COVER FEATURE

Brain-Computer Interfaces, Virtual Reality, and Videogames

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Major challenges must be tackled for brain-computer interfaces to mature into an established communications medium for VR applications, which will range from basic neuroscience studies to developing optimal peripherals and mental gamepads and more efficient brain-signal processing techniques.

Far beyond science-fiction clichés and the image of a person connected to cyberspace via direct cerebral implants as in *The Matrix*, brain-computer interfaces (BCIs) can offer a new means of playing videogames or interacting with 3D virtual environments (VEs).

Only in recent years have research groups been attempting to connect BCIs and virtual worlds. However, several impressive prototypes already exist that enable users to navigate in virtual scenes or manipulate virtual objects solely by means of their cerebral activity, recorded on the scalp via electroencephalography (EEG) electrodes. Meanwhile, virtual reality (VR) technologies provide motivating, safe, and controlled conditions that enable improvement of BCI learning as well as the investigation of the brain responses and neural processes involved.

STATE OF THE ART

VR technologies and videogames can be powerful BCI companions. Researchers have shown that BCIs provide suitable interaction devices for VR applications[1] and videogames.[2] On the other hand, the community now widely accepts that VR is a promising and efficient medium for studying and improving BCI systems.

Brain-computer interaction with virtual worlds

Interactions with VE can be decomposed into elementary tasks[3] such as navigating to change the viewpoint or selection and manipulation of virtual objects.

In virtual worlds, current BCI systems can let users change the camera position in a VE toward the left or right by using two different brain signals, such as left- or right-hand motor imagery (MI) or two steady-state visual-evoked potentials (SSVEPs) at different frequencies. MI-based BCIs have also been used to control the steering of a virtual car,[4] explore a virtual bar,[1] or move along a virtual street[5] or through a virtual flat.[6] These BCIs typically provide the user with one to three commands, each associated with a given task.

Concerning selection and manipulation of virtual objects, developers base most BCIs on P300 or SSVEP signals. In these applications, virtual objects generally provide a stimulus that triggers a specific and recognizable brain signal that draws the user's attention to the associated object to select and manipulate it. Those BCIs let the user turn on and off devices such as a virtual TV or lamp using the P300,[7] or manipulate more complex objects such as virtual avatars using SSVEP.[8]

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Virtual reality for studying and improving BCI

Researchers can use VR to study and improve brain-computer interaction. The technology also helps researchers perform safe and perfectly controlled experiments. For example, it has enabled the simulation of wheelchair control with a BCI[5] and various BCI groups have used it to study how users would react while navigating in a complex 3D environment using a BCI in close to real-life conditions.[6,9]

Several studies have compared feedback consisting of classical 2D displays with feedback consisting of entertaining VR applications.[4,6] These studies show that users' performance ranked higher with VR feedback than with simple 2D feedback. Moreover, evidence suggests that the more immersive the VR display, the better users perform.[1,6] Even though some observations await confirmation, VR appears to shorten BCI learning and increase users' performance by increasing their motivation.

TYPICAL APPLICATIONS

Several universities and laboratories have pursued the creation of more compelling interaction with virtual worlds using BCI, including University College Dublin, MediaLabEurope, Graz University of Technology, University College London, the University of Tokyo, and INRIA.

MindBalance videogame

Researchers at University College Dublin and MediaLabEurope have created *MindBalance,*[8] a videogame that uses BCI to interact with virtual worlds. As Figure 1 shows, the game involves moving an animated 3D character within a virtual environment. The objective is to gain one-dimensional control of the character's balance on a tightrope using only the player's EEG. The developed BCI uses the SSVEP generated in response to phase-reversing checkerboard patterns. The SSVEP simplifies the signal-processing methods dramatically so that users require little or no training.

The game positions a checkerboard on either side of the character. These checkerboards are phase-reversed at 17 and 20 Hz. Each game begins with a brief calibration period. This requires the subject to attend to the left and right checkerboards, as indicated by arrows, for 15 seconds each. The system uses the recorded data to calibrate the BCI and adapt its parameters to the current player's EEG. This process repeats three times.

