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Limitations in the Full Replication of Human Consciousness by Brain-Computer Interfaces: A Biological and Mathematical Analysis

Yuchen Zhao

School of Science, Auckland University of Technology, Auckland, New Zealand
helixcyan@163.com

Abstract. The rapid development of brain-computer interfaces has made memory uploading, brain controlling of some basic functions of computers, and the treatment of diseases or disabilities like paralysis and blindness possible. However, human consciousness cannot be fully replicated. This paper analyzes why brain-computer interface (BCI) cannot completely replicate human consciousness via a literature review method from three aspects: the limitations of BCI technology, the non-replicability of consciousness, and the challenges of interdisciplinary integration. Research shows that technical issues such as low signal precision and data scarcity restrict its reliability, subjective experiences and nonlinear neural activities of consciousness are difficult to simulate by programs, and that decoding neural signals is not equivalent to reproducing consciousness. Existing theories of consciousness lack engineerable equations, so human consciousness cannot be replicated completely under current situation.

Keywords: brain-computer interfaces (BCIs), human consciousness models, neurological deficiencies, mind replication, health and longevity

1. Introduction

Brain-computer interfaces (BCIs) enable direct neural-to-computer communication, offering transformative potential for healthcare, neuroscience, and virtual reality [1]. BCIs, whose concept was first proposed by Vidal in 1973, are designed for applications including automation and body control (medical care), education, gaming and entertainment, security, neuroergonomics, and neuromarketing, and they also provide a bypass for patients with neurological diseases who cannot interact with the environment via their peripheral nerves [2]. BCIs can decode brain signals and link these electrical activities to physical movements without peripheral nerves or muscles involved [2]. A total of 25,336 Scopus records showed exponential growth of BCI research, with China leading since 2019, followed by the United States [2]. Concerns of BCIs often include medical safety, data privacy, cybersecurity, and ethical issues [2]. There are three types of BCIs based on their interaction with the human brain: invasive, semi-invasive, and non-invasive, and most research articles focus on non-invasive ones. They are also classified by the data processing methods, like deep learning, linear classifiers, and hybrid models. BCI development uses brain data from electroencephalography

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(EEG), functional magnetic resonance imaging (fMRI), magnetoencephalography (MEG), and near infrared spectroscopy (NIRS), and EEG is most common due to its non-invasiveness, high temporal resolution, low cost, and portability [3].

The human brain is the most complex and vital organ in a human body, which is composed of billions of neurons with intricate connections and other sophisticated structures like neurotransmitters. The complex nature of the human brain, especially the neural connections and signaling pathways, further contribute to the near impossibility of emulating human cognition and awareness at a natural level. Different models and theories are proposed to try to explain the nature of consciousness. Five main models are Global Neuronal Workspace Theory (GNWT), Predictive Processing (PP), Higher-Order Theories (HOT), Recurrent Processing Theory (RPT), and Integrated Information Theory (IIT) [4]. Besides, the Temporospatial Theory of Consciousness (TTC), a widely discussed model, links time, space, and neural activity to explain the structure of consciousness [5]. Most of the models also try to explain the Hard Problem of Consciousness, Qualia, and Explanatory Gap, all of which focus on how physical processing and signals translate into subjective feelings and experience [6]. This study explores why consciousness cannot be fully replicated. It analyzes limitations in BCI development, the irreproducible nature of consciousness itself, as well as challenges in computational capacity and physical understanding, and also discusses potential future directions.

The research uses literature review and analysis as its main method. It aims to bridge the knowledge gap between BCI technology and the replication of human consciousness, provide guidance for future industrial applications, and encourage more in-depth interpretations of consciousness from biological and mathematical perspectives.

