Proceedings of the 3rd International Conference on Signal Processing and Machine Learning
DOI: 10.54254/2755-2721/4/20230474

A review on BCI and VR: From past interactions to future development

Shuyan Hao

Beijing National Day School, Beijing, 100039, China

Hao_shuyan@outlook.com

Abstract. A cutting-edge method in the fields of game entertainment and medical rehabilitation is the fusion of virtual reality (VR) and brain-computer interfaces (BCI). However, as the technology is still in its infancy, along with its development, there are many limitations as well that could be improved in the future. This paper reviews the achievements of BCI-VR in two of the most promising fields: neurorehabilitation and game entertainment in the past ten years. Meanwhile, it also summarizes the current limitations in these fields coupled with potential pathways for further research in the future. To conclude, in the realm of neurorehabilitation for the use of BCI-VR, there are technologies from a hybrid BCI-VR system to a closed-loop real-time BCI-VR system for gait therapy system, and even a multi-model BCI-VR. There are also studies on the utility of BCI-VR in clinical medicine. While for the application of BCI-VR in the game entertainment industry, on the one hand, there are quite a lot of achievements ranging from using a multimodal BCI to control the protagonist of a VR game to allowing players to do multitasks, as well as the later improvements on the real-time operation and feedback experience for the user. On the other hand, there are still some limitations such as low accuracy and a limited number of action demands. In the future, the investigation will still be continued.

Keywords: Brain-Computer Interface, Virtual Reality, BCI-VR, Neurorehabilitation, Game Entertainment.

1. Introduction

Instead of using the typical brain signal output channels (peripheral nerve and muscle tissue), the brain may now connect with computers thanks to a cutting-edge approach called brain-computer interface (BCI) [1]. BCI was widely used in the fields such as medical rehabilitation [2], robotics [3], as well as game entertainment [4]. Virtual reality (VR) technology creates virtual environments (VEs) by utilizing computer graphic systems. Users are submerged in a virtual three-dimensional environment where they can engage [5]. With the considerable advancements made in their respective fields of BCIs and VR over the past fifty years [6], the interaction of the two has also made important progress [7]. BCI with VR, also known as BCI-VR, is a new field with increasing popularity. With the help of this technology, individuals can encounter a stimulating virtual reality environment that is fully immersive, increasing their engagement and immersion [8]. The BCI-VR system has a variety of appealing applications in the field of rehabilitation medicine, especially for the treatment of stroke, spinal cord injury (SCI) [9], attention deficit hyperactivity disorder (ADHD) [10], Alzheimer's disease (AD) [1], and Parkinson's disease patients since it can combine the advantages of BCI and VR (PD)While in the game entertainment area, VR and BCI are both outstanding prospects for improving the fun and pleasure possibilities in video games [11]. However, BCI-VR exposes many difficulties through the cooperation of the two technologies. This review aims to overview the development of BCI-VR specifically in the fields of neurorehabilitation and game entertainment, some of the problems faced by the technology, and its potential future pathway. This research combs some significant breakthroughs of BCI-VR and organizes them in chronological order within the past ten years, which supplements to this research field.

2. Current status of the research on BCI-VR in neurological rehabilitation

There is growing interest and research into the possible role of BCI-VR technology in improving recovery from central nervous system damage. A hybrid BCI-VR system with individualized motor training in a VR environment was proposed by Badia et al. in 2012. The system made use of brain processes for operation and monitoring, as well as a neurofeedback paradigm that employed mental imagery to activate secondary or indirect pathways and gain access to unharmed corticospinal regions [12]. To help people with SCI develop their navigational skills, Zheng et al. presented an experimental study on virtual-navigation activities in 2013 [13]. In 2015, Luu et al. proposed a real-time closed-loop BCI system for post-stroke gait rehabilitation. To manage the walking motions of a virtual avatar while walking on a treadmill, they used scalp electroencephalography (EEC). EEC was utilized to decipher the lower limb joint angles. Their investigation demonstrated that it is able to learn to operate a walking avatar while experiencing both standard and abnormal visuomotor disturbances, involving cortex modifications, using a closed-loop BCI [14]. In 2016, Salisbury et al. carried out two pilot studies that ensure novel technology's viability throughout the subacute phase of neurorehabilitation [2]. Towards the creation of a ground-breaking training paradigm for boosting the efficacy of rehabilitation from the top down, Luu et al. conducted a second study later in 2017 to investigate how cortical involvement changes during human treadmill walking with and without BCI control of a walking avatar [15]. In order to help persons with ADD and ADHD become more focused, Alchalabi et al. developed a VR game using wireless wearable BCI devices in the same year. There was also a non-drug approach to treating schizophrenia suggested by Fer-Fernandez-Caballero et al. using BCI and VR technologies [13]. An MI-based BCI and VR system for stroke rehabilitation was introduced by Lupu et al. in 2018 [16]. Due to some of the limitations of BCI-VR, most recently, the emergence of a new technology is noteworthy-hybrid BCI-VR. The fundamental components of a hybrid BCI-VR are the integration of multi-modal sensors and the combined usage of BCI paradigms. In 2022, Wen et al. examined the BCI-VR systems incorporating performance capture, eye tracking, and Electro-Oculogram and Electromyography respectively [17]. They discovered that a hybrid BCI-VR can enhance the precision and quantity of the operational instructions provided, as well as the participants' motivation in some aspects.