When playing the game, the user must control the animated character, which is walking a tightrope while being subjected to random movements to the left and right. If the user does not accurately attend to the correct side to control the character after initially losing balance (first degree), the character will move to a more precarious (second degree) state of instability, then, progressively, to an unrecoverable state (third degree), at which point the character falls.

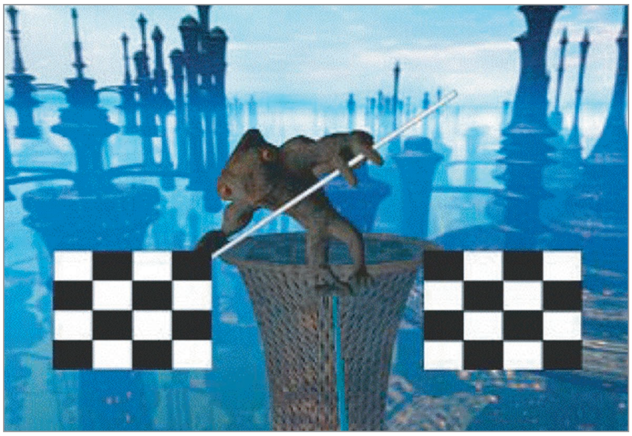


Figure 1. The MindBalance *videogame. The player must control the balance of a virtual character walking a tightrope by applying visual attention to two flickering checkerboards.*

For correct user control, the animated character will move up a degree of balance until perfectly upright, allowing forward progress to resume. Audiovisual feedback streams into the user's file, providing information on the character's stability. The visual feedback shows the degree of inclination in relation to the tightrope.

The BCI's performance proved to be robust in resisting distracting visual stimulation in the game's visually rich environment and relatively consistent across six subjects, with 41 of 48 games successfully completed.

The average real-time control accuracy across subjects was 89 percent. Some subjects achieved better performance in terms of success in completing the game. This suggests that either practice or a more motivated approach to stimulus fixation results in a more pronounced visual response.

Dual university collaboration

In a first experiment designed by researchers at Graz University of Technology and University College London's virtual reality laboratory, a tetraplegic subject mastered control of his wheelchair's simulated movements along a virtual street populated with 15 virtual characters (avatars),[5] as Figure 2 shows.

Earlier, during an intensive training period of approximately four months, the participant learned to control the synchronous Graz-BCI. During the wheelchair simulation, the subject moved from avatar to avatar while progressing toward the end of the virtual street, using only imagined movements of his feet. He could only move forward along the virtual street when the system detected foot motor imagery (MI). Experimenters requested that the subject stop as close to an avatar as possible. The avatar talked to the participant whenever the participant could stand close to it for one second, after which the avatar walked away.

After a while, of his own free will, the participant could imagine another foot movement and start to move

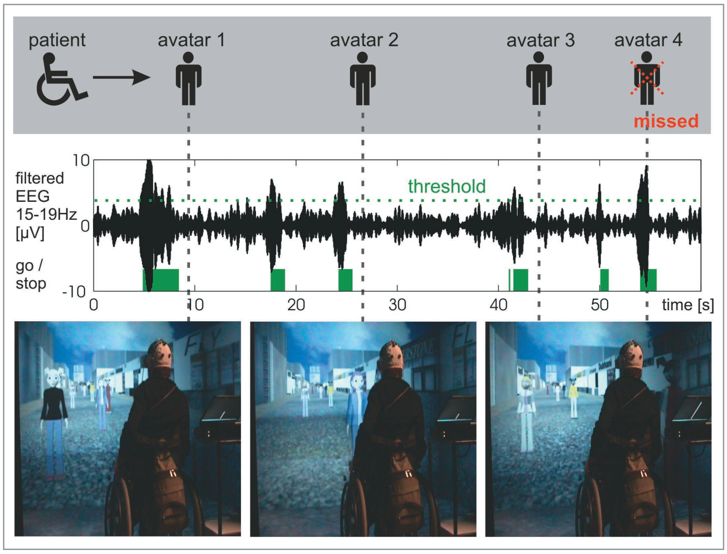


Figure 2. Simulation of wheelchair control in a VE for a tetraplegic patient using foot motor imagery. The subject must "walk" down the virtual street using motor imagery, stopping in front of some avatars for a discussion.

