Human-Computer Interaction in Brain-Computer Interfaces via Virtual Environments

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ABSTRACT

Brain-Computer Interfaces (BCI) aim to establish communication between the human brain and computers, yet face efficiency and reliability challenges. Recent research suggests that leveraging Virtual Environments (VEs) could enhance Human-Computer Interaction (HCI) in BCI systems. This paper explores how VEs' characteristics can enhance HCI, potentially addressing BCI drawbacks, with a focus on recent advances and future trends in the field.

INTRODUCTION

Brain-Computer Interfaces (BCI) are systems that attempt to establish communication between the human brain and a computer in order to replace the natural connection between central nervous system (CNS) and musculoskeletal system. The interest on BCI research has been greatly increased due to a wide variety of applications, including neurorehabilitation, robotic devices, exoskeletons, and domotic systems. Although BCI research started in the sixties, this technology is not efficient or reliable yet for everyone at any time. Over the past few years, some researchers such as Fabien Lotte and Camille Jeunet have argued that main BCI flaws could be associated with human-computer interaction (HCI) issues . As can be seen in Figure 1, virtual environments (VEs) have many distinctive features that can significantly improve HCI in highly demanding and interactive systems such as BCI. The present paper moves on to describe in greater detail five key points:

(i) Main characteristics of VEs
(ii) How those characteristics can improve HCI
(iii) How the improvement of HCI via VE may help to overcome several drawbacks of BCI
(iv) Extensive revision of recent advances in the field
(v) Strong tendencies of this research area

Virtual Environments: System Requirements and User Concerns

People's remarkable perceptual abilities challenge the development of Virtual Environments (VEs) capable of deceiving human perception. VEs encompass system requirements like 3D generation and Human-Computer Interaction (HCI), alongside sensory output interfaces such as auditory, visual, and haptic devices. Interaction techniques include graphical interfaces, speech recognition, and tracking systems for immersive experiences. User concerns involve achieving cognitive equivalence between virtual and real worlds, emphasizing presence, immersion, user characteristics, and involvement. Immersion relies on sensory presentation quality and interaction level, while individual differences in perception, cognitive representation, skills, and involvement significantly impact virtual interactions.

Achieving high user involvement depends on control over sensor mechanisms and positive social interaction within the VE, facilitating complete immersion and detachment from reality. Addressing both technological and human aspects is crucial for effective VE design, ensuring seamless integration and user engagement in virtual environments.

Figure 1: Structure of a virtual environment on the basis of two key elements: system requirements and user concerns.

Finally, user skills vary significantly across individuals, distorting the virtual interaction. Some instances of such skills are perceptual-motor abilities, mental states, traits, needs, preferences, and experience. Last but not least, the last element of VEs in terms of user concerns is involvement. The relation between the VE as a space and the individual body is called involvement. When the level of control that users have over the virtual sensor mechanisms is high, and their social interaction with the VE is good, users focus on the system suppressing possible constraints of the VE. As a result, users forget the real environment achieving a complete involvement.

Improvement of Human-Computer Interaction via Virtual Environments

3D representations in Virtual Environments (VEs) significantly enhance user experience (UX) compared to 2D representations, as they stimulate cognitive processes crucial for Human-Computer Interaction (HCI). These processes, including spatial memory storage, attention, and perception, are actively engaged as users navigate and explore the VE, offering potential for modulation to align with research goals and user needs.

VEs excel in fostering user engagement and positive UX, contributing to efficient HCI and validated as effective, safe, and motivating platforms for user-system interaction. However, VEs alone cannot optimize HCI, as user interaction within them may become inefficient without consideration of human factors and user characteristics alongside realistic and sophisticated design principles.

Integration of Virtual Environments and Brain-Computer Interfaces

VEs are extensively utilized in BCI development to enhance motivation and immersion across various scenarios, from daily life situations to video games. Applications include controlling virtual cars, navigating virtual environments like bars or flats, and exploring virtual streets. Common uses include domotic systems where avatars manipulate virtual objects like lights or TVs. Other applications span wheelchair control, flying simulators, and virtual city environments. BCI functions as a non muscular communication channel, involving calibration and control stages.

