethics 14(3):365–386

Grübler G, Al-Khodairy A, Leeb R et al. (2013) Psychosocial and ethical aspects in non-invasive EEG-based BCI research—a survey among BCI users and BCI professionals. Neuroethics 7(1):29–41

Guzmán LH (2022) Chile: Pioneering the protection of neurorights. https://courier.unesco.org/en/articles/chile-pioneering-protection-neurorights. Accessed 9 Sept 2023

Hochberg LR, Bacher D, Jarosiewicz B et al. (2012) Reach and grasp by people with tetraplegia using a neurally controlled robotic arm. Nature 485(7398):372–375
Hondula DM, Kuras ER, Longo J, Johnston EW (2018) Toward precision governance: infusing data into public management of environmental hazards. Public Manag Rev 20(5):746–765
Hughes CL, Flesher SN, Weiss JM et al. (2021) Neural stimulation and recording performance in human sensorimotor cortex over 1500 days. J Neural Eng 18(4):1–13
Ienca M, Haselager P, Emanuel EJ (2018) Brain leaks and consumer neurotechnology. Nat Biotechnol 36(9):805–810
Ifft P, Shokur S, Li Z et al. (2013) A brain machine interface that enables bimanual arm movement in monkeys. Sci Transl Med 5(210):210ra154
International Bioethics Committee (IBC) (2022) Ethical issues of neurotechnology: report. https://unesdoc.unesco.org/ark:/48223/pf0000383559. Accessed 9 Sept 2023
Inzlicht M, McGregor I, Hirsh JB, Nash K (2009) Neural markers of religious conviction. Psychol Sci 20(3):385–392
Jebari K, Hansson SO (2012) European public deliberation on brain machine interface technology: five convergence seminars. Sci Eng Ethics 19(3):1071–1086
Khan S, Aziz T (2019) Transcending the brain: is there a cost to hacking the nervous system? Brain Commun 1(1):1–10
Kim S, Callier T, Tabot GA et al. (2015) Behavioral assessment of sensitivity to intracortical microstimulation of primate somatosensory cortex. Proc Natl Acad Sci USA 112(49):15202–15207
Klein E, Brown T, Sample M et al. (2015) Engineering the brain: ethical issues and the introduction of neural devices. Hastings Cent Rep 45(6):26–35
Klein E (2015) Informed consent in implantable BCI research: identifying risks and exploring meaning. Sci Eng Ethics 22(5):1299–1317
Kringelbach ML, Jenkinson N, Owen SL, Aziz TZ (2007) Translational principles of deep brain stimulation. Nat Rev Neurosci 8(8):623–635
Landau O, Cohen A, Gordon S, Nissim N (2020a) Mind your privacy: privacy leakage through BCI applications using machine learning methods. Knowl Based Syst 198:105932
Landau O, Puzis R, Nissim N (2020b) Mind your mind: EEG-based brain-computer interfaces and their security in cyber space. ACM Comput Surv (CSUR) 53(1):1–38
Laxton AW, Tang-Wai DF, McAndrews MP et al. (2010) A phase I trial of deep brain stimulation of memory circuits in Alzheimer's disease. Ann Neurol 68(4):521–534
Lebedev MA, Nicolelis MA (2006) Brain–machine interfaces: past, present and future. Trends Neurosci 29(9):536–546
Lee SW, Fried SI (2017) Enhanced control of cortical pyramidal neurons with micromagnetic stimulation. IEEE Trans Neural Syst Rehabil Eng 25(9):1375–1386
Limousin P, Foltynie T (2019) Long-term outcomes of deep brain stimulation in Parkinson disease. Nat Rev Neurol 15(4):234–242
Lozano AM (2000) Vim thalamic stimulation for tremor. Arch Med Res 31(3):266–269
Lyons KE, Pahwa R (2008) Deep brain stimulation and tremor. Neurotherapeutics 5(2):331–338
Martinovic I, Davies D, Frank M et al. (2012) On the feasibility of side-channel attacks with brain-computer interfaces. Accessed 19 Sept 2023. https://doi.org/10.5555/2362793.2362827
Mazurek KA, Schieber MH (2021) Injecting information into the mammalian cortex: progress, challenges, and promise. Neuroscientist 27(2):129–142
McCullagh P, Lightbody G, Zygierewicz J, Kernohan WG (2014) Ethical challenges associated with the development and deployment of brain computer interface technology. Neuroethics 7(2):109–122
McFarland D, Wolpaw JR (2017) EEG-based brain–computer interfaces. Curr Opin Biomed Eng 4:194–200
Mittelstadt B (2019) Principles alone cannot guarantee ethical AI. Nat Mach Intell 1(11):501–507
Moses DA, Leonard MK, Makin JG, Chang EF (2019) Real-time decoding of question-and-answer speech dialogue using human cortical activity. Nat Commun 10(1):1–14
Mudgal SK, Sharma SK, Chaturvedi J, Sharma A (2020) Brain computer interface advancement in neurosciences: applications and issues. Interdiscip Neurosurg 20:1–8
Munyon CN (2018) Neuroethics of non-primary brain computer interface: focus on potential military applications. Front Neurosci 12:696
Negi S, Bhandari R, Rieth L et al. (2010) Neural electrode degradation from continuous electrical stimulation: comparison of sputtered and activated iridium oxide. J Neurosci Methods 186(1):8–17
Nicolas-Alonso LF, Gomez-Gil J (2012) Brain computer interfaces, a review. Sensors 12(2):1211–1279