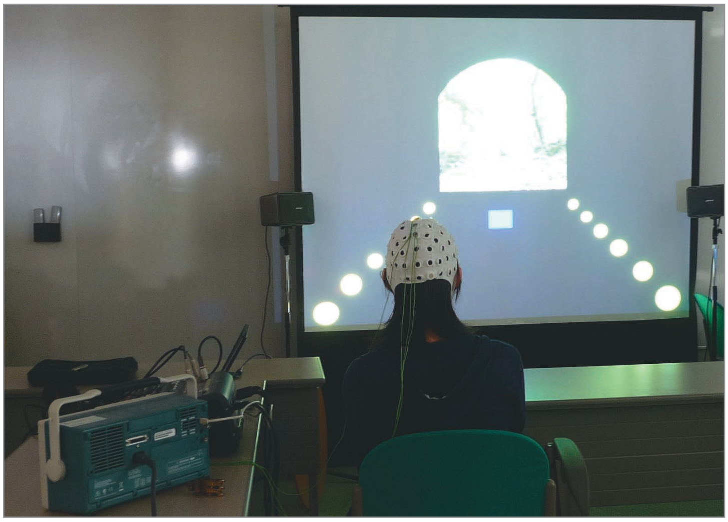


Figure 3. Monitoring drivers' alertness level in a virtual reality driving simulation using BCI and P300 signals.

again toward the next avatar, until he finally reached the end of the street. Over two days, the tetraplegic participant performed 10 runs of this experiment and could stop by 90 percent of the 15 avatars and talk with them. In four runs, he achieved a performance of 100 percent. These results demonstrate for the first time that a tetraplegic person, sitting in a wheelchair, could control his movements in a VE by using an asynchronous BCI based on one single EEG electrode.

In a second study,[6] the Graz researchers explored the use of BCI toward "real-world applications." This study showed that 10 naïve participants could be trained, in a synchronous paradigm of only three sessions, to navigate freely through a virtual apartment. At every junction they could decide, by themselves, how they wanted to explore the VE. The researchers designed this virtual apartment to be as lifelike as possible, with goal-oriented tasks, a high cognitive workload, and variable decision periods for the participants. All participants could perform long and stable MI over a minimum time of two seconds.

In this paradigm, the researchers indicated the decision period's start with only a "neutral" cue consisting of two arrows. Subjects could decide for themselves which motor imagery they wanted to perform and therefore which direction to select. The variable trial duration depended only on how quickly or slowly participants wanted to reflect on their decision. After the selection, the system automatically turned and guided the subject to the next junction.

Researchers instructed the participants to go to a predefined target room. All participants accommodated the variable trial length and variable inter-trial interval successfully. Overall, the study revealed a statistically significant performance increase during the sessions with virtual feedback.

University of Tokyo

The University of Tokyo has conducted several experiments using SSVEP brain signals as a "virtual joystick" to navigate 3D immersive VE.[10] For example, they employed the CABIN environment, a virtual reality room made of five screens. In these experiments, researchers positioned two virtual buttons on the left and right sides of the VE displayed around the user. Both buttons flickered, with a frequency of 6.9 Hz for the left button and 4.8 Hz for the right button. The participants were requested to gaze at either button to move the camera toward the left or right. The detection of a given SSVEP enabled the system to identify the button that generated this SSVEP—the button at which the user gazed. Subsequently, the system would perform the corresponding camera rotation. These experiments revealed that the system could classify the two states of brain activity with a success rate of about 70 to 80 percent.

Researchers at the University of Tokyo also worked on a system to maintain car drivers' alertness levels. In this study, a P300, generated with audio stimulus, indicated the driver's state of concentration when placed in a virtual driving environment, as Figure 3 shows.