3. Current status of the research on BCI-VR in game entertainment

BCI-VR has also been employed in various fields other than medical neurorehabilitation. For instance, it has gained much progress in the game entertainment industry too. In 2013, Leeb et al. carried out a study using multimodal BCI to control the main character penguin in a VR game. They found out that under the variations in visual complexity and task demand, a transfer of skills is possible. Additionally, a second motor task would not affect the way that the BCI performed. Thus they discovered a suitable approach to multimodal BCI implementation which allows users to perform multi-tasking parallelly [18]. In 2015, in order to elicit Steadystate Visually Evoked Potential responses, Koo et al. provided an immersive BCI that makes use of a virtual-reality head-mounted display And they show that visual stimuli in VRHMD do in fact increase BCI user engagement. An experiment on a VR maze game utilizing SSVEP elicited by visual cues on neighboring cells had been used to prove their method. In this game, the objective is to direct a ball into a target location in a 2D grid map in a 3D space by sequentially selecting one of four surrounding cells. According to the results, the average information transfer rate for VRHMD is 10% better than it is for monitor displays, and users report that the suggested method makes it simpler for them to play games [19]. In 2016, based on the steady-state visually evoked potentials paradigm and the Emotiv EPOC headset, a prototype three-class brain-computer interface

DOI: 10.54254/2755-2721/4/20230474

system is created by Martišius et al.. For user feedback, An online target shooting game developed in the OpenViBE setting was employed. As a consequence of real-time output and operation, their findings demonstrate the potential of BCI as an interaction tool for complicated applications. The outcomes further demonstrate the viability of BCI even when utilizing consumer-grade and low-cost EEG acquisition equipment with limited resolution. The topic can therefore be prepared by a non-expert supervisor due to the decreased system cost, mobility, and subject preparation time that is made possible by this. The BCI technology may be employed by the general population so they can experience amusing apps, games, and virtual reality by enhancing system cost and ergonomics [20]. By developing and running a BCI-VR application for real-time signal processing, MacMahon et al. showed in 2018 that it is feasible to create a low-cost, accessible, BCI-VR game control development environment prototype [21]. Users can manage a simple 3D object within a simple Virtual Reality Environment thanks to real-time signal processing, which concentrates on extracting ERD/ERSs from the Precentral Gyrus (Motor Cortex).

4. Current limitations of BCI-VR

While BCI-VR has been developed at a relatively fast pace in the last decade, there are still many existing limitations. Some of the limitations are due to BCI itself, which causes prevention from extensive application of BCI-VR. For instance, a meager amount of action commands, and poor precision [8]. More questions are waiting for a resolution. For example, the BCI system's current information transfer rate is insufficient. In the BCI system, EEG signals are flimsy and susceptible to outside interference, including those from motor, electromyography, and electrooculography. The external world considerably disturbs the EEG signal, especially when the subject performs a lot of motions in the virtual scenario. Subjects require extensive motor imagining training before formally employing the MI-based BCI-VR, and the individual differences exist in how training affects brain control accuracy in the BCI-VR system. Simultaneously, it is necessary to improve the virtual scene's accuracy of brain control. Future research must focus on enhancing the generalization performance and accuracy of the EEG analysis approach. The P300 and SSVEP paradigms-based BCI-VR system places users in a passive state, and to monitor the virtual role, that affects the interaction experience between the user and the virtual role, they should closely examine the inputs in the VR setting. [13]. Furthermore, in the multi-model sensors BCI-VR system, the development is still hampered by technological issues, such as the best Feature extraction and data-fusion algorithms for high-dimensional data [17]. When putting BCI-VR into the application, as a series of commands are extracted, the number of false negatives rises. Walking, undesirable facial expressions, and eye movement all create noise signals in EEG recordings. In some cases, during the user experience process, these distortions are difficult to prevent and impossible to eliminate [7]. The usability of BCI and VR, managing technological problems, and financial viability are some of the other core concerns. More realistic visual paradigms may be required. Few research organizations have access to the virtual environments used in many laboratory studies since they are not widely used in commerce. Other facilities that are common in use are also extremely costly and the price lies above the average asset of the majority of common people. Arrays of screens that enable full-body engagement are not affordable to many people, not to mention the whole set of equipment. The financial feasibility largely depends on the future development of technology. The adoption of technology in clinical medicine will certainly be hampered by cost considerations with huge expenditure on equipment, staff training, and statistician support. Therefore, mainstream rehabilitation implementation would be financially challenging, particularly in light of recent health care developments that have resulted in decreasing pay for clinical services and an emphasis on bundled services [2].

