A low-Cost, Open-Source, BCI-VR Game Control Development Environment Prototype for Game based Neurorehabilitation

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Abstract — **In this paper we present a low-cost and open-source brain-computer interface (BCI) virtual-reality (VR) Game Control Development Environment prototype, which we demonstrate using real-time signal processing of Electroencephalography (EEG) event-related desynchronization and synchronization changes (ERD/ERS) within the Precentral Gyrus (Motor Cortex), allowing a user to control a 3D object within a Virtual Reality Environment. This BCI-VR system prototype was functionally tested on multiple participants and demonstrated live before an audience during the 2017 'Hack the Brain' at the Dublin Science Gallery. The availability of such an open-source, effective, BCI-VR Game Control Development Environment, at a level acceptable for industry experimentation, has the potential to open up this field to a much wider range of researchers and games developers and to assist the investigation of gaming experiences which both incorporate the specific control features available through BCI as a core element of the game play and the potential for its use in neurorehabilitation.**

Keywords— BCI, VR, Brain Computer Interface, Virtual Reality, Event-Related Potentials, open-source, Game Development, Neurorehabilitation

I. INTRODUCTION

Jacques J. Vidal first coined the phrase Brain Computer Interface (BCI) as a system for direct communication between a human being and a technical system based on neural activity (Vidal, 1973). A BCI system is designed to measure neocortical activity and use this data as an input signal to a computer for conveying output messages and commands to external applications or devices [47].

BCI systems utilize a range of different EEG signals which can be classified into six specific categories. Two of these EEG features, the Steady-State Visual Evoked Potentials (SSVEPs) and the P300 Evoked Potential (EP), can be triggered automatically by particular external stimulus presented to the user, while the other four EEG features - the Sensorimotor rhythms (SMRs) mu and beta, the Slow Cortical Potentials (SCPs), the cortical neuronal action potentials, and EEG pattern mapping - need to be learned by the user through self-regulation and feedback [16].

The initial focus of research around BCI was in the development of certain neuroprostheses and as a form of neurorehabilitation. In the area of neuroprostheses BCI has been used to create devices to assist people with severe disabilities, such as Amyotrophic Lateral Sclerosis (which can leave a person unable to move physically) [13], in order to allow two-dimensional computer control for spelling devices, environmental control, generic cursor control applications [39], or even control complex robotics devices such as wheelchairs [12]. In the area of neurorehabilitation for acquired physical disabilities, such as stroke, BCI feedback has been shown to be a key component as when information is visually returned to the user of the success or failure of an intended act, this observation can modify sensorimotor activity and improve neural plasticity [2].

Although the initial focus of BCI system research was to provide new communication and rehabilitation methods for patients suffering from serious physical disabilities, these advances led researchers and developers to start examining the application of BCI to games for use by healthy people. Studies have demonstrated examples of BCI applications being used to control traditional games such as "Pacman" [36], "Pinball" [6], "Tetris" [34] and even "World of Warcraft" [43] [1].

A new form of gaming also began to emerge based on designs which incorporated the specific controls features available through BCI as a core element of the game. One of the first of these was "Brainball" where the Beta and Alpha waves are measured to allow two players control a ball on a table through their state of relaxation, with the ball rolling away from the person who is most relaxed and toward the other player, with the ultimate objective of moving the ball to the opponent's end zone [14]. Another game, "Bacteria Hunt", used two BCI features to record users mental state; firstly, alpha waves as a measure of relaxation, and secondly SSVEP to evaluate concentration on a specific game element, both of which control an aspect of the game world, which involved hunting for objects on a 2D plane [28]. In "Brain Invaders" analyses of P300 features is used in a game where a set of alien characters are shown on a grid and the user is tasked with destroying a specific alien target solely by concentrating on it [8].

Parallel research in the field of neurorehabilitation began to explore the use of Virtual Reality (VR) technology as a method of presenting neurofeedback to a subject [3] and multiple

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prototypes have been developed to enable users to interact with VR environments. Healthy participants have explored virtual spaces [21][37], manipulated virtual objects [18], and patients with spinal-cord injuries have controlled wheelchairs through virtual spaces [19] using Event Related Potentials. Evoked potentials such as P300 have been used to control objects in a virtual apartment [5].

