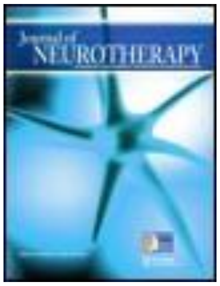


Journal of Neurotherapy: Investigations in Neuromodulation, Neurofeedback and Applied Neuroscience

Open-ViBE: A Three Dimensional Platform for Real-Time Neuroscience

Cédric Arrouët ME [a] , Marco Congedo PhD [a] , Jean-Eudes Marvie PhD [a] , Fabrice Lamarche PhD [a] , Anatole Lécuyer PhD [a] & Bruno Arnaldi PhD [a]

[a] Synthése d'Image, Animation, Modélisation et Simulation (SIAMES) project, National Institute for Research in Informatics and Random Systems (ERISA) , Rennes, France

Published online: 08 Sep 2008.

To cite this article: Cédric Arrouët ME , Marco Congedo PhD , Jean-Eudes Marvie PhD , Fabrice Lamarche PhD , Anatole Lécuyer PhD & Bruno Arnaldi PhD (2005) Open-ViBE: A Three Dimensional Platform for Real-Time Neuroscience, Journal of Neurotherapy: Investigations in Neuromodulation, Neurofeedback and Applied Neuroscience, 9:1, 3-25, DOI: 10.1300/J184v09n01_02

To link to this article: http://dx.doi.org/10.1300/J184v09n01_02

PLEASE SCROLL DOWN FOR ARTICLE

© International Society for Neurofeedback and Research (ISNR), all rights reserved. This article (the "Article") may be accessed online from ISNR at no charge. The Article may be viewed online, stored in electronic or physical form, or archived for research, teaching, and private study purposes. The Article may be archived in public libraries or university libraries at the direction of said public library or university library. Any other reproduction of the Article for redistribution, sale, resale, loan, sublicensing, systematic supply, or other distribution, including both physical and electronic reproduction for such purposes, is expressly forbidden. Preparing or reproducing derivative works of this article is expressly forbidden. ISNR makes no representation or warranty as to the accuracy or completeness of any content in the Article. From 1995 to 2013 the *Journal of Neurotherapy* was the official publication of ISNR (www. Isnr.org); on April 27, 2016 ISNR acquired the journal from Taylor & Francis Group, LLC. In 2014, ISNR established its official open-access journal *NeuroRegulation* (ISSN: 2373-0587; www.neuroregulation.org).

THIS OPEN-ACCESS CONTENT MADE POSSIBLE BY THESE GENEROUS SPONSORS

SCIENTIFIC ARTICLES

Open-ViBE: A Three Dimensional Platform for Real-Time Neuroscience

Cédric Arrouët, ME
Marco Congedo, PhD
Jean-Eudes Marvie, PhD
Fabrice Lamarche, PhD
Anatole Lécuyer, PhD
Bruno Arnaldi, PhD

ABSTRACT. *Background*. When the physiological activity of the brain (e.g., electroencephalogram, functional magnetic resonance imaging,

---

Cédric Arrouët, Marco Congedo, Jean-Eudes Marvie, Fabrice Lamarche, Anatole Lécuyer, and Bruno Arnaldi are all affiliated with the Synthèse d'Image, Animation, Modélisation et Simulation (SIAMES) project, National Institute for Research in Informatics and Random Systems (ERISA), Rennes, France.

Address correspondence to: Marco Congedo, SIAMES project, National Institute for Research in Informatics and Random Systems (IRISA), Campus de Beaulieu 35042, Rennes, France (E-mail: loretabiofeedback@yahoo.com).

The authors would like to express their gratitude to Dr. Noland White for reviewing a draft of the manuscript. This work was partially supported by the International Society of Neuronal Regulation (ISNR).

Journal of Neurotherapy, Vol. 9(1) 2005
Copyright © 2005 ISNR. All rights reserved.
Digital Object Identifier: 10.1300/J184v09n01_02

etc.) is monitored in real-time, feedback can be returned to the subject and he/she can try to exercise some control over it. This idea is at the base of research on neurofeedback and brain-computer interfaces. Current advances in the speed of microprocessors, graphics cards and digital signal processing algorithms allow significant improvements in these methods. More meaningful features from the continuous flow of brain activation can be extracted and feedback can be more informative.

Methods. Borrowing technology so far employed only in virtual reality, we have created Open-ViBE (Open Platform for Virtual Brain Environments). Open-ViBE is a general purpose platform for the development of three dimensional real-time virtual representations of brain physiological and anatomical data. Open-ViBE is a flexible and modular platform that integrates modules for brain physiological data acquisition, processing, and volumetric rendering.

Results. When input data is the electroencephalogram, Open-ViBE uses the estimation of intra-cranial current density to represent brain activation as a regular grid of three dimensional graphical objects. The color and size of these objects co-vary with the amplitude and/or direction of the electrical current. This representation can be superimposed onto a volumetric rendering of the subject's MRI data to form the anatomical background of the scene. The user can navigate in this virtual brain and visualize it as a whole or only some of its parts. This allows the user to experience the sense of *presence* (being there) in the scene and to observe the dynamics of brain current activity in its original spatio-temporal relations.

Conclusions. The platform is based on publicly available frameworks such as OpenMASK and OpenSG and is open source itself. In this way we aim to enhance the cooperation of researchers and to promote the use of the platform on a large scale.

Copyright © 2005 ISNR. All rights reserved.

KEYWORDS. EEG, real-time neuroimaging, neurofeedback, brain-computer interface, virtual reality, Open-ViBE, OpenMASK, MEG

INTRODUCTION

Since the pioneering work of Berger (1929) the electroencephalogram (EEG) has become a proven source of information for clinicians and researchers. First attempts to interpret EEG time series relied on visual inspection of their shape. In neurology, the morphology of EEG is still valuable (e.g., in the diagnosis of epilepsy). The development of electronic devices combined with the Fast Fourier Transform algorithm (FFT; Cooley & Tukey, 1965), allowed the analysis of the EEG spectral components and related measures (e.g., autocorrelation, coherence, etc.), initiating the era of quantitative EEG (qEEG). During the 1970s and 1980s, the introduction of micro-computer technology revolutionized approaches to EEG, marking the transition from analog to digital processing. However, it has only been in the past few years that electronic technology and signal processing algorithms have become powerful enough to support the development of advanced real-time applications. EEG analysis in real-time is important for at least two reasons. First, it best exploits the high-temporal resolution of EEG, which makes the use of EEG and magnetoencephalography (MEG) in real-time preferable over other neuroimaging techniques such as functional magnetic resonance imaging (fMRI). Second, it enables the provision of effective feedback to the person whose EEG is being recorded. Several independent domains are interested in these kinds of tools: neurofeedback (NF), virtual reality (VR), and brain-computer interface (BCI), among others.

In this article, we review the most recent studies carried out in these three domains having real-time brain imaging as a common denominator. We show that behind the apparent heterogeneity, and despite the diverse background, they are all converging toward a common framework that makes use of similar methods. We believe that in the future, all of them will benefit from the advances of the others. Within this line of thoughts, we hope that the identification of a "crossroad" for these three major lines of research will stimulate further interdisciplinary collaborations and cross-publications.