Calibration trains a machine to recognize user brain patterns, while control enables device manipulation based on brain state modulation through external or internal stimuli. Invasive methods like electrocorticography and noninvasive methods like EEG are employed for signal acquisition, with EEG being widely favored. Feature generation and translation enable control signal generation for device operation in BCI systems.

BCI systems are categorized as active, reactive, and passive. Active systems rely on user-generated commands, often using motor imagery tasks like slow cortical potentials, sensorimotor rhythms, and movement-related cortical potentials. Reactive systems respond to external stimuli such as visual or auditory cues, typically detecting event-related potentials like the P300 associated with selective attention and memory. Steady-state evoked potentials are also utilized in reactive systems for sensory input decoding. Passive systems, on the other hand, monitor users' mental states without direct control, detecting factors like mental workload, fatigue, and errors during interactions with various systems.

Relevance of Brain-Computer Interfaces-

BCI development faces challenges in portable and reliable technology, accurate algorithms, feedback techniques, and interactive methods. Recent advancements in hardware and software, coupled with greater understanding of the central nervous system (CNS), drive BCI research. Additionally, recognition of needs among individuals with neurological disorders like cerebral palsy and stroke fuels BCI progress.

Industrial and medical sectors show keen interest in BCI applications, spanning replacement of CNS function, restoration of mobility, enhancement of human reactions, supplementation of natural CNS output, and improvement of device functionality. Applications range from assisting those with neurodegenerative diseases to enhancing human capabilities and aiding in industrial tasks.

Controversial Issues -

Despite increasing promises, Brain-Computer Interfaces (BCIs) still face several pitfalls. Firstly, inadequate attention to end-user requirements, including human aspects, learning strategies, and interactive design, contributes to BCI illiteracy, where up to 40% of healthy users struggle to control active BCI systems. Secondly, user behavior and experience depend heavily on coping with control tasks, previous abilities, and motivation, necessitating effective training procedures and feedback methods.

Thirdly, real-world environments pose challenges such as noise and dynamics, requiring versatile and robust signal processing and pattern recognition algorithms. Lastly, there's a lack of clear metrics for assessing BCI performance, with current metrics often focusing on machine factors like accuracy, but not necessarily indicating user comfort or task concentration. Addressing these pitfalls is crucial for advancing BCI technology towards more effective and user-friendly systems.

How Can VE Improve BCI in Terms of HCI?

BCI development extends beyond system design to encompass high-quality Human-Computer Interaction (HCI), crucial for exhaustive user training. Key aspects of this training include repetition, feedback, and motivation, essential for users to learn control tasks and automate them over time. However, isolating cognitive processes in BCI control while disregarding human factors and environmental demands complicates HCI in BCI applications. Virtual Environments (VEs) have emerged as an attractive solution, enriching HCI by providing appropriate sensory feedback and enabling users to learn control tasks under realistic conditions.

Users exhibit greater comfort and motivation when manipulating BCI systems in VEs due to their immersive nature and ability to offer a wide range of interaction possibilities. VEs not only enhance BCI performance but also facilitate prototyping and are feasible for diagnostic and therapeutic purposes. Their immersive nature fosters a sense of presence, aiding BCI performance by accurately representing real-life elements and providing meaningful feedback within a contextualized environment. Users can perceive and interact with mental tasks more explicitly in VEs, fostering sensory information and agency, thus enhancing user engagement and learning.

BCI Implementation under More Realistic Situations-

Laboratory settings pose limitations on human interaction, but virtual simulations enable more direct interaction with the environment, facilitating learning under realistic conditions. Additionally, the impact of human factors and distractions on BCI usability can be studied concurrently in virtual environments. The term "realistic situation" extends beyond technological sophistication to encompass the relevance of the virtual environment for users, which can significantly impact system performance. For instance, a study involving imagining the drawing of Chinese characters demonstrated that explicit representation of tasks in virtual environments could enhance Motor Imagery (MI) generation.