2. Reasons why consciousness cannot be fully replicated

2.1. Limitations of BCI development

Primary obstacles of BCI performance include the scarcity of high-quality training datasets, the poor spatial and temporal resolution inherent in non-invasive signals, and significant inter-subject difference in neural activity, which can hardly be improved even with the assistant of artificial intelligence (AI) [7]. EEG-based BCIs for cognitive/attention training were also reported to have device accuracy problems, and the small sample sizes limited the credibility of experimental results [8]. Nevertheless, the effects of BCI treatment for different age groups, and limited evidence and methodological biases (e.g., poor sample randomization) may lead to falsely significant results suggesting that BCIs improve brain functions for older people [9]. Alongside with individual variety and the lack of experimental data, technical issues are also key limitations of BCI development. AI/ML-based closed-loop BCIs face key challenges: diverse and non-standardized decoding/encoding methods, limited long-term and ethically robust training studies, hardware limits (e.g., sampling rate and channel capacity), and poor transferability between open- and closed-loop settings [10]. These factors restrict reliability, cross-study comparison, and clinical scalability [10]. Non-invasive BCIs using EEG or fMRI are mostly studied, but few research articles have been published on invasive BCIs like those created by Neuralink, Blackrock Neurotech, and Synchron, indicating invasive BCIs may still face safety, effectiveness, privacy, technical, or ethical issues. Updated legislations and more reliable data are required for the study of the effects of invasive BCIs.

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2.2. The non-replicability of consciousness

Reliable counting methods estimate the total number of neurons in the human brain to be about 86 billion, and published estimates range broadly from roughly 30 to 125 billion [11]. Of these, around 10-20 billion are located in the cerebral cortex, while the cerebellum contains the majority, between 50 and 70 billion neurons [11]. In comparison, the brainstem, striatum, and diencephalon have a total of around 700 million neurons [11]. Estimates suggest the adult human brain contains on the order of 10^{14}-10^{15} synapses with each neuron forms roughly 1000 synaptic connections on average, though reported values range from 1000 to 10000+ per neuron [11]. Modeling a brain with ~100 billion neurons and ~10000 synapses per neuron requires 7-23 petabytes (PB), depending on model complexity (topologic, point, or geometric), and storage needs are similar in scale for 86 billion neurons, so for a synapse average of 1000 per neuron, 0.6-2 PB are needed [11]. In addition, Positron Emission Tomography (PET) results show that there are at least 19 different receptors and transporters and 9 neurotransmitter systems in the human brain, including dopamine, glutamate, GABA, serotonin, acetylcholine, opioid, and cannabinoid, with uneven distribution in the brain [12].

A fundamental limitation of BCIs lies in their inability to reproduce qualia, or the gap between physical activities and subjective experience. For example, Large Language Models (LLMs) like GPT-4 are unable to simulate human consciousness because they cannot solve The Hard Problem, while only functioning by perception, and simulating a cognitive function (e.g., planning) is different from replicating a behavior or experience [13]. Another difficulty is the subjectivity of individual experiences. Some scientists argue that experiences are personal, which naturally resist environmental or third-person verification, so third-person observations of consciousness lack authenticity [14]. Moreover, consciousness might be a biological phenomenon that depends on the specific nature of living organisms, which cannot be computed or replicated by programs [15]. This view is supported by some psychologists, who believe the inherent and difficult-to-objectify nature of the mind and consciousness challenges strict quantification, which in turn undermines mind reproducibility [16]. Complexity in math regarding the brain and low computational power of current device add to the problem. AGI based on classical computation cannot replicate a mind physically and logically [17]. Besides, neural activities in human brain are dynamic and non-linear, and no known method can perfectly simulate the exponential operation and the constantly changing status.

2.3. Difficulty in interdisciplinary integration

Interdisciplinary work in BCI is challenging because neuroscience, engineering, and computing use very different approaches. Each scientist may only understand a part of the knowledge, and there are often issues in collaboration and communication across subjects. Decoding neural signals doesn't translate to consciousness directly, because human awareness relies on complex biological processes that machines cannot fully mimic. Moreover, BCI development tend to focus on decoding signals responsible for single neural functions, like language, eyesight, and movement, whereas human consciousness could be beyond the sum of all the functions. Thus, BCI can replicate some brain functions, but complete and real-life human consciousness remains out of reach.