The article is organized as follows: in the next three sections we review typical studies that make use of real-time neuroimaging on NF, VR, and BCI, respectively. We will give emphasis to EEG and to those studies in which the three modalities have been combined. In the ensuing section we outline our contribution, the Open-ViBE system. Open-ViBE has been conceived as a general-purpose platform serving as a high-level base for the development of real-time functional imaging applications. The platform, still under development, is meant to be a state of the art, high-performance, open source template that other researchers may easily accommodate for specific purposes. The platform currently allows the three dimensional (3D) interactive visualization and navigation of the cerebral volume using EEG data. Based on a dense grid of electrodes, Open-ViBE estimates neocortical current density using Low-Resolution

Electromagnetic Tomography (LORETA; Pascual-Marqui, 1995, 1999; Pascual-Marqui, Michael, & Lehmann, 1994) or Standardized Low Resolution Brain Electromagnetic Tomography (sLORETA; Pascual-Marqui, 2002). Open-ViBE virtually reproduces the anatomical space by volume rendering of Magnetic Resonance Imaging (MRI) slices, and/or superposes on it objects which graphical attributes co-vary with the current density estimation. The result is a virtual, real-time, *functional* brain in which the subject can navigate and from which he/she can obtain complex feedback, *preserving the spatio-temporal pattern of the signal*. As we will discuss, our choice of development framework on which Open-ViBE is based makes it a flexible and powerful template that can be adapted to specific purposes in all three real-time domains we consider here.

NEUROFEEDBACK

Neurofeedback (EEG biofeedback) is a technique used in behavioral medicine as an adjunct to psychotherapy. An electronic device records EEG activity at a particular scalp location, extrapolates physiological measurements from the signal, and converts it to a visual and/or auditory object dynamically co-varying with the brain signal. For example, the length of a bar in a graph may vary continuously as a function of signal amplitude (smoothed in time) in one or more frequency band-pass regions. The process is truly real-time; that is, the object continuously represents brain activity with a minimum delay (< 500 milliseconds). Typically, over 20 to 40 sessions of thirty minutes each, spaced two or three days apart, the subject acquires greater awareness about the signal and learns how to shape it in a desired direction, which leads to a modification of brain electrical activity.

Research in this field started in the late 1960s (e.g., Engstrom, London, & Hart, 1970; Nowlis & Kamiya, 1970; Travis, Kondo, & Knott, 1974). Whereas first attempts were aimed at the acquisition of control over the posterior dominant rhythm (also known as alpha: 8-13 Hz), today the application of the technique is mainly clinical. Several successful protocols have been established for the treatment of Attention Deficit Hyperactivity Disorder (Barabasz & Barabasz, 1996; Lubar, 1991, 1997; Lubar & Shouse, 1976; for a review see Fuchs, Birbaumer, Lutzenberger, Gruzelier, & Kaiser, 2003 and Vernon, Frick, & Gruzelier, 2004), unipolar depression (Rosenfeld, 2000), and epilepsy (Lubar & Bahler, 1976; Lubar et al., 1981; Sterman, 1973, 1981; Swingle, 1998). For other disorders such as traumatic brain injury (Thornton, 2002), anxiety disorders (Moore, 2000), chronic fatigue syndrome (James & Folen, 1996), and learning disabilities (Fernandez et al., 2003) research is in progress. Most protocols employ measurements based on FFT as the source of feedback. Meanwhile, advances in electrophysiology have enabled the investigation of alternative EEG measurements. For example, an established line of research has shown that individuals can acquire volitional control over slow cortical potentials (SPCs; Hinterberger et al., 2003).

Neurofeedback has traditionally been circumscribed to EEG. In the past few years, we have seen increasing interest in fMRI neurofeedback. The first published report was by Yoo and Jolesz (2002); however, in this study the feedback delay was so long (around 20 seconds) as to prevent any comparison with EEG real-time research. Weiskopf et al. (2003) implemented a neurofeedback system based on fMRI to allow subjects to observe and control their own blood oxygen level-dependent (BOLD) response. The subject's BOLD signals were continuously fed back with a latency of less than two seconds, and the subject achieved significant changes of local BOLD responses in the anterior cingulate cortex. DeCharms et al. (2004) showed that by means of fMRI neurofeedback, subjects could achieve an increase of activation in the sensorimotor cortex. With three training sessions of 20 minutes each, subjects were able to enhance their control over brain activation that was anatomically specific to the target region of interest (ROI) without causing muscle tension. These results are in line with the work of Pfurtscheller et al. (2000) who have been extensively using mental imagination of specific movements to produce specific EEG activity at will. These experiments, along with others, show that by means of either EEG or fMRI neurofeedback we can successfully acquire some sort of control over circumscribed brain areas and regulate them. Such control has been termed *self-regulation*. While researchers are reporting good results, some limitations seem to exclude fMRI neurofeedback from widespread clinical use. The cost of fMRI scanners prevents the use of the technique outside institutional facilities such as hospitals and large research centers. Although the feedback delay after fMRI processing has recently been reduced to a few seconds, it still suffers from inherent limitations due to the physical acquisition process and the hemodynamic response modeling of the BOLD signal. In particular, the peak of the BOLD hemodynamic response has a delay greater than three seconds (Aguirre, Zarahn, & D'Esposito, 1998). Another limitation is the typical setting of the acquisition room. This is a cause of significant discomfort for some individuals because of the constrained position within the scanner and the loud noises emitted by the equipment. Additionally, whereas the magnetic field created during an MRI session is not supposed to be harmful, biofeedback training typically requires several tens of sessions, and the consequences of repeated exposure to strong magnetic fields (which increase brain temperature) are not yet known.

If specific neocortical regions are of interest, an alternative solution to fMRI neurofeedback is provided by tomographic EEG biofeedback (Congedo, 2003; Congedo, Lubar, & Joffe, 2004). The main limitation of traditional EEG biofeedback is its limited spatial resolution. By the use of distributed inverse solution such as LORETA or sLORETA, much higher spatial resolution can be achieved for EEG and MEG data, preserving the excellent high temporal resolution of EEG/MEG. Other advantages include the true non-invasiveness (which does not impose limits to the number of sessions), the comfortable setting (typically, sitting in a reclined chair), and the suitable use on a larger scale due to the fact that modern EEG acquisition equipment is relatively inexpensive, especially as compared to other neuroimaging methods. Furthermore, modern EEG acquisition equipment is typically portable, and can often fit within a laptop computer case. The main limitation of the technique is the blindness to subcortical sources, which contribute very little to the observable scalp EEG, and henceforth cannot be reconstructed by EEG/EMG inverse solutions. Thus, if the target ROI is subcortical, the use of fMRI is the only solution currently available. Also, fMRI neurofeedback has to be the technique of choice in situations where spatial resolution is more important than temporal resolution.