5. Future potential improvement for BCI-VR

Since there are so many problems still waiting to be solved, it can be told some potential ways for future development for BCI-VR. This paper lists several potential developments in the future. First of all, future studies have to enhance the BCI-VR system's real-time preprocessing capabilities for EEG signals.

DOI: 10.54254/2755-2721/4/20230474

Improved accuracy and generalization performance are required for the EEG analysis method. It must be researched whether a more organic brain-machine interface mode based on P300 or SSVEP would make the BCI-VR system more helpful in practical applications [1]. Furthermore, the effects of various stimulus fidelity and immersion levels, as well as their potential clinical efficacy, must be studied in more detail [2]. Also, a vital innovation should focus on methods to improve user experience. There should be a way that can be found to simplify the use of MI base BCI system, stereotyping some of the orders that users always mean to imagine, thus decreasing the difficulty of utility by participants and making the technology more humanized. Moreover, a way should be figured out to reduce the impact of inevitable distractions made by the subject’s surroundings on the signals in the BCI-VR. Or there should be specific rooms in hospitals especially built for neurorehabilitation patients using BCI-VR equipment. However, before that, the extraordinary price of the equipment must first be cut down. Further studies need to search how these facilities could be upgraded and simplified in configuration and usage.

6. Conclusion

Past scientists have already devoted a lot to the relatively novel field of BCI-VR. Looking back at the past, there are technologies from a hybrid BCI-VR system to a real-time closed-loop BCI-VR system for gait rehabilitation when utilizing BCI-VR in neurorehabilitation, even to a multi-modal BCI-VR. Related research on the utility of BCI-VR in clinical medicine has also been made. At the same time, BCI-VR has also achieved a lot in the game entertainment industry, from using a multimodal BCI to control the protagonist of a VR game to allowing players to do multitasks, as well as improving the real-time operation and feedback experience for the user. Though many problems are still waiting to be solved, a significant step has already been taken in BCI-VR. In the future, further studies would be needed to continue investigating issues such as improving the BCI-VR system's ability to preprocess EEG inputs in real-time or further improvements in the user’s experiences. All in all, future development will become more and more rapid since science and technology are advancing at an unparalleled rate. Despite there is still a long way ahead of combining BCI and VR to realize the ultimate aim of generalizing the technology or popularizing it in every household, BCI-VR will be certain to gain nourishment in such a rapidly changing high-technology world and reach its summit someday soon. And as a helpful and serviceable technology in all walks of life, BCI-VR is sure to benefit the future world.

References

[1] Wen, D., Fan, Y., Hsu, S. H., Xu, J., Zhou, Y., Tao, J., ... & Li, F. (2021). Combining brain-computer interface and virtual reality for rehabilitation in neurological diseases: A narrative review. Annals of physical and rehabilitation medicine, 64(1), 101404.

[2] David B. Salisbury, Marie Dahdah, Simon Driver, Thomas D. Parsons & Kathleen M. Richter (2016) Virtual Reality and Brain Computer Interface in Neurorehabilitation, Baylor University Medical Center Proceedings, 29:2, 124-127, DOI: 10.1080/08998280.2016.11929386.

[3] Berger, T. W., Chapin, J. K., Gerhardt, G. A., McFarland, D. J., Principe, J. C., Soussou, W. V., ... and Tresco, P. A. (2008). Brain-Computer Interfaces: An international assessment of research and development trends. Springer Science and Business Media.

[4] Alomari, M. H., Abubaker, A., Turani, A., Baniyounes, A. M., and Manasreh, A. (2014). EEG mouse: A machine learning-based brain-computer interface. Int. J. Adv. Comput. Sci. Appl, 5, 193- 198.

[5] Vasiljevic, G. A. M., & de Miranda, L. C. (2020). Brain–computer interface games based on consumer-grade EEG Devices: A systematic literature review. International Journal of Human–Computer Interaction, 36(2), 105-142.

