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Unlocking the Mind: Revolutionizing the Metaverse with Brain-Computer Interfaces

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Abstract: The current exploration of the Metaverse has now become a focus of research as research has deepened and technology has improved. Based on summarizing the experience of previous research, this paper explores the relationship between Brain-Computer Interface (BCIs) and Metaverse, and analyzes the possibilities, diversity, and creativity that BCIs offer to Metaverse research. Through user cognitive state monitoring, digitized body control, virtual interaction, and imagined voice communication, BCIs enhances the connection between the human brain and external devices to produce a more realistic feeling, thus making it seem as if one is immersed in a world that is unprecedentedly real and unnoticeable. In addition, this paper will focus on the role and application of virtual interaction in four different periods: online shopping, gaming, learning platforms and scientific research. There exists great progress in the application of Metaverse and BCIs in education, healthcare, social contact, and industrial engineering, but there are still many issues to be resolved in cybersecurity, health risks, and ethics.

Keywords: Metaverse, BCI, virtual interaction, possibility

1. Introduction

Metaverse, which consists of the words Meta and Verse (meta comes from the Greek word with the prefix meaning transcendence and verse meaning universe) [1]. Like the Internet, the Metaverse will help people to connect with people in other places and break through the limitations of distance infinitely more. What's more, it can simulate the real environment and even create imaginary virtual things, and can touch and feel these virtual things with all organs as in the real world. Based on the integration of technologies such as Virtual Reality (VR) and Augmented Reality (AR), multi-sensory interactions with virtual environments, digital objects and people are realized [2]. The metaverse is currently moving slowly, and its development relies heavily on advances in hardware and software, especially in areas such as AR and VR. However, little has been explored in the field of biology. Current research favors metaverse and brain-computer interface (BCI) collaborations for advancing metaverse applications in biology. By integrating with the intricacies of brain neuroscience, individuals can truly enter another “real” world. Therefore, the strong connection between BCI and the Metaverse, and how this connection can be utilized to facilitate the emergence of the Metaverse, is the focus of this study. This study demonstrates the relevance of BCIs through a literature review and describes the process by which researchers are utilizing BCIs to implement the Metaverse in the context of the relationship between the Metaverse and BCIs.

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2. BCIs

BCIs, also referred to as a brain machine interface (BMI), is a hardware and software communications system that enables humans to interact with their surroundings, without the involvement of peripheral nerves and muscles, by using control signals generated from electroencephalographic activity. BCI creates a new non-muscular channel for relaying a person's intentions to external devices such as computers, speech synthesizers, assistive appliances, and neural prostheses. That is particularly attractive for individuals with severe motor disabilities. Such an interface would improve their quality of life and would, at the same time, reduce the cost of intensive care [3]. BCl technologies can enable various innovative applications for the Metaverse through this neural path way, such as user coanitive statemonitorina, digital avatar control, virtual interactions, and imagined speech communications [4].

2.1. User cognitive state monitoring

User cognitive state monitoring plays a pivotal role in the development and implementation of BCIs. This process involves the continuous assessment of cognitive states, such as attention, workload, and emotional state, using real-time data collected from brain activity. In recent years, the use of passive BCI systems has become increasingly common in various applications.For example, EEG-based cognitive state monitoring can predict user states, enhancing interaction quality in contexts such as digital environments and user experience (UX) design [5]. Moreover, advanced deep learning models are being employed to detect cognitive states through multimodal data, such as facial emotions, in adaptive environments [6]. These monitoring systems not only improve user interaction but also contribute to optimizing task performance through real-time feedback [7]. In the Metaverse, BCI systems can predict cognitive load, stress, and emotional responses to ensure that users are not overwhelmed. By continuously decoding and tracking human cognitive states, these systems offer enhanced ways to interact with and explore the Metaverse, making virtual experiences more engaging, accessible, and user-centric.

2.2. Digital avatar control

BCIs has emerged as a significant tool in enabling direct communication between the human brain and external devices, including digital avatars. BCIs leverage neural signals to allow users to interact with virtual environments in Metaverse without relying on physical movements, making it particularly beneficial for individuals with motor disabilities. The control of digital avatars through BCIs can be achieved using various signal processing methods, such as Steady-State Visual Evoked Potentials (SSVEP) and P300, which have been successfully integrated into virtual reality (VR) environments for real-time avatar control [8].In particular, recent advancements have shown that BCIs can enable patients with severe paralysis to communicate through digital avatars. By interpreting brain signals, the avatar can represent speech and gestures, thus providing a means of interaction for individuals who would otherwise be unable to communicate. Furthermore, BCIs are becoming integral to the development of a human-centric Metaverse, where avatars controlled by brain signals offer users an immersive, perceptual presence in virtual spaces [4].