The most widespread clinical use of neurofeedback is probably for attention enhancement. The treatment of Attention Deficit Hyperactivity Disorder (ADHD), a childhood syndrome, has reported promising results since the pioneering work of Lubar and Shouse (1976). For children in general, and especially for hyperactive children, the whole treatment can be too boring if the feedback is provided with traditional means such as bar and line graphs. That is why current practice almost universally makes use of feedback returned in the form of video games. The key point is that neurofeedback requires a considerable learning effort from the part of the participant. Performing well in a video game is generally a good motivation for a child. This lets us see directly how VR may be employed to facilitate the neurofeedback learning process. In a virtual environment (VE) it is easy to provide specific stimuli that can be used to capture the subject's attention and enhance their motivation. The first study in this direction has been carried out by Cho et al. (2002). They developed the Attention Enhancement System™ combining virtual reality and neurofeedback with the goal of assessing and treating ADHD. The

VE was a classroom containing a whiteboard, a desk, a large window allowing the user to look outdoors, a teacher, and a girlfriend. Clearly, such a VE more realistically simulates the *natural learning environment* of children and, by association, may facilitate natural learning in the actual classroom, where children with ADHD experience most problems and where they usually display more maladaptive behaviors. In this VE, children were asked to perform some cognitive training courses (e.g., form recognition) and the authors noticed that the use of an immersive VR system (see next section) was more effective for keeping children's attention as compared to a VR system based on a traditional computer display.

VIRTUAL REALITY

People generally associate virtual reality (VR) with the use of sophisticated and somehow bulky interfaces such as head-mounted displays (U.S. Patent No. 2.955.156, 1960) or data gloves (Zimmerman, Lanier, Blanchard, Bryson, & Harvill, 1987). Even researchers find it difficult to circumscribe this field and standard definitions are still subject to numerous discussions. This difficulty is a consequence of the large and heterogeneous set of tools, methods and applications used in VR. It seems that the term "virtual reality" was introduced by Myron Krueger in his famous books about "artificial reality" (Krueger, 1991). The Sensorama Simulator™ (U.S. Patent No. 3.050.870, 1962) is considered today as the first-ever workstation of virtual reality. The Sensorama™ was a whole-in-one environment, providing artificial sensations in the visual, auditory, tactile and olfactory modalities. It featured 3D video, stereo sound and vibrating seat systems.

When considering the different definitions proposed for virtual reality, we note that some notions and concepts are more frequently used. Such notions are: interaction, immersion, presence, and real-time (Burdea & Coiffet, 2003). Thus, we define a virtual reality system as an *immersive* system that provides the user with a sense of *presence* (the feeling of being there) by means of plausible interactions with a synthetic environment simulated in *real-time*. *Interaction* appears as the cornerstone of a virtual reality system. The sensory stimulations related to the interaction with a virtual environment are then the sources of the feeling of immersion.

Among the five human senses, vision is probably the one most widely used by virtual environments. Innovative visual displays such as the Cave™ of Cruz-Neira, Sandin, Defanti, Kentyon, and Hart (1992) were extensively developed in the past decade. Cave™-like virtual environments are immersive cubic spaces. The user is surrounded by two to six screens which are rear-projected in order to display stereoscopic images. The full system (i.e., with six views) can provide a 360-degree field of view in all directions. Another kind of immersive system is a wide-screen display, which provides the user with a very large field of view. Those systems are commonly used for industrial project review. In both cases, 3D objects can be displayed "flying" around the user, providing incredible sensations of living environments.

The predominant sense for interaction is the sense of touch (Burdea, 1996) since it is the only one for which the active component of interaction is possible. Indeed, hundreds of force-feedback and tactile interfaces have been developed and some of them have found commercial success such as the Phantom™ force-feedback arm (Massie & Salisbury, 1994), and the Virtuose™ (Haption, Clamart, France) which is a six degrees-of-freedom, force-feedback arm. That means that the Virtuose™ can return force and torque in all directions. For instance, it could be used to navigate in a virtual 3D brain.

Clearly, VR grows with the development of technology. Only three years ago, the VR systems we just presented were extremely bulky and expensive. In the meanwhile, the evolution of graphics hardware and high-end workstations, together with costs reductions of large LCD or flat plasma screens, make a reality center affordable to many. Several recent software solutions such as OpenSG (Reiners, Voss, & Behr, 2002) allow the transparent use of workstation clusters (a set of workstations, equipped with recent 3D hardware, interconnected using a 100 Mbits per second Ethernet network) to perform intensive tasks of virtual world simulation and rendering. One should note that such a cluster, equipped with three Intel Pentium IV™ and graphics hardware such as Nvidia FX™ or ATI Radeon™, is able to perform these tasks more than ten times faster than a three-year-old SGI Onyx II™ super-computer. Graphics cards are able to render more than one million textured and lighted polygons per second, thus they are able to display very rich visual representations of complex virtual environments. Furthermore, thanks to recent functionalities like hardware synchronization, it is now possible to perform the rendering using stereovision. This last mechanism produces a slightly different image for each eye. By wearing special glasses, the user is completely immersed in the 3D space. That is to say, 3D objects that make up the scene will be virtually placed in the empty volume that separates the user from the screen and in the infinite space behind the screen. It should also be noted that the stereovision mechanism does not necessitate a wide-screen display. It can be performed using any kind of high-resolution screen.

VR systems have been applied to a large number of applications (for a review see Burdea & Coiffet, 2003). VE have been developed for the purpose of entertainment (video games, theme parks), education and science (physical simulations, virtual classrooms), arts and design (interactive sketching or sculpture, CAD software, architecture reviews), industrial simulations (assembly or maintenance operations, data visualization) or medicine. For example, surgeons are particularly interested in using virtual environments to simulate and train themselves to perform surgical procedures (Satava & Jones, 2002). This could potentially reduce the number of training sessions that are currently spent on real patients. VR can also be used to treat patients suffering from specific phobias (e.g., claustrophobia; Krijn et al., 2004). The advantage is that in a safer and entirely controlled virtual environment, people can manage their fear more effectively. For a review of medical applications of virtual reality see Satava and Jones (2002).

BRAIN-COMPUTER INTERFACE

Typical computer user interfaces include a keyboard and a mouse. Research in human-computer interface (HCI) has always tried to improve and to simplify the control of electronic devices. Brain-computer interface (BCI) aims to use a new communication channel, *the activity of the brain*. The goal is to achieve the so called "think and make it happen without physical effort" paradigm (Garcia Molina, Ebrahimi, Hoffman, & Vesin, 2004). A typical BCI system consists of a signal acquisition device and a signal processing device. The latter outputs device-control commands. During a training phase, the participant tries repeatedly to accomplish a specific mental task. After a sufficient number of trials, given that the brain activity can be extracted in the form of a consistent, valid, and specific feature, a classification algorithm is able to translate it into a unique command. The motivation for BCI research is multiple. In medicine it springs from the problem of alleviating the condition of people suffering of complete or almost complete muscle paralysis. As a consequence of amyotrophic lateral sclerosis, brainstem stroke, brain or spinal cord injury, multiple sclerosis and many other diseases, human beings may find themselves unable to communicate with the external world. Such a severe condition is called "locked-in syndrome." A BCI system opens a channel of communication for these individuals. Beyond medical applications, BCI can also be useful for healthy people by providing them with an additional communication media, one's own *thoughts*, of which the full capabilities are still largely untapped. The use of BCI in multimedia research (e.g., game controls requiring dexterity) lets us foresee many technological multimedia applications and several fantastic scenarios. In this respect, the interest in BCI is not confined solely to clinical applications.