Participants using this paradigm achieved higher system accuracy compared to those using traditional methods, indicating the importance of contextualized virtual environments in leveraging users' previous knowledge and improving EEG signal modulation through MI activity. This underscores the significance of providing appropriate environmental conditions in virtual environments to enhance BCI performance.

User Mental State -

User mental state plays a crucial role in achieving stable performance in Brain-Computer Interface (BCI) systems. The modulation of EEG signals through Motor Imagery (MI) activity is significantly influenced by the user's mental balance, making control tasks more differentiable. For instance, a study designed an interactive system for mindfulness and meditation, utilizing virtual reality (VR) technology to create immersive experiences.

By tracking hand movements and recording EEG activity, the system facilitated meditation and mindfulness practices, enhancing MI training effectiveness. Similarly, another study proposed a virtual environment where users controlled an avatar based on their levels of concentration, utilizing ERP-based BCIs. This setup significantly improved user-system interaction, emphasizing the importance of maintaining concentration for BCI performance enhancement.

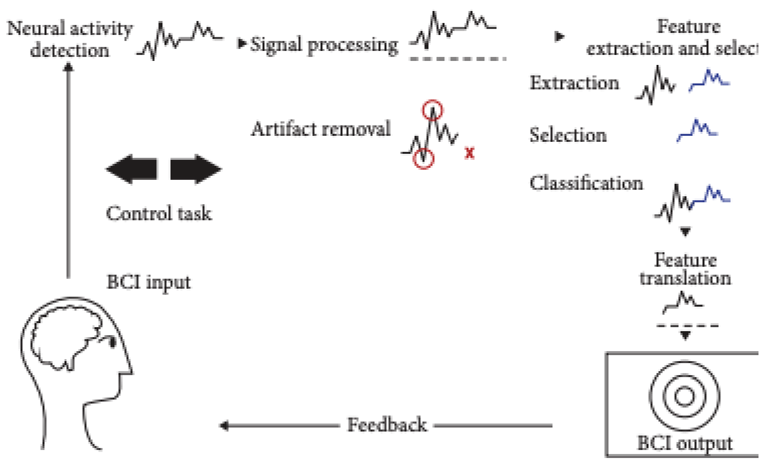

FIGURE 2: Block diagram of a brain-computer interface system.

Advances in the Field

In the realm of BCI systems, Virtual Environments (VEs) have seen widespread application, particularly in Active and Reactive BCIs for navigation and enhancing user motivation. Reactive BCIs have been employed for controlling household devices and virtual avatars using evoked potentials like P300 and steady-state visual evoked potentials (SSVEPs). Simulation scenarios in VEs range from daily activities to more engaging experiences such as playing tennis or immersive virtual plays. Research on VE applications in BCIs emphasizes human behavior, learning, adaptability, and the significance of virtual scenarios in facilitating Motor Imagery (MI) skills acquisition and improving EEG pattern recognition efficiency.

This research underscores the importance of using VEs to enrich Human-Computer Interaction (HCI), providing sensory-enriched interfaces that enhance user comfort and attention. Prioritizing user learning and adaptation could significantly enhance BCI performance, highlighting the importance of focusing on human factors alongside computational algorithms. Future discussions delve into VEs as working environments and control panels, navigation purposes in BCI systems, and the relevance of user mental state in sensory-enriched environments. Notably, recent works in this area are summarized for further exploration.

Conclusion

The first applications of VEs in BCI research concerned the strength of user motivation, the maintenance of attention for longer periods, and the implementation of favorable feedback mechanisms. However, virtual technology had been only seen as a tool to render illusory effects of realism by means of 3D graphics and electronically equipped helmets, headphones, goggles, and gloves. At present, tridimensional representations have become an attractive alternative to enrich HCI since they stimulate cognitive processes that take place while the user navigates and explores VEs, which are mainly associated with workload management, long term memory access, visuospatial processing, regulation of emotions and attention, and decision-making. The evidence presented thus far shows that VEs can set out working environmental conditions, maximize the efficiency of BCI control panels, implement navigation systems based not only on user intentions but also on user emotions, and regulate user mental state to increase the differentiation between control and uncontrolled modalities.

Conflicts of Interest-

The authors declare that they have no conflicts of interest.

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