O'Brolchain F, Gordijn B (2014) Brain–computer interfaces and user responsibility. In: Grübler G, Hildt E (eds.) Brain-computer interfaces in their ethical, social and cultural contexts. Springer, pp. 163–182
Pal G, Mangone G, Hill EJ et al. (2022) Parkinson disease and subthalamic nucleus deep brain stimulation cognitive effects in GBA mutation carriers. Ann Neurol 91(3):424–435
Pickersgill M (2021) A consideration of the social dimensions and implications of neuroimaging research in global health, as related to the theory-ladened and theory-generating aspects of technology. NeuroImage 236:118086
Poulsen K (2008) Hackers assault epilepsy patients via computer. https://www.wired.com/2008/03/hackers-assault-epilepsy-patients-via-computer/. Accessed 26 May 2022
Postan E (2020) Narrative devices: neurotechnologies, information, and self-constitution. Neuroethics 14(2):231–251
Postan E (2016) Defining ourselves: personal bioinformation as a tool of narrative self-conception. J Bioethical Inqu 13(1):133–151
Pugh J (2020) Clarifying the normative significance of 'personality changes' following deep brain stimulation. Sci Eng Ethics 26:1655–1680
Rafferty J (2021) Brain computer interfaces: a new existential risk factor. J Futures Stud 26(2):51–65
Rainey S, Maslen H, Savulescu J (2020) When thinking is doing: responsibility for BCI-mediated action. AJOB Neurosci 11(1):46–58
Reardon S (2023) Mind-reading machines are here: Is it time to worry? Accessed 5 May 2023 https://doi.org/10.1038/d41586-023-01486-z
Greenberg BD, Malone DA, Friehs GM et al. (2006) Three-year outcomes in deep brain stimulation for highly resistant obsessive–compulsive disorder. Neuropsychopharmacology 31(11):2384–2393
Rieger JW, Reichert C, Gegenfurtner KR et al. (2008) Predicting the recognition of natural scenes from single trial MEG recordings of brain activity. NeuroImage 42(3):1056–1068
Roelfsema PR, Denys D, Klink PC (2018) Mind reading and writing: the future of neurotechnology. Trend Cogn Sci 22(7):598–610
Sankar T, Chakravarty MM, Bescos A et al. (2015) Deep brain stimulation influences brain structure in alzheimer's disease. Brain Stimul 8(3):645–654
Santhanam G, Ryu SI, Yu BM et al. (2006) A high-performance brain–computer interface. Nature 442(7099):195–198
Schicktanz S, Amelung T, Rieger JW (2015) Qualitative assessment of patients' attitudes and expectations toward BCIs and implications for future technology development. Front Syst Neurosci 9:1–11
Schlosser M (2019) Agency. https://plato.stanford.edu/archives/win2019/entries/agency/. Accessed 3 Nov 2022
Schmid JR, Friedrich O, Kessner S, Jox RJ (2021) Thoughts unlocked by technology—a survey in germany about brain-computer interfaces. NanoEthics 15(3):303–313
Scott SH (2006) Converting thoughts into action. Nature 442(7099):141–142
Schlaepfer TE, Bewernick BH, Kayser S et al. (2014) Deep brain stimulation of the human reward system for major depression—rationale, outcomes and outlook. Neuropsychopharmacology 39(6):1303–1314
Shen FX, Wolf SM, Bhavnani S et al. (2021) Emerging ethical issues raised by highly portable MRI research in remote and resource-limited international settings. NeuroImage 238:118210
Stevner ABA, Vidaurre D, Cabral J et al. (2019) Discovery of key whole-brain transitions and dynamics during human wakefulness and non-REM sleep. Nat Commun 10(1):1–14
Tang J, LeBel A, Jain S, Huth AG (2023) Semantic reconstruction of continuous language from non-invasive brain recordings. Nat Neurosci 26:858–866
Tamburrini G (2009) Brain to computer communication: ethical perspectives on interaction models. Neuroethics 2(3):137–149
Tehovnik EJ, Slocum WM (2009) Depth-dependent detection of microampere currents delivered to monkey V1. Eur J Neurosci 29(7):1477–1489
UNESCO (2023) Preliminary study on the technical and legal aspects relating to the desirability of a standard-setting instrument on the ethics of neurotechnology. https://unesdoc.unesco.org/ark:/48223/pf0000385016. Accessed 9 Sept 2023
Van Steen M, Kristo G (2014) Contribution to roadmap. https://www.semanticscholar.org/paper/Title%3A-Contribution-to-Roadmap-Umcu-Umcu/5cb411de3db4941d5c7ecfc19de8af9243fb63d5. Accessed 25 May 2022
Versalovic E, Diamond M, Klein E (2020) "Re-identifying yourself": a qualitative study of veteran views on implantable BCI for mobility and communication in ALS. Disabil Rehabil Assist Technol 17(7):1–8
Visser-Vandewalle V, Andrade P, Mosley PE et al. (2022) Deep brain stimulation for obsessive–compulsive disorder: a crisis of access. Nat Med 28(8):1529–1532
Vlek RJ, Steines D, Szibbo D et al. (2012) Ethical issues in brain–computer interface research, development, and dissemination. J Neurologic Phys Ther 36(2):94–99
Volkmann J (2004) Deep brain stimulation for the treatment of Parkinson's disease. J Clin Neurophysiol 21(1):6–17
Volkova K, Lebedev MA, Kaplan A, Ossadtchi A (2019) Decoding movement from electrocorticographic activity: a review. Front Neuroinformatics 13:1–20