Over the past decade, BCI research has increased considerably. In 1995 there were only a handful of active BCI research groups. In 2002 the figure was around four times larger (Wolpaw et al., 2000). While we are writing, the trend is still upward. This rapid development of BCI research has been possible for two main reasons. First, today we have a better knowledge of brain activity, thus it has been possible to identify a few mental processes suitable for target features. Second, advances in real-time classification algorithms and the available power of inexpensive computers have filled the need for computational complexity and power.

Among the first researchers carrying out studies on BCI is the group in Gratz, Austria (Pfurtscheller et al., 2000). They used EEG signals recorded from sensorimotor areas during mental imagination of selected limbs' movements. Trials were classified on-line and used, for example, for cursor control. The Graz BCI™ system has been used by a quadriplegic patient to control the opening and closing of a hand orthosis. The subject imagined feet or right-hand movements, which controlled respectively the opening and the closing of the orthosis with 90 to 100% accuracy. The BCI system by Wolpaw, Birbaumer, McFarland, Pfurtscheller, and Vaughan (2002) was also aimed to control a prosthetic device. Subjects were trained with the Wadsworth BCI™ to move a cursor in one or two dimensions using their mu or beta rhythms. Most subjects achieved significant control over the cursor after two to three weeks of two to three, 40-minute sessions per week. In the first sessions, most subjects were also using motor imagery, but in the latter sessions, they could themselves replace it by more fitting strategies. Birbaumer et al. (2000) developed a communication device using EEG signals for completely paralyzed patients. Their Thought Translation Device™ used slow cortical potentials (SCPs) and permitted three patients to learn to spell by selecting letters on a tree-like language support program.

To achieve a better interface system Trejo et al. (2003) combined the use of EEG and electromyography (EMG) as neuroelectric interfaces. EMG signals were used to control an imaginary flight stick or to type the digits 0 through 9 on a virtual numeric keypad; whereas, EEG signals were successfully used to control a one-dimensional graphic device, like a cursor, or to detect physical keyboard typing activity. Using the imaginary flight stick, subjects were asked to fly and land two virtual "Boeing" aircrafts. The control of both was adequate for normal maneuvers. It seems that integrating several electrophysiological measurements, between modalities (e.g., EMG and EEG) and within modalities (e.g., complex EEG features) is a promising approach for the development of human-computer interfaces. The main objective of the Berlin BCI™ developed by Krepki, Blankertz, Curio, and Mûller (2003) was to let the EEG-based BCI system learn and adapt itself to the user's brain signal properties, so to make the training procedure as short as possible. Initially, participants were provided with a simple visual feedback of their intention (moving left or right) by a thick black cross moving over the screen. Then, the authors adapted the well-known "Pacman" video game as a visual biofeedback. The Pacman progressed independently by one straight step every 1.5 to 2 seconds, while the user could make it turn left or right. The color of the Pacman gave the user feedback on the direction the Pacman intended to take in the next step. Reviewing this literature, it appears obvious that BCI systems may be applied to a myriad of specific multimedia problems.

Bayliss (2003) proposed that a virtual reality environment could be useful for the training phase of a BCI system since it provides complex and controllable experimental environments. In order to compare the robustness of the evoked potential P3 over virtual and non-virtual environments, the author conducted experiments where subjects were asked to control devices like a lamp, a stereo system, a television set, etc. The results showed that there were no significant differences between the performance obtained in the virtual and in the non-virtual environment, suggesting that the P3 is suitable for BCI control in VE. Friedman et al. (2004) are on the early stages of investigating the usage of a BCI in a fully immersive system. Their goal is to evaluate how people respond to such an interface, and how their response is related to their sense of presence in VE. The paradigm used is the same as in the Graz BCI™ system, that is, imaginary movements. The achieved results show that research still needs to be done in order to navigate in a highly immersive system.

OPEN-VIBE

In both NF and BCI systems, the interaction aspect is given by the feedback loop. In the target region of the brain physiological activity is continuously recorded and the features are continuously extracted (e.g., alpha power). This information is fed back to the participant in the form of an object (visual, auditory, or both), in which one or more characteristics co-vary in real-time with the extracted feature. The loop is closed somehow by the brain, which establishes a connection between the target region and the structure implicated into the perception of the object. The object can be complex as in the case of videogames, but usually only up to three features are extracted simultaneously in real-time. Thus, in current NF implementations there it is still not possible to monitor several regions of the brain at the same time, nor is it possible to have a global view of the brain.

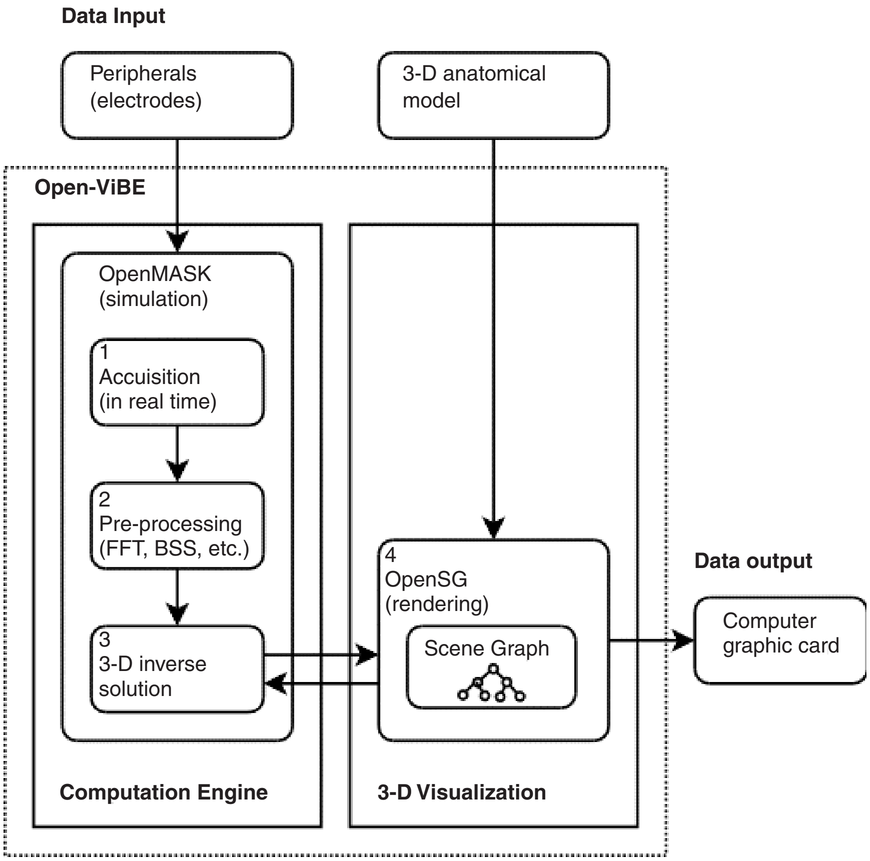
In order to overcome these limitations we have conceived Open-ViBE (Open source platform for virtual brain environment), a general purpose platform for real-time 3D virtual brain visualization. The idea is to use 3D functional electromagnetic data (e.g., sLORETA) to represent brain activity in a realistic 3D brain model. The participant's EEG is converted into intracranial current density, which is depicted conserving as much as possible the real spatial and temporal relations of the signal. The participant can virtually navigate into his/her brain and watch its electromagnetic dynamics. Possible applications include, but are not limited to, NF and BCI. Incoming data can be obtained also by fMRI, MEG, or any other suitable method. Open-ViBE may also prove useful for EEG data analysis since it enables a holistic form of data inspection.