This has in turn led to the investigation into the use of BCI-VR in games. The BCI feature SSVP featured in the VR game "MindBalance", where a player must correct a tightrope walking character's balance by directing their focus on checkerboards at either side of the screen [17]. In "Thinking Penguin" a subject can control the main virtual character, a penguin, which slides down a snowy mountain slope by triggering a jump action via BCI Sensorimotor rhythms (SMRs) with additional steering using a game controller [20]. In another example a sensorimotor BCI was used to enable a subject to navigate a virtual helicopter to any point in a 3D space with forward/backward transition and elevation up/down control by modulating their sensorimotor rhythms related to the larger and smaller imagined movements of their arm and hand [38][9].

BCI systems offer some interesting and unique options for game development beyond just being combined with other interfaces as a form of hybrid control to supplement conventional input mechanisms. For example, BCI systems could be used to detect emotional responses or user engagement and then adapt the game play, modify the display, or other parameters, based on the user's state. The covert communication offered by BCIs could be of value in team games that require secrecy and the ability to send control signals milliseconds faster could provide an advantage in competitive gaming [4]. In neurorehabilitation, BCI games can be used to improve training or performance with some motor tasks and skills. Further with the combination of VR to BCI, users make fewer mistakes and report they are easier to use than other interfaces, and that it was more natural and usable than less immersive BCIs [21].

While academic researchers have access to expensive medical grade laboratory equipment, their studies tend to focus on system performance and the feasibility of BCI, but they tend have little experience in game development. Game developers understand game design and player motivation, which specifies challenge, fantasy and sociality as key factors, and could help increase the functional outcomes for neurorehabilitation, but have difficulty in accessing affordable BCI game development environments [1].

There are currently several low cost BCI products on the market, such as the Emotive EPOC [10] and the NeuroSky MindWave [27] available for BCI with the Neurable headset available for BCI-VR [30]. However, all of these products are proprietary systems requiring developers to purchase licenses for both professional and commercial use.

In this study we investigated if it is possible to provide an open source based low-cost, BCI-VR game control development environment prototype, in order to make this area much more accessible and affordable to a wider range of games developers and researchers and assist the investigation of gaming experiences which both incorporate the specific control features available through BCI as a core element of the game play and the potential for its use in neurorehabilitation.

The remainder of this paper is organised as follows: Section 2 discusses the methodology we employed to design and develop the game development environment prototype. The experiments and results are presented in Section 3, which is followed in Section 4 by conclusions and directions for future work.

II. Methodology

The methodology we employed was to design and build the hardware for the low-cost, open-source, BCI-VR game control development prototype, and to create a basic demonstration BCI-VR game, which used focused on the ERD/ERS sensorimotor rhythms from the user's Precentral Gyrus (Motor Cortex) in order to manipulate a 3D object within a basic Virtual Reality Environment. Further on, we tested and validated the prototype using this game.

A. Equipment

We focused exclusively on using low cost and off-the-shelf tools and technologies to develop the prototype system. An OpenBCI Cytron Biosensing Board (Fig. 1) provided the bio-sensing microcontroller used to sample the users electrical brain activity (EEG), and OpenViBE, a free open-source software platform, was used to design, develop and run the BCI modules for acquisition, pre-processing, processing and visualization of the acquired brain signal data.

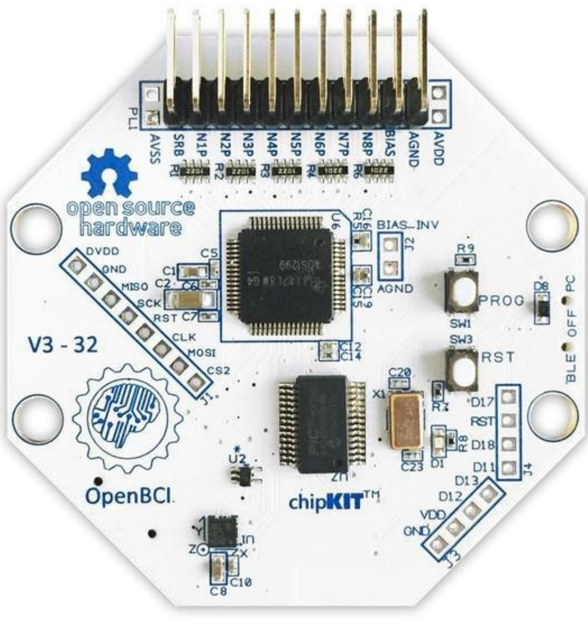

Fig. 1. OpenBCI Cytron Board [31]

The Virtual-Reality Peripheral Network (VRPN) provided a device-independent and network-transparent interface to connect the OpenViBE application to an OSVR Hacker Development Kit 2 (Fig. 2), used to render the 3D VR scenes to the user. Finally, we used the Unreal Game Engine and development environment to create the 3D VR environment.