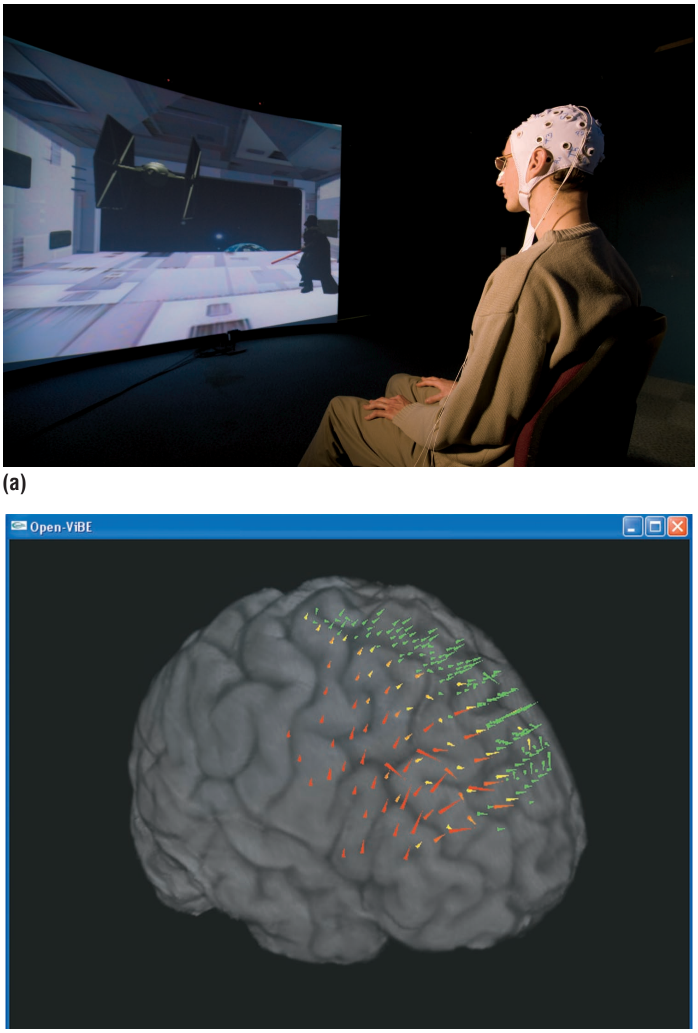
The study revealed that the driver's alertness declined throughout the experiment as the P300 amplitude decreased. This occurred because the drivers received constant feedback. By actively changing the source of audio stimuli, depending on the current P300, the system kept the user alert by keeping the P300's amplitude high, thus preventing the user from falling asleep. This auditory BCI system actively monitored the cognitive state of the drivers and warned them during drops in alertness.

INRIA

Providing entertaining applications and enhanced neurofeedback in VR, INRIA has designed several BCI systems that provide interaction with VR applications. One, called "use the force," was inspired by a sequence in *Star Wars*. Participants in the INRIA experiment were asked to control the takeoff of a virtual spaceship by using real or imagined foot movements, as Figure 4 shows. The system relied on a simple but asynchronous BCI. Researchers conducted a large-scale study and evaluated this application with 21 naïve subjects. They studied both the subjects' performance and preferences in a challenging situation: a first-time session, using a single EEG electrode, with no human or machine learning and during a public exhibition.[11]

The setup relied on OpenViBE software, a general-purpose and open source platform for both BCI and VR (www.irisa.fr/bunraku/OpenViBE). Results showed that, without training, half the subjects could control the application and the virtual object's motion by using real foot movements. A quarter of the subjects could control the spaceship by using imagined foot movements.

The results of subjective questionnaires filled out following the system's use showed the need to provide subjects with continuous and complete visual feedback, even when encountering the noncontrol state of no foot movement detected. Further, the whole application appeared enjoyable and motivating to the participants.



(a) **(b)**

Figure 4. Controlling a virtual spaceship. (a) "Use the force" application: The user must lift a virtual spaceship by imagining foot movements; (b) Neurofeedback and 3D visualization of brain activity: Each 3D object represents the activity of a given brain region, reconstructed using an inverse solution.