The conception of a general purpose platform for brain activity visualization and analysis needs to take various aspects into account. First, the conception has to be modular and flexible so that the system can easily be adapted to any specific need. The underlying visualization part of the system must be able to manage a wide variety of visualization peripherals (e.g., classical display, head-mounted display, wide screen display, and stereo display; the last two allowing a better perception of depth, which is particularly useful for the user to locate himself in the 3D environment). The processing of brain activity data (e.g., EEG, fMRI, etc.) requires considerable computing power. Open-ViBE is intended to run on an ordinary PC so as to be affordable for a larger community. The underlying system should also manage the distribution of calculations on a PC cluster so as to allow high-performance applications. The development of interfaces based on brain activity requires knowledge over various fields of research. In order to facilitate the cooperation of such various research teams, the application and its source code should be made open (i.e., the *source code* should also be freely available). Finally, the platform also has to be portable to be used by many researchers in various domains; that is to say, it should be available for the most widespread operating systems, notably, GNU/Linux™ (Free Software Foundation, Boston, MA) and Windows© (Microsoft Corporation, Redmond, WA).

Those considerations have directed our choice for the development framework towards OpenMASK (Open Modular Animation and Simulation Kit; Margery, Arnaldi, Chauffaut, Donikian, & Duval, 2002). OpenMASK has been developed at the IRISA (Institut de Recherche en Informatique et Systèmes Aléatoires) in the SIAMES (Synthèse d'Image, Animation, Modélisation et Simulation) project. This framework has been conceived for the development and execution of modular applications in the fields of animation, simulation and virtual reality. It comes with multi-site (e.g., distributed simulation) and/or multi-threaded (for parallel computations) kernels which allow an easy distribution of calculations. Whereas OpenMASK manages the simulation part of the system, OpenSG (Open Scene Graph) is used for the rendering part. Figure 1 represents a schematic of how operations are performed by Open-ViBE. The data provided by the acquisition system (EEG, fMRI, etc.) enter the OpenMASK "computation engine" block, where adequate pre-processing is performed (digital filtering, recursive blind source separation [BSS] for artifact rejection, denoising, etc.). Filtered data are then sent to the "3D inverse solution" module, where current density is estimated for visible brain regions. Those current density values are sent to the OpenSG visualization kernel, which displays the degree of activation of selected brain regions by means of 3D objects placed according to the standard Talairach and Tournoux space (1988; Figure 2). The system also permits focus on one or more specific ROIs, if needed (Figure 3). Depending on the position and orientation of the observer, the computation of current density may be restricted. This is managed thanks to the continuous output of the OpenSG rendering kernel, in the "3D visualization" block. We are now going to detail the two main blocks which are OpenMASK for the simulation component and OpenSG for the rendering component.

The kernel of OpenMASK handles the execution of what we call a simulated object which is abstractly defined as a triplet (inputs, activity function, and outputs). Inputs and outputs, associated to each simulated object, are data flows of a given type: scalars, vectors, matrices or, more generally, user-defined types. The activity function describes the behavior of each simulated object and can be interpreted as a complex filtering function synthesizing outputs from current input values and eventually past inputs (this property allows the introduction of delay, smoothing, and/or temporal inertia for example) or can be interpreted as an output generator (pre-recorded data). Building an OpenMASK application con-

FIGURE 1. Open-ViBE data flow overview.



sists of describing classes of simulated objects and interconnecting them through inputs and outputs. This property enables the development of very complex and configurable applications from the set of basic simulated objects used to transform the primitive inputs. More importantly, this enables *communication* among simulated objects (i.e., object activity may depend on each other). In Open-ViBE this property is used to provide a highly configurable toolkit for analysis and visualization of brain activity. For example, a typical Open-ViBE application is real-time visualization of brain activity from recorded EEG. The simplest application is built on four modules (see Figure 1):

1. The acquisition module provides recordings of the EEG signal (in real-time or off-line).
2. The FFT (Fast Fourier Transform) module transforms the EEG signal into a frequency domain (power or amplitude vs. frequency).
3. The sLORETA module can be conceived as a spatial filter. It transforms the output of the FFT module in order to derive the inverse 3D solution and outputs activations associated to each part of the brain.
4. The rendering module uses the previously computed activations to determine the geometry and color of 3D objects representing cerebral activity inside the region of interest.

If the removal of artifacts from the original signal before the rendering process is a goal, a module dedicated to artifact removal (AR module) can be inserted between modules 2 and 3 (or 1 and 2) before computing the inverse solution. This way, different sorts of filtering processes can be dynamically added or removed (enabling interactive ap-

FIGURE 2. Using LORETA, the cerebral volume (grey matter) is divided in 2394 voxels of 7×7×7 mm^3 each. Current density at each voxel is represented by a cone where color and size co-vary with amplitude. The orientation of the cone indicates the direction of the current density vector in 3D. The brain volume is seen from the right of the head.