Fig. 2. OSVR Hacker Development Kit 2 [35]

B. *Environment Setup*

In order to build and use the end-to-end development environment we used the following software:

- Unreal Engine 4: was used to create the basic VR game [42].
- OpenVIBE: was used to train and run the BCI, and to send the control commands, via VRPN, to Unreal [32].
- VRPN: was used to connect the BCI controller within the Unreal Project to the OpenViBE scenario [45].
- CMake: was needed to build a 64bit version of VRPN [7].
- Visual Studio 17 Free Community Edition was the IDE we used for the project [11].
- Virtual COM Port drivers: FTDI devices for OpenViBE USB device to appear as an additional COM port available to the PC [46].

The setup for connecting the OpenBCI Cyton board to the OpenViBE software required some additional configuration. Firstly, the default FTDI latency is too large for EEG applications, so the USB Serial Port of the OBCI board Latency Timer properties were changed from 16 ms to 1 ms. Secondly, the COM Port Advanced Settings Receive and Transmit settings in the USB Transfer Sizes section were both changed from 4096 to 64 bytes, and finally the Latency Timer of the BM Options section was reduced down to 1 [32].

The setup for connecting the Unreal Project to the OpenViBE scenarios also required some additional configuration. VRPN (Virtual-Reality Peripheral Network) was used to connect the BCI controller within the Unreal Project to the OpenViBE scenario. VRPN is a device-independent and network-transparent system for accessing virtual reality peripherals in VR applications. At the time of writing only 32-bit versions of the VRPN client were available, so we used the source code, CMake and Visual Studio to build a 64bit version of VRPN, which is required by Unreal.

The EEG headset was setup with the electrodes positioned at: F3, F4, C3, Cz, C4, P3, P4 in the international 10:20 system. The ground electrode was positioned on the left ear lobe A1 and the bias electrode was positioned on the right ear lobe A2 (Fig. 3).

The channel numbers for the 10/20 electrode setup specified above were identified in the OpenViBE Acquisition Server setup and then the OpenViBE Controller scenario described in the Section D. Game Design was run to collect live EEG data and send that data to the Unreal Engine via VRPN.

Finally, the Unreal Engine game project file was opened and the game application is run as a "VR Preview" for stereoscopic output to the OSVR headset.

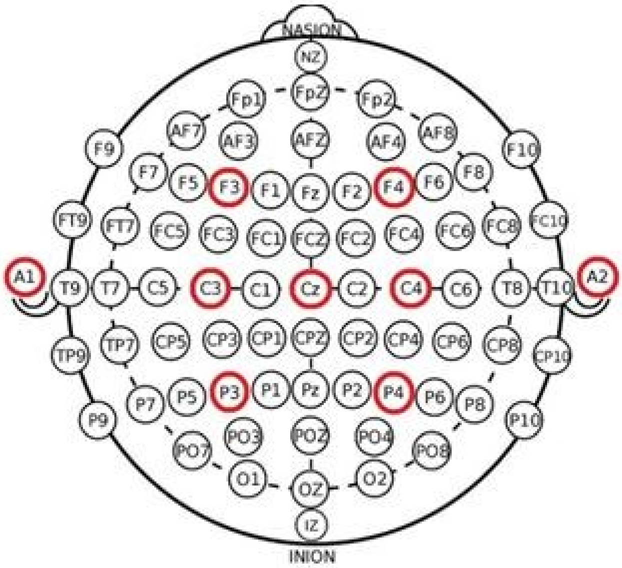

Fig. 3. The 10/20 Electrode Setup *[41]*

C. *BCI Event-Related Potentials Signal Acquisition*

The BCI-VR system needs to record activity directly from the brain non-invasively, and the system must be under intentional user control, i.e. the user must actively determine to perform a mental task to accomplish a desired goal with the system [13]. In order to achieve this, we focused on two EEG rhythms, the Rolandic mu rhythm in the alpha range of 7-13Hz (Fig. 3), and the sensorimotor rhythm (SMR) in the mid-beta range of 13-15Hz associated with the motor-cortical areas directly related to the brain's motor output channels.