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3. Future directions

3.1. Current progress

As for theories on cognition, the five models are often debated worldwide, with GNWT being the most accepted model, while there isn't a generally recognized conclusion. Meanwhile, even if any of the theories is true, it could not guide the complete mind replicating procedure for now, because none of them propose clear mathematical functions or objective conditions for all biological activities in the brain. GNWT: Consciousness is the broadcast protocol. Information becomes conscious only when it is uploaded to a high-bandwidth network and accessible to all functional modules of the system. PP: Consciousness is the optimal simulation. The brain functions as an inference engine, constantly generating 'best-guess' models to explain sensory data and minimize biological surprise. HOT: Consciousness is meta-representation. A state only becomes conscious when a secondary, higher-level thought monitors and categorizes the primary data-essentially a Master-Sandbox hierarchy. RPT: Consciousness is a feedback loop. Perception is not a one-way street; it requires localized, back-and-forth communication within the sensory cortex to solidify an experience. IIT: Consciousness is an intrinsic mathematical value. It emerges when a system's unified collective output is greater than the simple sum of its fragmented sub-processes [4]. Apart from those frequently discussed, new models have been proposed recently. For instance, TTC posits that consciousness arises from the brain's intrinsic spatiotemporal activity, which is spontaneous, translating time and space into a 'common currency' for neural and mental behaviors [5].

Electric or magnetic signals inside the brain are often acquired using non-invasive neuroimaging techniques like EEG and fMRI via machines. To filter out interference from the skull to get better signal quality, some companies insert metal electrodes directly into brain tissues and fix them on neurons or blood vessels. The received signals are then decoded and translated using Machine/Deep Learning (ML/DL) algorithms, such as Convolutional Neural Networks (CNNs), Recurrent Neural Network (RNN, e.g., Long Short-Term Memory (LSTM)), Transformers (e.g., Large Language Model (LLM) like GPT), Random Forest (RF), Support Vector Machine (SVM), and hybrid models like CNN+LSTM [18]. These models demonstrate different effectiveness and accuracy in decoding neural signals related to pain [18]. The CNN-LSTM hybrid architecture outperforms both traditional and standalone deep learning models, reaching a benchmark accuracy of 96.06% [19]. Existing ML/DL algorithms are often used to interpret EEG results, and combined models sometimes have higher accuracy rate. However, both neuroimaging techniques and computational logistics may need to be improved in the future, with deeper understandings of physical principles related to cognition as well as methods enhancing computational power.

As for BCI projects of different companies, Neuralink's N1 implant uses 1024 channels on 64 flexible polymer threads (16 electrodes per thread, 4-6 μm thick, 20 μm wide, 250-300 kΩ impedance) to record single-unit, local field, and subthreshold cortical activity [20]. The system is fully implantable, with robotic insertion guided by real-time imaging, and is under human trials for cursor control in spinal cord injury and ALS [20]. Synchron's Stentrode is an endovascular device with 16 iridium-oxide-coated electrodes mounted on a self-expanding nitinol scaffold, deployed via the jugular vein to the superior sagittal sinus [20]. It records ECoG signals through the vessel wall and has demonstrated stable motor decoding with typing rates up to 14 characters/min and >90 % accuracy over 12 months [20]. Precision Neuroscience's Layer 7 interface is a 4096-microelectrode subdural array (50-380 μm diameter, 10-50 kΩ) enabling mesoscale cortical recordings and real-time decoding of imagined speech with >85 % accuracy [20]. Paradromics' Connexus array has >1600 penetrating Utah-style electrodes (1-1.5 mm, <10 μm tip, 100-300 kΩ) with on-chip amplification

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and 30 kHz/channel sampling, whose acute human recordings have been demonstrated, with bidirectional stimulation in development [20]. Endovascular BCIs, like Synchron's Stentrode, collect cleaner neural signals from the brain than non-invasive device without the need of craniotomy [21]. Together, Neuralink and Paradromics prioritize high-resolution intracortical recordings, while Synchron and Precision focus on minimally invasive approaches, with all platforms moving toward bidirectional functionality.

Except for BCI device, there are other projects focused on the human brain. The Blue Brain Project has modeled neural circuits in detail, including rat neocortical columns, revealing how complex neuronal activity emerges, whose simulations lay groundwork for larger brain models and inspire brain-like computing [22]. Yet major challenges remain: scaling to whole brains, validating models with experimental data, managing ethical issues around potential consciousness, and addressing environmental and animal welfare concerns [22]. Similarly, the Human Brain Project advanced multiscale brain modeling, data integration, and neuromorphic computing, yet challenges remain in complexity, infrastructure sustainability, data standardization, ethical considerations, and achieving full-scale simulations [23].