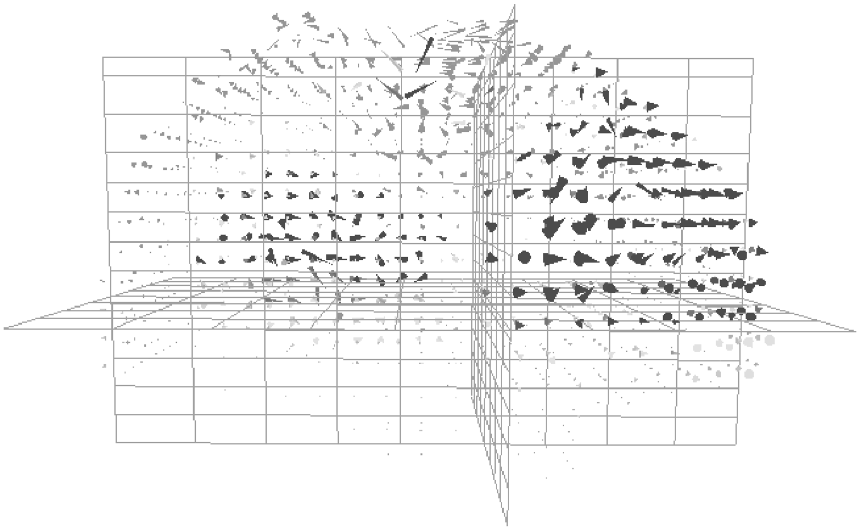
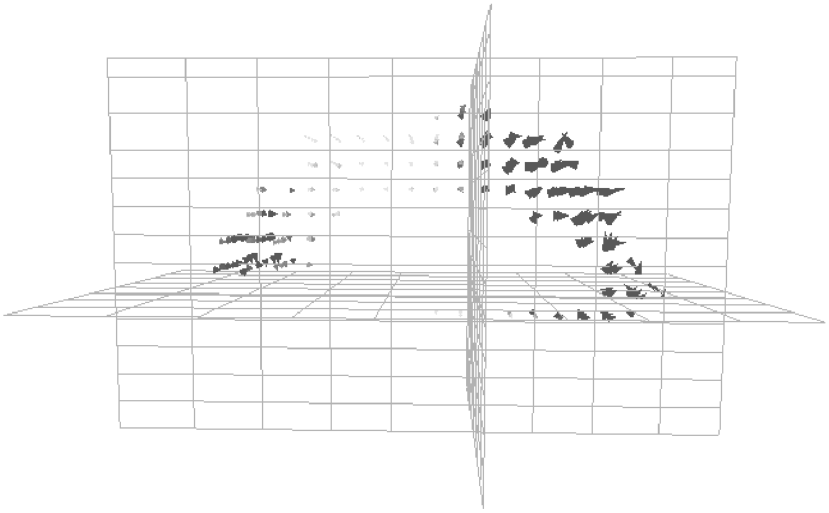


FIGURE 3. As in Figure 2, but the solution space has been restricted to the cingulate gyrus.

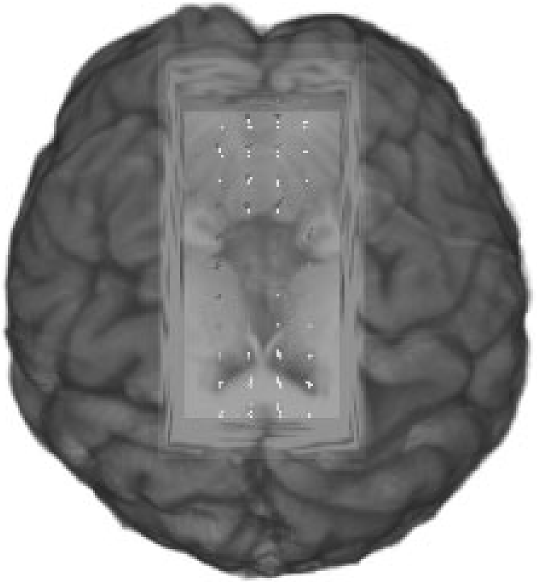


plication configuration during signal analysis and/or rendering) and different kinds of algorithms can easily be tested while improving the performances of the system. Moreover, each module (or filter) can be distributed independently as a separate simulation object and can be used for creating other real-time applications needing brain data analysis and/or visualization. This property should facilitate the exchange of different results obtained by specialists while rapidly enabling their utilization in different fields of application such as neurofeedback, virtual reality or brain-computer interface.

Open SG is used as the rendering back-end. It is a portable scene graph system, based on Open Graphics Library (Open GL; see Segal & Akeley, 1993), which aims at creating real-time graphics programs, in our case real-time 3D brain activity visualization and analysis system. Therefore, we make intensive use of its functionalities to perform the rendering of our 3D models. More precisely, we make use of the classical hardware accelerated polygonal functionalities to render the geometric primitives that represents local brain activity. In addition, we use 3D textures to represent the brain volume that is used to provide the user with visual localization facilities (Figure 4). This functionality is achieved by simply feeding MRI slices. It is also provided by OpenSG and is hardware accelerated on most currently available 3D computer graphics cards. It maps a 3D texture, which represents a regular 3D grid of brain material densities, onto a simple box. It is then possible to operate Boolean operations on the box using some other geometric primitives such as planes, cones or spheres. For instance, it is possible to remove a section of the textured mapped cube to have a look inside the brain (Figure 4). The geometric primitives are then superimposed on the brain representation which allows the user to locate the NF signals on the brain. In our experimentations we tried many new paradigms to navigate around and inside the brain using different Boolean operations (especially subtraction) together with different geometric primitives (particularly geodesic spheres). With our system we are able to render a 2562×56×256-voxel (256 MRI slices with resolution 256×256) volumetric brain together with 2394 cones at a minimum frame rate of 7 images per seconds, which allows for sufficient interactivity.

By comparison with classical brain visualization systems, OpenViBE adds the immersion aspect. It is meant to be an immersive environment that gives a wide field of view to the user, providing both local and global vision of the brain. The user can focus on a region of interest while

FIGURE 4. 3D texture rendering of individual MRI (T1) slices. Part of the brain is clipped by a parallelepipedic transparent object allowing the user to visualize the cingulate gyrus. The brain is seen from the top.



still viewing the whole brain. In addition, the use of stereo vision fills the space between the screen and the user with the virtual environment. Those two aspects, immersive and stereo visualization, provide the user with the sense of *presence*, which is a fundamental concept of virtual environments that we hypothesize may be beneficial for the efficacy of neurofeedback and BCI systems.

DISCUSSION

In this paper we reviewed recent NF and BCI research, giving emphasis to their similarities, notably the interaction between the user and the system. We outlined some developments in VR that can be employed in NF and BCI systems to enhance their feedback capabilities. This review served as a background to introduce Open-ViBE, a general platform conceived to build brain virtual environments based upon any kind of real-time neuroimaging data. In particular, we gave an example of an EEG real-time feedback providing application.

The most appreciable qualities of neurofeedback are that it is non-invasive and that it requires an active role on the part of the patient. In some cases, neurofeedback training may completely replace the use of psychoactive medications. This quality makes it a preferred choice especially in the case of children and adolescents, individuals for which the balance of neurotransmitters and the brain anatomy are still in formation. The validity of the signal fed back to the user is crucial for optimal results. Unfortunately, in current NF systems the feedback is buried into noise, henceforth the chance of non-contingent reinforcement is high. With the use of VR in NF, we aim to improve the feedback and facilitate the training, which is also a first step in BCI systems, while by the use of recent blind source separation methods (Cichocki & Amari, 2002) we plan to incorporate efficient real-time automatic denoising routines.

Whereas NF has existed since the late 1960s, BCI is a very young field. Regardless of the BCI system used, the training part to tune the BCI classification algorithm is a fundamental aspect of its success. Clearly, methods used in NF and in BCI are very similar in this regard. Results in BCI research, albeit encouraging, are still of limited use. In fact, the maximum reported number of binary commands per minute that a human subject has been capable to achieve is around 20 (Wolpaw et al., 2000). Such a transfer rate is a great achievement for people suffering with locked-in syndrome, where any rate is better than nothing; but, as the same time, it is still too low for practical non-clinical applications.