A subject's movement, or the preparation for a movement, is directly associated with a short-duration decrease of amplitude in both mu and beta nearly a full second before the actual movement and is known as an Event Related Desynchronization (ERD) seen at central electrode sites, as identified in the international 10:20 system. The mu recovers to baseline level within a few seconds while the beta displays a brief ERS ending after the movements' execution [33].

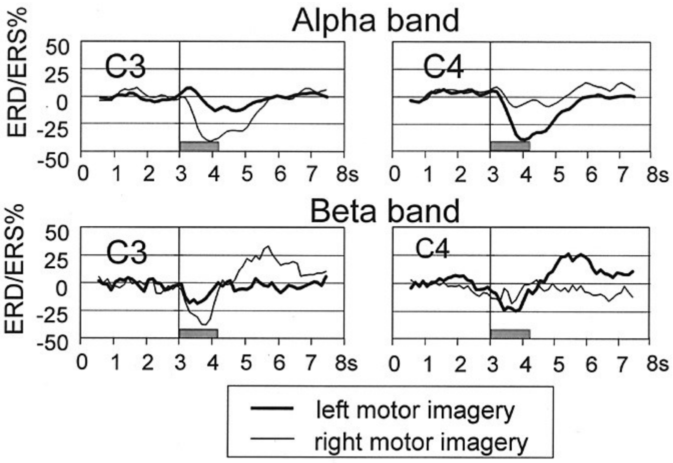

Fig. 4. An average ERD/ERS curves recorded over left and right sensorimotor cortex C3 and C4 electrode locations during motor imagery in the alpha and beta range showing a band power increase (ERS) and decrease (ERD) with respect to the baseline while a grey bar indicates the time period of the cue presentation. [33]

D. Game Design

In order to design an ERD/ERS based BCI two phases are required: an offline training phase, which calibrates the system, and an online phase, which uses the trained BCI to recognise mental states and translate them into game controls [40]. In the BCI-VR game control system we used a set of scenarios, based on templates provided by OpenVIBE, which target motor imagery based on a subject's imagined hand movements.

The BCI follows a closed-loop process composed of several steps, which involve brain activity measurement to obtain signals reflecting the user's brain activity, followed by pre-processing to clean and denoise the input data and feature extraction, followed by classification to assign a class to a set of features corresponding to a mental state. A command is associated to this identified mental state in order to control the game [22].

To achieve this, the following software elements were utilised:

1) Acquisition: First step is to acquire EEG data while the subject imagines right and left-hand movements. This is composed of 40 trials of 20 left and 20 right instructions with the order randomized within a session and the acquired training signal data written into a General Data Format (GDF) file.

2) Trainer: This is a pre-processing step before feature extraction and classification which maximises the difference between two signal class matrices using a Common Spatial Pattern (CSP) on the subject-specific frequency bands. The CSP method creates spatial filter coefficients according to the Common Spatial Pattern algorithm which maximize the variance of one class while simultaneously minimize the variance of the other.

3) Classifier: The most favourable frequency bands are then obtained from the resulting pre-processed training signals using logarithmic Band Power (BP) for feature extraction. The features are identified by filtering the signal in the alpha/beta frequency bands and selecting four seconds of signal half a second after the instruction was shown to the user (Left and Right). The signal is then split into blocks of 1 second every 16th second and the logarithmic band power is computed by squaring it, averaging it over the time-window and computing its logarithm. The matrices are then converted into feature vectors which are then passed to the Linear Discriminant Analysis (LDA), which identifies the signal class, i.e., "left" or "right", depending on the hand chosen for the imagined movement and produces a configuration file at the end of the experiment which will be used during online sessions.

4) Controller: The controller can now be used online. Firstly, the previously produced CSP spatial filter is used prior to feature extraction. Then during the feature extraction, the signal is again filtered in the alpha/beta range and the filtered signal is split into blocks of 1 second every 16th second and the logarithmic band power is computed with the matrices converted into feature vectors. Finally, the feature vectors are classifier with the LDA classifier sending either a negative or positive value for each class which allows the manipulation of the 3D object within the Virtual Environment.