2.3. Virtual interactions

This integration of BCI with virtual reality (VR) has garnered significant attention in recent years, and its potential is expanding even further within the Metaverse. Studies have shown that users can control virtual objects, navigate environments, and perform tasks solely through neural activity, enhancing their sense of immersion and presence in virtual spaces [9]. Beyond entertainment, BCI

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holds great promise in virtual collaboration, where users can interact with shared virtual environments for remote teamwork and collective operations. Additionally, virtual environments provide a safe and controlled training space for individuals with physical disabilities, allowing them to engage in tasks otherwise challenging in the real world. The combination of BCI and VR not only offers rich interactive feedback but also induces strong feelings of embodiment through illusions of movement within the virtual body. As a result, the combination of Metaverse and BCI technology is shifting virtual interaction from physical control to more direct brain signal-based interaction, opening new pathways for the future of virtual reality and interaction.

2.4. Imagined speech communications

BCIs can decode neural activity associated with imagined speech by analyzing brain signals using non-invasive methods like electroencephalography (EEG). This enables the translation of neural signals into text or synthetic speech, providing a powerful tool for those who have lost the ability to speak. Studies have demonstrated that BCI systems can recognize and process imagined speech patterns, aiding in communication restoration for individuals with severe impairments [10-11]. The ability to reconstruct intended speech from neural signals has shown great promise, particularly in decoding low-frequency and cross-frequency brain activity to achieve reliable speech output [12-13]. Such systems not only expand communication options for speech-impaired individuals but also represent a major advancement in creating more accessible and personalized virtual environments within the Metaverse .In essence, combining BCI technology with the Metaverse to enable imagined speech communication offers a powerful tool for enhancing virtual experiences, making them more inclusive and accessible, and offering individuals with speech disorders a new means of expression and interaction in digital spaces.

2.5. The relationship between BCI and metaverse

BCI technology is poised to play a transformative role in the development of the metaverse by enabling more immersive and intuitive human-computer interactions. BCIs allow users to interact with virtual environments directly through neural activity, offering hands-free control and personalized experiences within the metaverse [4]. This integration will significantly enhance the level of immersion and user experience in virtual spaces by combining BCI with AR/VR technologies, potentially leading to a "full-dive VR system" where users experience the virtual world as if it were reality. Additionally, BCI can monitor the cognitive state of users, adapting virtual environments in real-time based on their mental and emotional responses [4]. Such innovations open possibilities for remote control, telepresence, and even collaborative work within the metaverse, all driven by the neural signals captured by BCIs [14].

3. Virtual interaction

Virtual interaction forms the foundation upon which the entire concept of immersive, digital environments is built. In the Metaverse, virtual interactions are not just a supplementary feature but the primary means by which users engage with each other, with digital objects, and with the environment itself. The quality and depth of these interactions directly affect the user experience and are fundamental to the success of the Metaverse.

3.1. Online shopping

The combination of BCI technology with the Metaverse is poised to revolutionize virtual interactions in online shopping platforms, creating a more immersive, intuitive, and personalized experience. The

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introduction of immersive technologies such as VR and AR allows users to interact with virtual products. For instance, virtual fitting rooms enable customers to try on clothes in a simulated environment, providing a realistic view of products from all angles, significantly reducing uncertainty in purchase decisions. This interaction enhances customer confidence and leads to increased conversion rates for retailers. Research highlights that virtual interactions, including social elements, further enhance the online shopping experience by facilitating a sense of community and real-time feedback during the decision-making process [15]. Virtual stores have further transformed e-commerce by providing an interactive space where consumers can explore products and interact with their features. In summary, the integration of BCI technology with the Metaverse offers groundbreaking possibilities for the future of online shopping.It brings together immersive virtual environments, personalized interactions, and real-time cognitive feedback to create a shopping experience that is more engaging, intuitive, and responsive to individual needs.

3.2. Game

Virtual interaction in gaming has transformed how players engage with game environments and each other, driven by technologies like Virtual Reality (VR), gesture-based interfaces, and multiplayer frameworks. In terms of Immersive Gameplay through VR, VR allows players to interact with 3D environments, increasing immersion and a sense of presence. This is achieved by enabling free navigation and realistic interactions within virtual worlds [16].In implications of Gesture-Based Interaction, hand gesture technology enables more natural interactions with virtual game environments, improving user experience by bridging the gap between the player and the virtual world [17].Also in terms of Social Interaction in Metaverse Games, Metaverse platforms enhance social dynamics in games, where VR plays a significant role in enabling players to communicate and collaborate more authentically, creating deeply interactive and social experiences.
These developments have pushed the boundaries of gaming, making the experience more immersive, interactive, and socially engaging.