The common characteristic of all systems we have taken into consideration in this paper is interactive analysis/visualisation of brain data. The notion of interactivity raises the problem of computation efficiency. Open-ViBE takes advantage of OpenMASK abilities in the field of parallel computation enabling efficient use of multiprocessor machines as well as computer PC clusters. Moreover, in OpenMASK each module is responsible for a specific computation which can be used by several other modules (i.e., one output can be connected to several inputs). This modularity enables the factorization of different operations by computing a transformation/filter once and reusing the output several times, when needed. Finally, the flexibility of the framework enables the link to highly efficient mathematical libraries such as BLAS (enabling intensive computation based on matrices; Dongarra, Du Croz, Duff, & Hammarling, 1990) or, in general, to any higher level libraries for digital signal processing.

The Open-ViBE system is meant to be the basis for further development of extremely efficient applications in neurofeedback, virtual reality and brain-computer interface. We aim to facilitate the creation of a community of interest composed of users and developers. With Open-ViBE, users can freely obtain the software and developers can easily contribute with modules or documentation, since the source code is shared. This way, the community may benefit from all advances. We believe that real-time neuroimaging will soon affirm itself as an independent but unified field of research within the neurosciences. Such a field will require specialized proficiency in digital signal processing, computer graphics, multimedia (audio and video), and brain physiology. Indeed, as for neuroscience in general, it appears that this new domain will flourish better in a multidisciplinary setting.

REFERENCES

Aguirre, G. K., Zarahn, E., & D'Esposito, M. (1998). The variability of human BOLD hemodynamic responses. *Neuroimage*, *8*, 360-369.

ATI Radeon™ Technologies Inc. Markham, Ontario, Canada. Retrieved May 10, 2004 from http://www.ati.com/.

Barabasz, M., & Barabasz, A. (1996). Attention deficit disorder: Diagnosis, etiology and treatment. *Child Study Journal*, *26* (1), 1-37.

Bayliss, J. (2003). Use of the evoked potential P3 component for control in a virtual apartment. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, *11* (2), 113-116.

Berger, H. (1929). Über das Elektroenkephalogram des Menschen. *Arch. F. Psychiat*. *87*, 527-570.

Birbaumer, N., Kübler, A., Ghanayim, N., Hinterberger, T., Perelmouter, J., Kaiser, J., et al. (2000). The thought translation device (TTD) for completely paralyzed patients. *IEEE Transactions on Rehabilitation Engineering*, *8* (2), 190-193.

Burdea, G. (1996). *Force and touch feedback for virtual reality*. New York: John Wiley and Sons.

Burdea, G., & Coiffet, P. (2003). *Virtual reality technology*. New York: John Wiley and Sons.

Cichocki, A., & Amari, S. (2002). *Adaptive blind signal and image processing: Learning algorithms and applications*. New York: John Wiley and Sons.

Cho, B. H., Lee, J. M., Ku, J. H., Jang, D. P., Kim, J. S. Kim, I. Y., et al. (2002, March). Attention enhancement system using virtual reality and EEG biofeedback. *Proceedings of the IEEE Virtual Reality Conference*, 156-164.

Congedo, M. (2003). Tomographic neurofeedback: A new technique for the self-regulation of brain activity. Unpublished doctoral dissertation, University of Tennessee, Knoxville.

Congedo, M., Lubar, J. F., & Joffe, D. (2004). Low-resolution electromagnetic tomography neurofeedback. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, *12* (4), 387-397.

Cooley, J. W., & Tukey, J. W. (1965). An algorithm for the machine calculation of complex Fourier series. *Mathematics of Computation*, *19*, 297-301.

Cruz-Neira, C., Sandin, D. J., Defanti, T. A., Kentyon, R. V., & Hart, J. C. (1992). The CAVE: Audio visual experience automatic virtual environment. *Communications of the ACM*, *35* (6), 64-72.

deCharms, R. C., Christoff, K., Glover, G. H., Pauly, J. M., Whitfield, S., & Gabrieli, J. D. (2004). Learned regulation of spatially localized brain activation using real-time fMRI. *NeuroImage*, *21* (1), 436-443.

Dongarra, J. J., Du Croz, J., Duff, I. S., & Hammarling, S. (1990). A set of level 3 basic linear algebra subprograms. *ACM Transactions on Mathematical Software*, *16*, 18-28.

Engstrom, D. R., London, P., & Hart, J. T. (1970). Hypnotic susceptibility increased by EEG alpha training. *Nature*, *227*, 1261-1262.

Fernandez, T., Herrera, W., Harmony, T., Diaz-Comas, L., Santiago, E., Sanchez, L., et al. (2003). EEG and behavioral changes following neurofeedback treatment in learning disabled children. *Clinical Electroencephalography*, *34* (3), 145-152.

Friedman, D., Slater, M., Steed, A., Leeb, R., Pfurtscheller, G., & Guger, G. (2004, March). Using a brain-computer interface in highly-immersive virtual reality. Paper presented at the IEEE VR Workshop, Chicago, IL.

Fuchs, T., Birbaumer, N., Lutzenberger, W., Gruzelier, J. H., & Kaiser, J. (2003). Neurofeedback treatment for attention-deficit/hyperactivity disorder in children: A comparison with methylphenidate. *Applied Psychophysiology and Biofeedback*, *28* (1), 1-12.

Garcia Molina, G. N., Hoffman, U., Ebrahimi, T., & Vesin, J. M. (2004). Direct brain-computer communication through EEG signals. IEEE EMBS book Series on neural engineering.

Heilig, M. (1960). *US Patent # 2.955.156*. Washington, DC: U.S. Patent and Trademark Office.

Heilig, M. (1962). *US Patent #3.050.870*. Washington, DC: U.S. Patent and Trademark Office.

Hinterberger, T., Veit, R., Strehl, U., Trevorrow, T., Erb, M., Kotchoubey, B., et al. (2003). Brain areas activated in fMRI during self-regulation of slow cortical potentials (SCPs). *Experimental Brain Research*, *152* (1), 113-122.

James, L. C., & Folen, R. A. (1996). EEG biofeedback as a treatment for chronic fatigue syndrome: A controlled case report. *Behavioral Medicine*, *22*, 77-81.

Krepki, R., Blankertz, B., Curio, G., & Müller, K. R. (2003). The Berlin brain-computer interface (BBCI): Towards a new communication channel for online control of multimedia applications and computer games. *9th International Conference on Distributed Multimedia Systems (DMS'03), 237-244*.

Krijn, M., Emmelkamp, P. M. G., Biemond, R., de Wilde de Ligny, C., Schuemie, M. J., & van der Mast, C. A. P. G. (2004). Treatment of acrophobia in virtual reality: The role of immersion and presence. *Behaviour Research and Therapy*, *42* (2), 229-239.

Krueger, M. (1991). *Artificial reality II*. Reading, MA: Addison-Wesley.