E. VR Tasks

The Unreal 3D VR project used as a demonstration of the BCI-VR game control development environment was developed by Toby Steele and Michael McMahon during the 2017 'Hack the Brain' hackathon at the Dublin Science Gallery [41]. The 3D VR comprised of a set of basic shapes, which can be rotated both left and right, and when viewed from the correct angle form a Celtic symbol (Fig. 5), but are unresolved from all other angles (Fig. 6).

Fig. 5. The Resolved Stereoscopic 3D VR image *[41]*

The online VR neurofeedback takes the live EEG signal data, analyses the subjects right/left motor imagery and provides real-time feedback by using the trained CSP filter and LDA classifier to output commands through the Analog VRPN Server, which can be interpreted by the Unreal Game Engine to control the elements within the Virtual Reality Environment [41].

Fig. 6. Unresolved Stereoscopic 3D VR image *[41]*

F. Experiment Setup

The experiment was explained to all subjects, who signed an informed consent form agreeing that they were aware of the procedure and its purpose. Also, no personal information was collected and after use all data was destroyed. The cap was placed on the participant with electrodes setup as per the 10/20 diagram ensuring the Cz electrode was placed on the vertex, and the electrodes are connected to the OpenBCI board. Signal verification was done by asking the participant to carry out a few tasks that generated detectable artefacts, such as blinking and clenching the jaw.

The first step in a BCI session was to run the signal acquisition scenario to acquire EEG data from the subject in order to train the classifier to discriminate right and left-hand movements. The scenario started an instruction sequence, which presented left and right arrows to the subject, who was requested to imagine left and right-hand movements when each arrow was displayed (Fig. 7). A cross appeared on screen five seconds prior to the arrow, so the subject was aware a training cue is about to appear. A training session contained twenty arrows of each type and lasted around seven minutes.

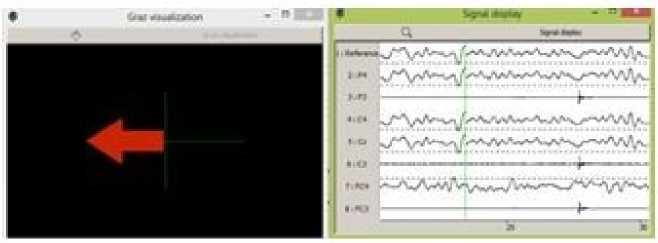

Fig. 7. Running the Acquisition Scenario *[41]*

Once the acquisition file was captured, the training scenario computed the Common Spatial Pattern (CSP), and then the Classifier Scenario trained the LDA classifier. The system was then ready to run the online BCI-VR for real-time signal processing of the ERD/ERS sensorimotor rhythms, so the OSVR HDK headset was placed on the subject, and the Unreal 3D project was launched.

Finally, the online VR Input scenario was run, which took the subjects live EEG signal data, analysed the subject's right/left motor imagery and provided real-time feedback by using the trained CSP filter and LDA classifier to output commands through the Analog VRPN Server, which could be interpreted by the Unreal Game Engine to control elements within a VR environment.

The subject tried to resolve the Celtic symbol using both left and right motor imagery and if possible hold the image in a resolved state. An observer could monitor the subject signals through visualizations on the monitor.

III. Experiments & Results

The testing process was focused on human interaction testing and not on the achievement of specific experimental tasks. Following approval by NUI Galway, Department of Information Technology, the BCI-VR system was tested on multiple participants at the 'Hack the Brain' Hackathon in the Dublin Science Gallery over the weekend of the 10th – 11th June 2017 and was also demonstrated live before an audience on the final day of the Hackathon (Fig. 8).

Fig. 8. Live demonstrate of BCI-VR at 'Hack The Brain' *[41]*

The main findings of the ad-hoc functional testing which occurred during the Hackathon were:

1) It was found that the majority of subjects could control the BCI-VR reporting that the environment responded to their right/left motor imagery.
2) One subject was able to hold the Celtic symbol in place for up to 15-20 seconds at a time.
3) All subjects found the immersive experience of VR to be helpful in focusing on the task when

compared to attempting the same task on a monitor.