[6] Fazel-Rezai, R., Allison, B. Z., Guger, C., Sellers, E. W., Kleih, S. C., & Kübler, A. (2012). P300 brain computer interface: current challenges and emerging trends. Frontiers in neuroengineering, 14.

DOI: 10.54254/2755-2721/4/20230474

[7] Reza A-A, Mohammad K, Dorian YC. (2019) Brain-Computer Interface in Virtual Reality.

[8] Cattan, G., Andreev, A., & Visinoni, E. (2020, November 14). Recommendations for integrating a p300-based brain–computer interface in virtual reality environments for gaming: An update. MDPI. Retrieved August 14, 2022, from https://www.mdpi.com/2073-431X/9/4/92/htm.

[9] With the ability to combine the benefits of BCI and VR, the BCI-VR system has a wide range of appealing applications in the field of rehabilitation medicine, particularly for the treatment of stroke, spinal cord injury (SCI).

[10] Rohani, D. A., Sorensen, H. B., & Puthusserypady, S. (2014, August). Brain-computer interface using P300 and virtual reality: a gaming approach for treating ADHD. In 2014 36th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (pp. 3606-3609). IEEE.

[11] Millán, J. D. R., Rupp, R., Mueller-Putz, G., Murray-Smith, R., Giugliemma, C., Tangermann, M., ... & Mattia, D. (2010). Combining brain–computer interfaces and assistive technologies: state-of-the-art and challenges. Frontiers in neuroscience, 161.

[12] Using a hybrid brain-computer interface and virtual reality system to monitor and promote cortical reorganization through motor activity and motor imagery training. IEEE Xplore. (n.d.). Retrieved July 31, 2022, from https://ieeexplore.ieee.org/document/6363609.

[13] Wen, D., Fan, Y., Hsu, S.-H., Xu, J., Zhou, Y., Tao, J., Lan, X., & Li, F. (2020, September 2). Combining brain-computer interface and virtual reality for rehabilitation in neurological diseases: A narrative review. Annals of Physical and Rehabilitation Medicine. Retrieved July 31, 2022, from https://www.sciencedirect.com/science/article/pii/S1877065720301184.

[14] T. P. Luu, Y. He, S. Brown, S. Nakagome and J. L. Contreras-Vidal, "A closed-loop brain-computer interface to a virtual reality avatar: Gait adaptation to visual kinematic perturbations," 2015 International Conference on Virtual Rehabilitation (ICVR), 2015, pp. 30-37, DOI: 10.1109/ICVR.2015.7358598.

[15] Luu, T.P., Nakagome, S., He, Y. et al. Real-time EEG-based brain-computer interface to a virtual avatar enhances cortical involvement in human treadmill walking. Sci Rep 7, 8895 (2017). https://doi.org/10.1038/s41598-017-09187-0.

[16] Lupu RG, Irimia DC, Ungureanu F, Poboroniuc M, Moldoveanu A. BCI and FES-based therapy for stroke rehabilitation using VR facilities. Wirel Commun Mob Com 2018;2018:1–8. http://dx.doi.org/10.1155/2018/4798359.

[17] The current research of combining multi-modal brain-computer interfaces with virtual reality. IEEE Xplore. (n.d.). Retrieved July 31, 2022, from https://ieeexplore.ieee.org/document/9310231.

[18] R. Leeb, M. Lancelle, V. Kaiser, D. W. Fellner, and G. Pfurtscheller, "Thinking Penguin: Multimodal Brain–Computer Interface Control of a VR Game," in IEEE Transactions on Computational Intelligence and AI in Games, vol. 5, no. 2, pp. 117-128, June 2013, doi: 10.1109/TCIAIG.2013.2242072.

[19] B. Koo, H. -G. Lee, Y. Nam and S. Choi, "Immersive BCI with SSVEP in VR head-mounted display," 2015 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), 2015, pp. 1103-1106, doi: 10.1109/EMBC.2015.7318558.

[20] Ignas Martišius, Robertas Damaševičius, "A Prototype SSVEP Based Real Time BCI Gaming System", Computational Intelligence and Neuroscience, vol. 2016, Article ID 3861425, 15 pages, 2016. https://doi.org/10.1155/2016/3861425.

[21] M. McMahon and M. Schukat, "A low-Cost, Open-Source, BCI- VR Game Control Development Environment Prototype for Game Based Neurorehabilitation," 2018 IEEE Games, Entertainment, Media Conference (GEM), 2018, pp. 1-9, doi: 10.1109/GEM.2018.8516468.