3.2. Research problems and other hypotheses

Despite major advances in BCI hardware and algorithms, key problems remain. Signal acquisition is limited by biology and physics, where non-invasive methods have low resolution and skull attenuation, while invasive systems raise safety and ethical concerns. Machine learning models mainly capture correlations, not causal neural mechanisms, so high accuracy does not mean reconstruction of the full cognitive architecture. Inter-subject variability and neural plasticity hinder generalization. In addition, consciousness theories lack unified mathematical form, limiting practical implementation.

Based on the cognition models mentioned above, it can be argued that human awareness may have a biological-mathematical dynamic regulation model (BMDR), where qualia and other phenomenon are provided by biological (or bio-chemical) activities, whether it originates spontaneously within the individual, is affected by others and the environment, or a receiver/monitor of something else not known in the universe. The 'mathematical' here means everything should have its universal mathematical equations or numerical solutions and can be replicated if these equations are verified. The receiving-processing-exporting process is dynamic and balanced for healthy/well-functioning brains, and regulated by biological natures (like genes, neural connections and plasticity, neurotransmitter concentration, feedback, and inborn psyche/individual will). Natural biological traits play key roles in finally shaping consciousness and decide cognitive patterns, because individuals' experiences differ given similar situations, while everything should be able to be explained with mathematics instead of emotions. Objective techniques should be improved if subjective problems cannot be explained yet. Thus, though facing harsh difficulties, BCI remains one of the most efficient techniques for digital replication of consciousness.

4. Conclusion

This paper examined why BCIs cannot fully replicate human consciousness from biological, mathematical, and interdisciplinary perspectives. Technical limits include restricted signal resolution, small datasets, inter-subject variability, and hardware constraints, limiting their precision and scalability. More fundamentally, issues such as qualia, subjectivity, nonlinear neural dynamics,

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and the lack of a unified computational definition of consciousness create structural barriers to digital replication.

Although machine learning and deep models have improved neural decoding, decoding signals is insufficient for reconstructing subjective awareness. Existing consciousness theories provide conceptual guidance but lack operational mathematical criteria for engineering use. Besides, fragmentation across disciplines further slows progress from theory to application.

This study is based on literature analysis rather than experimental validation, and some arguments remain speculative. Given the rapid development of AI and neurotechnology, conclusions may need to be revised. Future work should improve multimodal neural measurement, develop mathematically grounded models of neural integration, build larger datasets, explore neuromorphic or quantum-inspired computing, and strengthen collaboration across neuroscience, mathematics, engineering, and philosophy.

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References

[1] Tang, X., Shen, H., Zhao, S., *et al.* Flexible brain-computer interfaces. *Nat Electron, 6*, 109–118 (2023). https: //doi.org/10.1038/s41928-022-00913-9

[2] Samwel Kimambo, M., Massawe, L. V., Abdalla, A. T., *et al.* Brain-computer interface: Trend, challenges, and threats. *Brain Inform., 10*, 20 (2023). https: //doi.org/10.1186/s40708-023-00199-3

[3] Liu, H., Wei, P., Wang, H., *et al.* An EEG motor imagery dataset for brain computer interface in acute stroke patients. *Sci Data, 11*, 131 (2024). https: //doi.org/10.1038/s41597-023-02787-8

[4] Mudrik, L., *et al.* Unpacking the complexities of consciousness: Theories and reflections. *Neurosci. Biobehav. Rev., 170*, 106053 (2025). https: //doi.org/10.1016/j.neubiorev.2025.106053

[5] Huang, Z. Temporospatial nestedness in consciousness: An updated perspective on the Temporospatial Theory of Consciousness. *Entropy, 25*, 1074 (2023). https: //doi.org/10.3390/e25071074

[6] Loorits, K. Structural qualia: A solution to the hard problem of consciousness. *Front. Psychol., 5*, 237 (2014). https: //doi.org/10.3389/fpsyg.2014.00237

[7] Eldawlatly, S. (2024). On the role of generative artificial intelligence in the development of brain-computer interfaces. *BMC Biomedical Engineering, 6*(1), 4. https: //doi.org/10.1186/s42490-024-00080-2