4) It was found that asking the subjects to imagine playing tennis with the left and right hands in response to left/right signals during the acquisition phase greatly improved the quality of the EEG samples.

Unfortunately, due to the informal nature of a Hackathon we did not record the number of training sessions or feedback trials performed per subject and do not have results to indicate that the setup is providing above chance levels accuracy therefore future experimentation will be necessary to provide more rigorous evaluation of the results.

IV. Conclusions and Future Work

In this research we have shown that it is possible to create a low-cost, open-source, BCI VR game control development environment prototype and to test this system by designing and running a BCI-VR application for real-time signal processing focused on deriving ERD/ERSs from the Precentral Gyrus (Motor Cortex), which allowed users to manipulate a simple 3D object within a basic Virtual Reality Environment.

The testing process was focused on human interaction testing and not on competitive gameplay; however, the feedback and results from participants was enthusiastic and the BCI-VR system operated as designed.

The research has shown that on the software side there are some excellent open-source products, with the combination of BCILab for development and testing of new BCI methods combined with OpenViBE as a framework for implementing the resulting method plugin being particularly powerful. On the hardware side the OpenBCI Cyton Biosensing Board and VRPN RDK 2 are both quite affordable. Although it should be noted that current VR headsets do require high-end gaming PCs with significant graphics capability, it is expected that the majority of professional game developers would already work on a system with this type of specification. Additionally, the cost could be reduced further using more cost effective non-clinical electrodes and cap. The total Bill of Materials for the low cost, open source, BCI-VR system is shown in Table 1 below:

Table 1. Bill of Materials

Bill of Materials (BOM)	
OpenBCI Cyton Board	€406.00
OSVR HDK 2	€325.00
Alienware Aurora (VR Ready)	€1,429.00
g.tec g.GAMMAcap3	€170.00
g.tec g.LADYbirdPASSIVE ring electrode x 8	€272.00
OpenViBE	€0.00 (Open Source)
VRPN	€0.00 (Open Source)
Unreal Game Engine	€0.00 (free for non-commercial)
Total	**€2,602.00**

This Bill of Materials compares favourably on price to state of the art research systems such as, for example, the Brain Vision acti32Champ System which is commonly used in University Laboratories and retails at €41,000.

The significance of this research lies in two areas. Firstly, patients requiring neurorehabilitation can, as has been shown in numerous case studies, benefit of the intervention of BCI neurofeedback therapy. However, access to expensive research grade EEG equipment is restricted to hospitals and relatively few University laboratories, even for neuroscience and medical students, and virtually non-existent for game developers, while lower cost consumer BCI products tend to be proprietary systems. Wider access to a low cost, open source, BCI-VR development environment may foster greater innovation as games developers could potentially discover imaginative and radical BCI applications in the area of neurorehabilitation.

Secondly most BCI games to date have been used for research purposes to illustrate or test a BCI paradigm using game-like situations [29] with very simple gameplay mechanics - as so clearly demonstrated by our own BCI-VR project. With the availability of the BCI-VR development environment it is hoped that game developers and designers, who are the experts in creating engaging gameplay and interaction mechanisms which challenges the player, would explore the creation of BCI-VR games that drive engagement as means of enhancing performance, while entertaining and challenging participants [25]. This would prove beneficial for BCI games in general and for neurorehabilitation in particular. The gamification of rehabilitation would make the experience much more enjoyable which could in turn drive greater compliance and better outcomes [15].

However, it is not anticipated that the current generation of EEG caps, sensors and biosensing chips will become part of an everyday gaming equipment anytime soon. In addition to the issues already outlined in this paper, most of the consumer grade EEG systems still require bulky headsets, a local desktop computer to analyse the EEG data, and a one-to-one relationship between the user and the BCI system with a focus on specific functional areas of the brain related to a particular user behaviour.

This will be an area for future research as improved electronics and signal processing are allowing smaller, better, cheaper sensors, amplifiers and wireless technology, and could allow the BCI technology become effectively transparent. We plan to investigate the development of a BCI device which would combine an unobtrusive wearable cap, with integrated electrodes and a biosensing chip, that would be much more practical for longer term use by an unconstrained, freely-moving user, where wireless EEG metrics of mental activity could be collated through a cloud-based AI system for analysis, in order to learn individual user behaviour from whole brain network activity and to provide accurate real-time actionable feedback for gaming and medical applications..

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