INRIA also designed an application based on VR technologies that provides novel and more informative feedback about the user's brain activity.[12] This application lets users visualize brain activity, within the brain's volume, in a 3D real-time stereoscopic VE. To this end, the researchers based the application on an inverse solution, an algorithm that can reconstruct the activity in the brain volume by using only scalp measurements.

Thus, the user can visualize, in real time, multiple 3D objects the size and color of which represent activity in the corresponding brain region, as Figure 4 shows. Users can navigate "inside their brain" and focus on given brain regions. In the future, researchers hope that such an immersive neurofeedback mechanism will be more engaging and informative and will improve the users' ability to control brain activity.

FUTURE TRENDS AND CONCERNS

Research activity in the BCI field, now growing exponentially, could lead to belief that a connection between BCI and VR will bring wonders.

Mental revolution?

The public perception of BCI remains a challenge given concerns about the technology's potentially unethical uses, with many perceiving it as a "mind reading" technology. However, inspired by changes in the collective mind-set that accompanied several technological breakthroughs, such as the Internet, through good science, it should be possible to promote BCI for applications like videogames and virtual worlds. The recent large-scale deployment of gesture-based interaction via Nintendo's Wii console offers a good example of how an interface has changed the market and the way of playing and designing videogames.

This shift might be driven either by the technology's outstanding devices or through highly novel applications. In any case, explaining to the general audience the scope of what BCI can realistically be used to accomplish and the limitations of its use will require a great deal of effort.

Researchers must still identify new brain signals that provide reliable and robust control in virtual worlds.

Novel interaction and gameplay

The possibility of measuring cognitive states offers novel types of interaction paradigms. For example, the interaction protocol might become transparent to the user. In this way, the BCI would not be just a substitute for classical interaction peripherals such as joysticks or gamepads, but rather a complementary means of interaction. Measurements of brain activity could be used as input to change the interaction protocol or the virtual world's content and better adapt it to the user's cognitive state and individual brain responses.

Ultimately, this work seeks to create a totally intuitive control system with associated interaction of the remote virtual world using brain electrophysiological abilities: the *think-and-play* mode.

Novel uses and virtual applications

Videogame technologies have applications beyond entertainment. Recently, *serious games* have been proposed to repurpose videogames' core technology for other applications, such as simulation and training. Similarly, the novel connection between BCI and VEs can open up new application areas. Novel deployment in the videogame community might include the development of "cognitive training" software, which would let participants enhance their cognitive ability when performing certain tasks.

Under safe conditions, the combination of BCI and virtual worlds provides great motivation and potential positive engagement. These are good environments for diagnosis and for studying neural processes and brain responses. As such, researchers expect BCI and VR will make an important impact on the neuroscience community, where it could help foster a better understanding of the brain dynamics underlying different cognitive functions. For example, we can imagine a method that electrophysiologically measures visuospatial cognitive functions of early Alzheimer's disease subjects by studying their brain responses during a spatial navigation task in a VE.

More generally, this novel association could have implications in fields such as industry that could apply it to, for example, virtual prototyping and product manufacturing. Medicine could also find such technology useful for rehabilitation of neurological or psychiatric disorders that might benefit from neurofeedback training. Immersive VE could be used to provide patients with feedback on key psychological and neuropsychological variables measured using a BCI. This might compensate for, or perhaps even ameliorate, the neurological deficits detected.

Using a BCI to control prosthetic limbs might help further refine current prosthetic technology. Immersive VR could give patients the illusion that the prosthetics are actually their own limbs.

One inspiring future BCI application would enhance virtual interpersonal interactions. We can imagine collaborative virtual environments in which multiple users communicate and exchange mental information via a BCI, thus creating new ways of interacting with one another.

RESEARCH CHALLENGES

The BCI research field is still in its infancy. To mature, it must overcome several hurdles.