[8] Wang, Y. (2024). A comprehensive review of EEG-based brain-computer interfaces for attention training. *Theoretical and Natural Sciences, 63*(1), 159–164. https: //doi.org/10.54254/2753-8818/2024.17944

[9] Tsai, P. C. *et al.* (2025). Brain computer interfaces for cognitive enhancement in older people-challenges and applications: a systematic review. *BMC Geriatrics, 25*(1), 36. https: //doi.org/10.1186/s12877-025-05676-4

[10] Williams, C. *et al.* (2025). Advancing brain-computer interface closed-loop systems for neurorehabilitation: systematic review of AI and machine learning innovations. *JMIR Biomedical Engineering, 10*(1), e72218. https: //doi.org/10.2196/72218

[11] Nowinski, W. L. (2024). On human nanoscale synaptome: Morphology modeling and storage estimation. *PLOS ONE, 19*(9), e0310156. https: //doi.org/10.1371/journal.pone.0310156

[12] Hansen, J. Y. *et al.* (2026). Inter-individual variability of neurotransmitter receptor and transporter density in the human brain. *Brain Structure and Function, 231*(1), 13. https: //doi.org/10.1007/s00429-025-03069-2

[13] Jatit, R. (2025). The consciousness simulation gap: Evaluating and benchmarking AI models through functional decomposition. *J. Theor. Appl. Inf. Technol., 103*, 1452–1465. https: //www.jatit.org/volumes/Vol103No10/4Vol103No10.pdf

[14] Jimenez, M., Prieto, A., Hinojosa, J. A., & Montoro, P. R. (2025). Consciousness under the spotlight: The problem of measuring subjective experience. *WIREs Cogn. Sci., 16*, e1697. https: //doi.org/10.1002/wcs.1697
[15] Seth, A. K. (2024). Conscious artificial intelligence and biological naturalism. *Behav. Brain Sci., 47*, e123. https: //doi.org/10.31234/osf.io/tz6an
[16] Mayrhofer, R., Büchner, I. C., & Hevesi, J. (2024). The quantitative paradigm and the nature of the human mind: The replication crisis as an epistemological crisis of quantitative psychology in view of the ontic nature of the psyche. *Front. Psychol., 15*, 1390233. https: //doi.org/10.3389/fpsyg.2024.1390233
[17] Kauffman, S. A., & Roli, A. (2023). What is consciousness? Artificial intelligence, real intelligence, quantum mind and qualia. *Biol. J. Linn. Soc., 139*(4), 530–538. https: //doi.org/10.1093/biolinnean/blac092
[18] Alshehri, H., Al-Nafjan, A., & Aldayel, M. (2025). Decoding pain: A comprehensive review of computational intelligence methods in EEG-based brain-computer interfaces. *Diagnostics, 15*, 300. https: //doi.org/10.3390/diagnostics15030300
[19] Das, A. *et al.* Enhanced EEG signal classification in brain computer interfaces using hybrid deep learning models. *Sci. Rep., 15*(27161), 27161 (2025). https: //doi.org/10.1038/s41598-025-07427-2
[20] Bruce, J. L. Architectural design and implantation strategies of brain-computer interfaces: A comparative review of Neuralink, Synchron, Precision Neuroscience, and Paradromics. *Neurosci. Neurol. Surg., 18*(1), 1-6 (2025). https: //doi.org/10.31579/2578-8868/384
[21] Ognard, J. *et al.* Advances in endovascular brain computer interface: Systematic review and future implications. *J. Neurosci. Methods, 420*(110471), 110471 (2025). https: //doi.org/10.1016/j.jneumeth.2025.110471
[22] Arachchige, A. S. P. M. The blue brain project: Pioneering the frontier of brain simulation. *AIMS Neuroscience, 10*(4), 315-318 (2023). https: //doi.org/10.3934/Neuroscience.2023024
[23] Amunts, K. *et al.* The Human Brain Project-Synergy between neuroscience, computing, informatics, and brain-inspired technologies. *PLoS Biology, 17*(7), e3000344 (2019). https: //doi.org/10.1371/journal.pbio.3000344