3.3. Learning platform

The integration of BCI technology with the Metaverse in online learning platforms takes virtual interaction to a new level, significantly enhancing educational outcomes. While virtual interaction through video, chat, and group activities already promotes engagement, the addition of BCI enables a more direct and intuitive way for students to interact with the learning environment. By decoding brain signals, BCIs can track students' cognitive states, such as attention, engagement, and stress, allowing for real-time adaptation of learning content. Moreover, virtual platforms enable continuous learning by supporting both synchronous and asynchronous interactions, allowing for flexibility and ongoing collaboration [17]. In the Metaverse, BCIs facilitate immersive, hands-free interactions, where students can control avatars, access information, and engage in activities through thought alone. This can deepen the sense of presence, allowing students to "physically" interact with simulated objects and tasks in ways that mimic real-world experiences, fostering better understanding and retention [18]. In conclusion, virtual interaction in learning platforms boosts engagement, personalization, and continuous learning, while embracing cutting-edge technologies like the Metaverse.

3.4. Scientific research

In psychological studies, VR provides researchers with the ability to create complex, controlled environments that simulate real-world social settings, enabling participants to exhibit natural behavior while maintaining strict experimental controls. This capability has been instrumental in

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exploring human emotions, social interactions, and behavioral responses in ways that were previously difficult to achieve in physical environments. Additionally, in the field of human-computer interaction (HCI), VR enhances the interaction between users and virtual systems, allowing for real-time feedback and adaptive environments. Such applications are particularly beneficial in cognitive science research and educational settings, such as language learning [19]. Moreover, VR's ability to create immersive environments has revolutionized the study of social interactions, enabling researchers to investigate cooperation, conflict, and group dynamics in controlled virtual spaces. Beyond social and cognitive studies, VR is also extensively applied in education and training, where its immersive nature aids in skill development and the examination of cognitive load and learning outcomes in disciplines such as medicine and engineering [20]. Overall, the integration of VR in research has expanded the boundaries of scientific inquiry, providing innovative ways to explore human behavior, learning, and interaction.

4. Discussion

The integration of BCIs with the Metaverse offers numerous benefits, which significantly enhance user experiences and expand possibilities in virtual environments. BCIs enable users to interact with the Metaverse through brain signals, allowing for more intuitive, immersive, and seamless interactions, bypassing traditional input devices like keyboards and controllers. This direct brain-to-computer communication can enhance accessibility for individuals with physical disabilities, offering them new ways to engage with digital spaces and overcome barriers to interaction. In the context of rapid technological advancement, the integration of BCIs and the Metaverse has emerged as a focal point of research; however, this application is fraught with numerous risks. Firstly, the cybersecurity vulnerabilities of BCIs can lead to hacking, allowing unauthorized access to users' thoughts or commands, which can result in privacy breaches and manipulation. Secondly, the health risks associated with invasive BCIs cannot be overlooked, including surgical infections, tissue damage, and long-term neurological effects [21]. Moreover, the potential for "brain tapping" raises ethical concerns regarding the ownership of thoughts and user consent, which could be exploited within the Metaverse. In terms of mental health, prolonged immersion in virtual environments may contribute to issues such as addiction and desensitization, adversely affecting users' psychological well-being [22]. Finally, adversarial attacks could exploit BCIs by providing misleading sensory information, potentially leading to harmful physical or psychological reactions. Therefore, while BCIs hold the potential to enhance user experiences in the Metaverse, the existence of these risks necessitates stringent safety measures and ethical scrutiny in technological development and application.

5. Conclusion

In conclusion, the integration of BCIs technology into the Metaverse presents unprecedented opportunities for enhancing user experiences in virtual environments. Through applications such as user cognitive state monitoring, digital avatar control, virtual interaction and imagined speech communication, BCIs promise to deepen immersion and personalization within the Metaverse. However, these advancements come with significant challenges, including cybersecurity risks, ethical concerns about privacy and thought ownership, and potential adverse health effects. Moving forward, it is critical to address these risks while leveraging the transformative potential of BCIs to shape the future of virtual interactions and create more engaging, intuitive digital spaces. This article has some shortcomings, it only analyzes theoretically and lacks the support of experimental data. And the cited references are not perfect for all experiments, there are still places to improve. In the future, I will strengthen the improvement in experimental aspects and theoretical basis, and conduct in-depth

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research on how to enhance the Metaverse with BCI in practice, so as to realize the real virtual universe.What's more, Continued research and careful ethical consideration will be essential to ensuring that these technologies evolve in a way that maximizes their benefits while minimizing harm.

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