Vukov JM (2017) Three kinds of agency and closed loop neural devices. AJOB Neurosci 8(2):90–91
Wu S, Xu X, Shu L, Hu B (2017) Estimation of valence of emotion using two frontal EEG channels. https://ieeexplore.ieee.org/document/8217815. Accessed 2 Sept 2023
Weaver FM, Follett KA, Stern M et al. (2012) Randomized trial of deep brain stimulation for Parkinson disease: thirty-six-month outcomes. Neurology 79(1):55–65
Xu J, Guo H, Nguyen AT et al. (2018) A bidirectional neuromodulation technology for nerve recording and stimulation. Micromachines 9(11):1–14
Yuste R, Goering S, Arcas BAY et al. (2017) Four ethical priorities for neurotechnologies and AI. Nature 551(7679):159–163

Acknowledgements
This work was supported by the National Office for Philosophy and Social Sciences under Grant 19CZX043.

Author contributions
BY contributed to the ideation and conceptualization of the manuscript. X-yS and BY contributed to the writing, editing, and revision of the drafts of the manuscript.

Competing interests
The authors declare no competing interests.

Ethical approval
Ethical approval was not required as the study did not involve human participants

Informed consent
This article does not contain any studies with human participants performed by any of the authors.

Additional information
Correspondence and requests for materials should be addressed to Bin Ye.