Understanding brain interactions with VE

Further investigation into the human brain's cognitive and psychological functionalities will help develop a better understanding that could be exploited to improve BCI systems and their use in videogames and VR. Research must be conducted to elicit the influence of several VR application parameters on cerebral processes and BCI usage, such as the user's response to facing a virtual situation, the presence of feedback on multiple sensory channels, the effect of the virtual actions in the VE, and the role of presence. Documented responses to these studies will help explain some users' "BCI illiteracy": even after numerous training sessions, they never succeed in controlling a BCI successfully.

Further, no single brain signal dominates for practical BCI usage: P300 or SSVEP-based systems are less immersive and only help select the target, but the immersive motor-imagery-based systems are too slow for action control. Researchers must still identify new brain signals that provide reliable and robust control in virtual worlds.

Bringing BCI into real-life situations

Most researchers conduct BCI studies with very few participants, who often test in highly controlled environments. Thus, we must investigate the use of BCI in large-scale studies and in more "real life" situations. This will also pave the way for ethnographic studies that would help in defining the rules for applications of BCI in VR: defining ethics, studying the effects on social behavior, recommending limits, and promoting positive uses for BCI with videogames and virtual worlds. Ethnographic studies can also be key in helping provide a positive image for BCI among the general public.

Processing multiple signals in the virtual environment

Current BCI systems can offer transfer rates of up to 60 bits per minute—a harshly limited bandwidth compared to conventional human-computer communications media. Besides, using a BCI requires extensive training. Thus, researchers should study various methodologies to shorten the training period. Ultimately, the final BCI system, if it is to be used daily, must be highly efficient, robust, easy to use, and quick to calibrate: essentially plug and play.

More generally, increasing the signal-to-noise ratio, while essential, is one of the most challenging hurdles to stimulating BCI use in the field of interaction with 3D virtual environments. Researchers must develop innovative signal-processing methods, such as filtering and features extraction, because gamers will most likely still want to use motor actions. These are well known to generate considerable muscle artifacts in the recorded EEG.

Adapting hardware to the user's environment

Current BCI technology requires bulky devices such as caps that sport a dense array of electrodes. By researching a more efficient signal identifier, it might be possible to reduce the number of electrodes and simplify the traditional electrode cap.

Developing high-performance electrodes or studying other interface signals, such as optical topography, might prove beneficial. The use of active dry electrodes in EEG acquisition is a recent technical development. These electrodes can simply be attached to the subject's scalp with an elastic strap, whereas the gold standard method requires using gel and a more complex electrode cap.

Robust EEG acquisition and wireless operation would promote the ease and comfort of using BCI technology, which is critical in VR and games applications. Making an attractive BCI device that users and gamers would clamor to wear will require a significant design and marketing effort.

Given that it might be impossible to craft a single optimal brain sensor for VE interactions, developers need to investigate hybrid systems that use multiple cerebral sensors, such as EEG and EMG, eventually combined with other sensors such as position tracking and physiological measures. The compatibility between a brain-signals-acquisition system and typical VR peripherals—head-mounted displays, tracking systems, and haptic devices—presents an important obstacle that researchers must tackle.

Bringing BCIs into the HCI world

Signal-processing experts or electrophysiology specialists often develop BCIs. Yet few researchers from the human-computer interaction (HCI) community are working on this new means of interaction, probably due to the technology's limited availability and the strong expertise needed to comprehend BCIs.

Therefore, the current methods and paradigms devoted to interaction with games and VEs remain in their infancy. Going forward, we need researchers from the HCI domain to push the limits of BCI use within virtual worlds.

The connection between BCIs, videogames, and VR technologies offers a promising research area. Researchers have developed impressive prototypes in laboratories over the past few years. These let people navigate virtual worlds or manipulate remote virtual objects using only their cerebral activity. Major research challenges must be tackled for BCIs to mature into an established means of communication for VR applications, ranging from basic neuroscience studies to the development of optimal peripherals and mental gamepads, more efficient brain-signal processing techniques, and the invention of adapted interaction paradigms and innovative gameplay.

Over the long term, these innovations could pave the way to newer applications, such as novel types of neurorehabilitation. We imagine a future in which users have total intuitive control of remote virtual environments within some kind of think-and-play user interface.

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