Lubar, J. F. (1991). Discourse on the development of EEG diagnostics and biofeedback for attention deficit/hyperactivity disorders. *Biofeedback and Self-Regulation*, *16* (3), 201-225.

Lubar, J. F. (1997). Neocortical dynamics: Implications for understanding the role of neurofeedback and related techniques for the enhancement of attention. *Applied Psychophysiology and Biofeedback*, *22* (2), 111-126.

Lubar, J. F., & Bahler, W. W. (1976). Behavioral management of epileptic seizures following EEG biofeedback training of the sensorimotor rhythm. *Biofeedback and Self-Regulation*, *1* (1), 77-104.

Lubar, J. F., & Shouse, M. N. (1976). EEG and behavioral changes in a hyperkinetic child concurrent with training of the sensorimotor rhythms (SMR). *Biofeedback and Self-Regulation*, *1* (3), 293-306.

Lubar, J. F., Shabsin, H. S., Netelson, S. E., Holder, G. S., Whitsett, S. F., Pamplin, W. E., et al., (1981). EEG operant conditioning in intractable epileptic. *Archive of Neurology*, *38*, 700-704.

Margery, D. (2002). OpenMASK: Multi-threaded animation and simulation kernel. Theory and practice. Retrieved May 10, 2004 from http://www.openmask.org/.

Margery, D., Arnaldi, B., Chauffaut, A., Donikian, S., & Duval, T. (2002, June). OpenMASK: Multi-threaded or nodular animation and simulation kernel or kit: A general introduction. *VRIC 2002 Proceedings*, 101-110.

Massie, T., & Salisbury J. K. (1994). The PHANToM Haptic Interface: A device for probing virtual objects. *Proceedings of the ASME Winter Annual Meeting*, *55* (1), 295-300.

Moore, N. C. (2000). A review of EEG biofeedback treatment of anxiety disorders. *Clinical Electroencephalography*, *31* (1), 1-6.

Nowlis, D. P., & Kamiya, J. (1970). The control of electroencephalographic alpha rhythms through auditory feedback and the associated mental activity. *Psychophysiology*, *6* (4), 476-484.

Nvidia™, Santa Clara, California. Retrieved May 10, 2004 from http://www.nvidia.com/page/home/.

Pascual-Marqui, R. D. (1995). Reply to comments by Hämäläinen, Ilmonieni, and Nunez. In W. Skrandies (Ed.). Source localization: Continuing discussion on the inverse problem. *ISBET Newsletter*, *6*, 16-28.

Pascual-Marqui, R. D. (1999). Review of methods for solving the EEG inverse problem. *International Journal of Bioelectromagnetism*, *1* (1), 75-86.

Pascual-Marqui, R. D. (2002). Standardized low resolution brain electromagnetic tomography (sLORETA): Technical details. *Methods and Findings in Experimental & Clinical Pharmacology*, *24 D*, 5-12.

Pascual-Marqui, R. D., Michel, C. M., & Lehmann, D. (1994). Low resolution electromagnetic tomography: A new method for localizing electrical activity in the brain. *International Journal of Psychophysiology*, *18*, 49-65.

Pfurtscheller, G., Neuper, C., Guger, C., Harkam, W., Ramoser, H., Schlög, A., et al. (2000). Current trends in Graz brain-computer interface (BCI) research. *IEEE Transactions on Rehabilitation Engineering*, *8* (2), 216-219.

Reiners, D., Voss, G., & Behr, J. (2002, January). OpenSG: Basis concepts. Presentation at 1st OpenSG Symposium, Darmstadt, Germany. Retrieved May 10, 2004 from http://www.opensg.org/.

Rosenfeld, J. P. (2000). An EEG biofeedback protocol for affective disorders. *Clinical Electroencephalography*, *3* (1), 7-12.

Satava, R. M., & Jones, S. B. (2002). Medical applications of virtual reality. In K. Stanney (Ed.), *Handbook of virtual environments: Design, implementation, and applications* (pp. 937-958). Mahwah, NJ: Lawrence Erlbaum Associates.

Segal, M., & Akeley, K. (1993). The openGL graphics interface. Mountain View, CA: SGI™ Silicon Graphics Computer Systems. Retrieved May 12, 2004 from http://www.sgi.com/.

Sterman, M. B. (1973). Neurophysiologic and clinical studies of sensorimotor EEG biofeedback training: Some effects on epilepsy. *Seminar in Psychiatry*, *5* (4), 507-525.

Sterman, M. B. (1981). EEG biofeedback: Physiological behavior modification. *Neuroscience and Biobehavioral Reviews*, *5*, 405-412.

Sutherland, I. (1965). The ultimate display. In *Proceedings of IFIPS Congress (New York City)*, *2*, 506-508.

Swingle, P. G. (1998). Neurofeedback treatment of pseudoseizure disorder. *Biological Psychiatry*, *44*, 1196-1199.

Talairach, J., & Tournoux, P. (1988). *Co-planar stereotaxic atlas of the human brain*. New York: Thieme.

Thornton, K. E. (2002). The improvement/rehabilitation of auditory memory functioning with EEG biofeedback. *NeuroRehabilitation*, *17*, 69-80.

Travis, T. A., Kondo, C. Y., & Knott, J. R. (1974). Alpha conditioning: A controlled study. *The Journal of Nervous and Mental Disease*, *158*, 163-173.

Trejo, L. J., Wheeler, K. R., Jorgensen, C. C., Rosipal, R., Clanton, S. T., Matthews, B., et al. (2003). Multimodal neuroelectric interface development. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, *11* (2), 199-204.

Vernon, D., Frick, A., & Gruzelier, J. (2004). Neurofeedback as a treatment for ADHD: A methodological review with implications for future research. *Journal of Neurotherapy*, *8* (2), 53-82.

Weiskopf, N., Veit, R., Erb, M., Mathiak, K., Grodd, W., Goebel, R., et al. (2003). Physiological self-regulation of regional brain activity using real-time functional magnetic resonance imaging (fMRI): Methodology and exemplary data. *NeuroImage*, *19*, 577-586.

Wolpaw, J. R., Birbaumer, N., Heetderks, W.J., McFarland, D. J., Peckham, P. H., Schalk, G., et al. (2000). Brain-computer interface technology: A review of the first international meeting. *IEEE Transactions on Rehabilitation Engineering*, *8* (2), 164-173.

Wolpaw, J. R., Birbaumer, N., McFarland, D. J., Pfurtscheller, G., & Vaughan, T. M. (2002). Brain-computer interfaces for communication and control. *Clinical Neurophysiology*, *113*, 767-791.

Yoo, S. S., & Jolesz, F. A. (2002). Functional MRI for neurofeedback: Feasibility study on a hand motor task. *Neuroreport*, *13* (11), 1377-1381.

Zimmerman, T. G., Lanier, J., Blanchard, C., Bryson, S., & Harvill, Y. (1987). A hand gesture interface device. In *Proceedings of the SIGCHI/GI Conference on Human Factors in Computing Systems and Graphics Interface*, 189-192.

RECEIVED: 06/23/04
REVISED: 10/11/04
ACCEPTED: 11/07/04